Robotics 2020
Multi-Annual Roadmap

For Robotics in Europe

Horizon 2020 Call ICT-2017 (ICT-25, ICT-27 & ICT-28)

Release B 02/12/2016

SPARC
The Partnership for
Robotics in Europe

Rev A: Initial release for Comment.

Rev B: Final release.

Contents

{Note: This release of the MAR is designed to cover the Robotics and Autonomous Systems part of the ICT Call in Horizon 2020, specifically the targets set within ICT-25-2016-2017, ICT-27-2017 & ICT-28-2017 of Horizon 2020. This is the final "long form" version of the MAR to be produced.}

In this MAR Release…

It should be noted that this is the last release of the MAR in this format and that for the ICT-2018/19/20 work programmes a different shorter format will be adopted.

This version of the MAR relates to the Horizon 2020 Call ICT-2017 ICT-25, ICT-27 & ICT-28. It contains the following changes from the previous MAR release:

Introduction

This section remains substantially unchanged from the ICT-2016 version except for the addition of a brief overview of ICT-25, ICT-27 & ICT-28.

Domains

Since there is no Domain priority specified in ICT-2016 & ICT-2017 all of the Domain sections remain as an illustration of the breadth of robotics application. Some minor updating has taken place to the lists of current projects.

Two additional sub-domain sections have been added; Construction Robotics, Laboratory Robotics.

Robot Categories

The Robot Categories section remains unchanged from the ICT-2016 version

Abilities

The Ability section remains unchanged from the ICT-2016 version.

Technologies

The technology section contains some additions to the Navigation section.

Innovation

The Innovation section on Standards has been updated to reflect changes in standards since the 2015 MAR publication.

1. Introduction

This Multi-Annual Roadmap (MAR) is a companion to the Strategic Research Agenda (SRA) providing a greater level of technical and market detail.

It is updated annually as priorities, technologies and strategic developments shape European research development and innovation (R&D&I). The annual update follows a process that utilises the expertise within Topic Groups formed by euRobotics aisbl and seeks open consultation.

The priorities for R&D&I funding, including near market activities, will be derived from the MAR as a part of the annual review cycle. The MAR is referenced within the Horizon 2020 ICT work programme document. The work programme shares a common descriptive framework with the MAR and the MAR is used as a reference document for proposers and evaluators.

Robotics is a diverse field and this roadmap relies on expert opinion in each domain and technical cluster to provide and verify the information within it. The annual review process examines each key technical and market area to ensure material is brought up to date at least once per annum.

You, the reader, are encouraged to engage with this process and to contribute your knowledge to the content of this document. It will then reflect and sustain a live discourse on the current state of robotics technology. You can do this by joining euRobotics and by contributing to the associated Topic Groups.

1.1 MAR Content

The companion to this document, the Strategic Research Agenda (SRA), provides a high level strategic overview of the European robotics community and its objectives. It also provides a descriptive framework for robotics, its market, technology and robot types. This framework of description is used extensively in this roadmap.

This document, the Multi-Annual Roadmap (MAR), is a detailed technical guide that identifies expected progress within the community and provides an analysis of medium to long term research and innovation goals.

This document aims to provide the following:

- Further details of the applications and markets outlined in the SRA.
- Background and progress targets for the technologies outlined in the SRA.
- Basic information about the Public Private Partnership (PPP) and the Horizon 2020 instruments.
- An overview of potential impact on market domains of step changes in technical capability and system ability.
- An overview of applications and targets for progress in each area.
- An overview of the contribution robotics technology can make to the European Societal Challenges.

1.2 Reading the Roadmap

Each person will read this document, and the Strategic Research Agenda, with a different perspective. In creating this resource the aim has been to take these different perspectives into account.

1.2.1. Why read this document?

Do you work in an industry or service sector where you think robotics technology can be applied?

> *Then you may wish to start by identifying your particular market sector and working through the applications to uncover the types of robots and technologies that might be applicable to your market.*

Are you a researcher trying to understand the level of capability of a particular robotics technology?

> *Then you may wish to start by examining the technology clusters to find the technology you are interested in and then exploring the current and expected future capability and its impact on applications. You may also be interested in the general system abilities of robots to understand how the technology you are interested in might impact on these abilities.*

Are you a researcher who believes that they have a technology that could be of use to the robotics community?

> *Then you may wish to start by looking at the technology clusters to see if your technology can be fitted in. This may give you new ideas, or help you identify others providing similar technology. It may also lead you to which application domains may be the most likely to exploit your type of technology.*

Are you a policy maker trying to understand the European robotics community?

Then you may need to read the Strategic Research Agenda to gain a background understanding of robotics and its application. If you have already done this then you may find the sections in this document on markets useful in order to understand potential areas of application.

Are you involved in financing or managing start-ups and wish to understand the opportunities in robotics?

Then you may want to look at the different market domains and see where you can find opportunities, or may be you can identify a new area of application. You may also wish to examine the different technology sectors to see where current development is taking place or examine the current set of research priorities.

Are you a potential user of robotics technology and wish to understand the general capability level of robots?

Then you should examine the Abilities section and gain an understanding of what can be achieved with current technology and what might still lie in the future. Similarly you should examine the market domains so understand how robots are being applied in different industries and what the future might hold.

1.3 Understanding the MAR

1.3.1. MAR Background

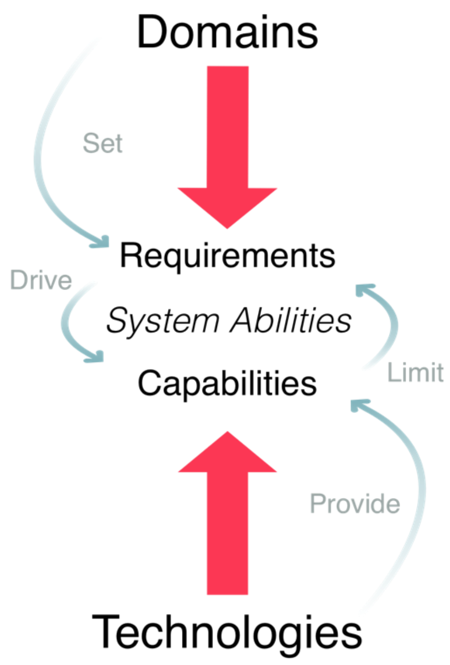
The MAR and SRA together provide a framework within which proposals aimed at the call ICT-2017 should fit. In particular proposals should demonstrate:

- A clear exposition of any step changes in technology that the proposed project aims towards
- The identification of Ability Levels that represent the current state of the art within the application area of the proposal, and a clear statement of the Ability Levels that will result from the proposal.
- An understanding of the target market requirements, even if those are not to be fully met within the proposed project
- An realistic understanding of the starting TRL of the proposed project justified against the TRL descriptions in this document.
- A target for the end TRL, together with a convincing description of how such a progression towards the proposed market goals can be made with the proposed plan and resource.
- A convincing delivery mechanism for achieving the impact claimed for the proposed project

The research and innovation actions detailed in ICT-2017 of the Horizon 2020 Call are based on this Roadmap which describes the progression of technologies and applications and the links between them.

The goals of the Roadmap are:

- To provide a common framework of description for robotics within Europe.
- To provide a clear set of goals for market relevant technical development.
- To illustrate the relevance of these goals with respect to future market opportunity.



The descriptive framework used within the MAR allows comparison between and within projects when referring to robotics technology and systems and helps to link technology development with user driven market needs. This is a conventional Road-mapping activity with market domains setting requirements and technologies driving capabilities that fulfil those requirements. The approach uses non-domain specific and non-technology specific System Abilities to map market requirements to technology capabilities and vice versa. This common goal approach helps identify the cross cutting technologies that impact on multiple market domains while allowing unforeseen technology developments to be integrated by referring to System Ability independently of technology.

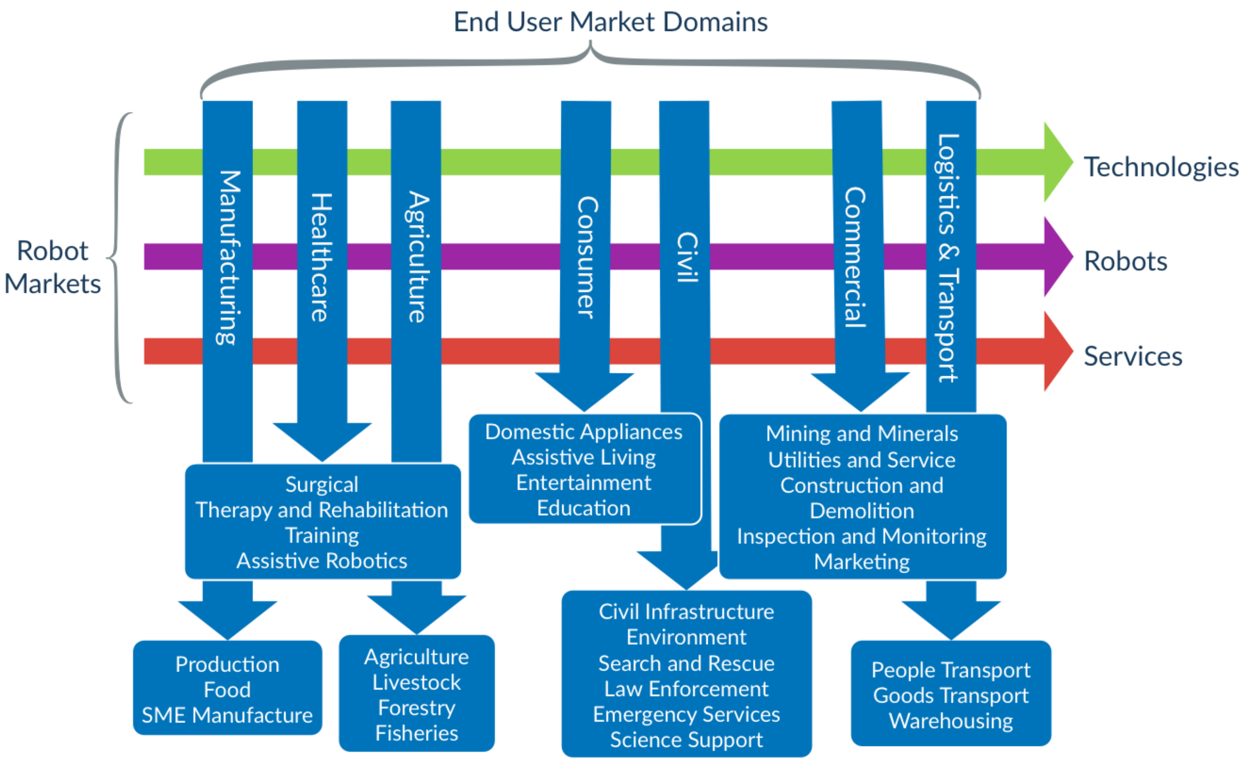
The roadmap identifies opportunities for innovation, current technical capability and sets out the R&D&I agenda for each Domain.

1.3.2. Structure of the MAR

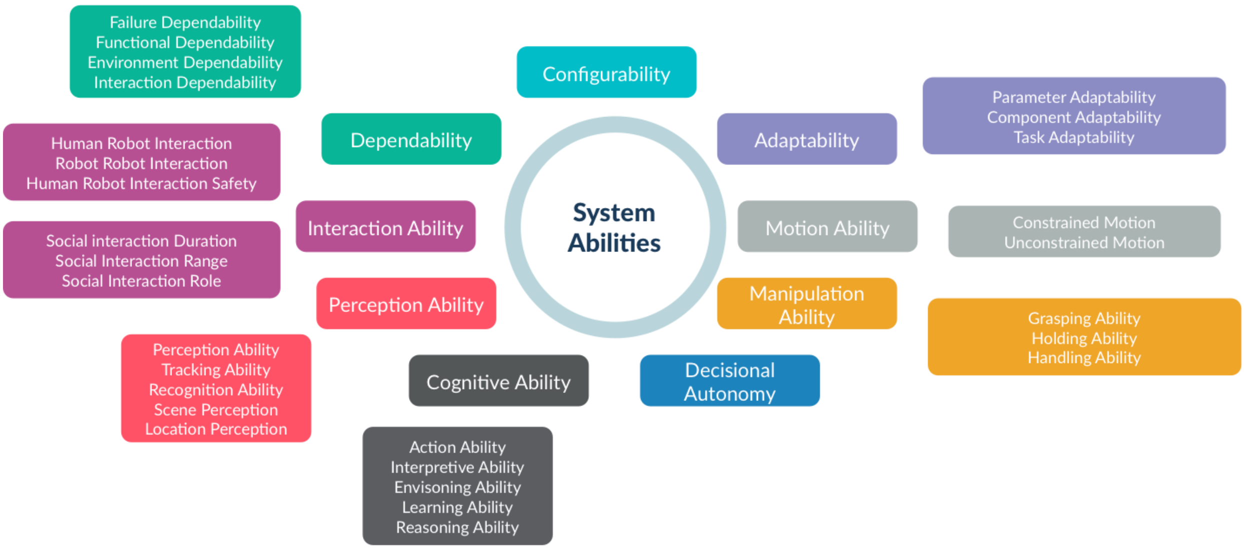
The MAR primarily covers three areas: Domains, System Abilities and Technologies.

The MAR should not be viewed as a linear document, each section should be taken in context and treated as a point of reference. The Domains detailed in the MAR are those highlighted by the SRA as being where Robotics Technology will have a high level of impact. Each System Ability and each Technology is detailed so that high level targets can be established. **It is not the intention of the MAR to be encyclopaedic.** It does not detail techniques and methods within each technology, nor does it attempt to detail all possible end applications for robotics technology. Its aim is to provide a strong indication of direction and priority.

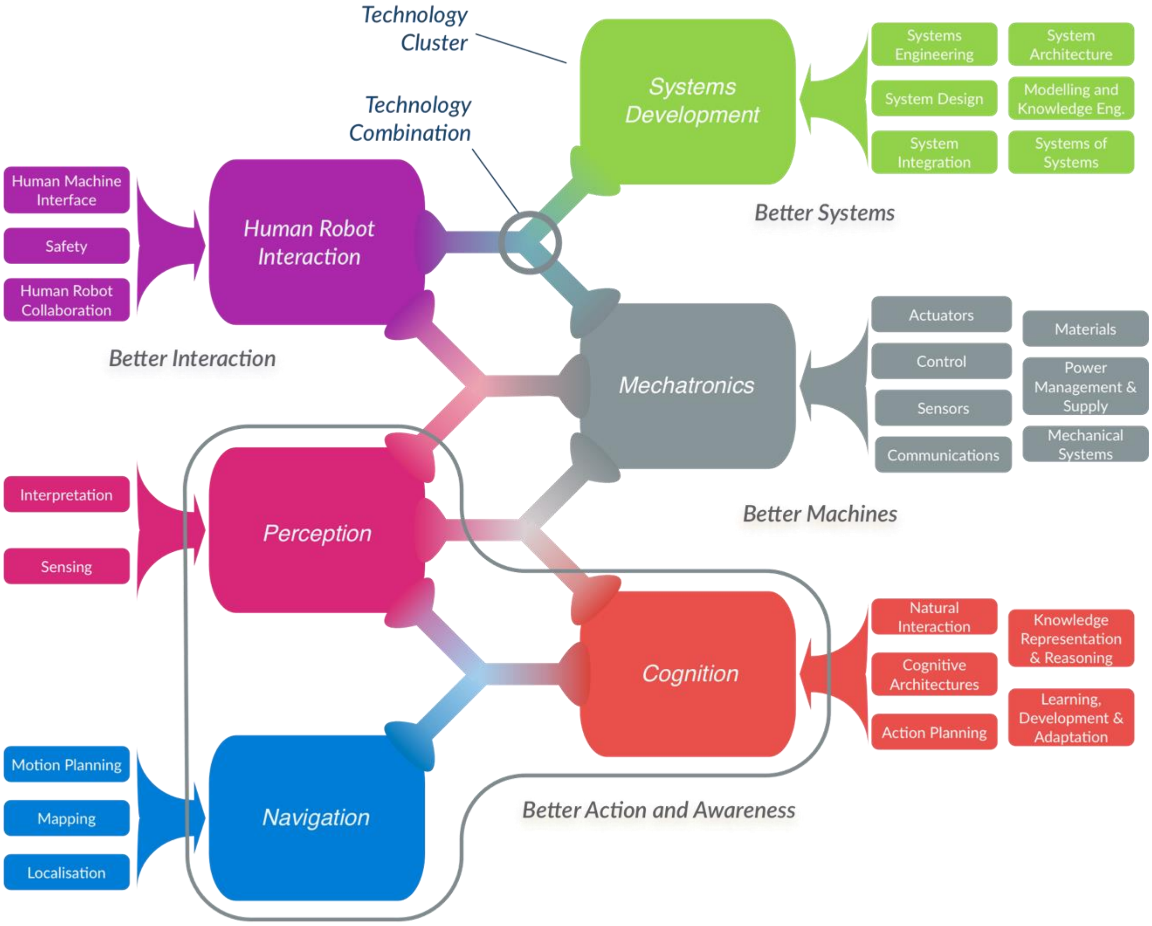
Domains are based on the different business models which in turn capture all parts of the market for robotics technology. The Domain overview moves beyond the simple division of markets into Industrial and Service and acknowledges the wide impact of robotics technologies and the importance of vertical end user markets.



System Abilities (Adaptability, Cognitive Ability, Configurability, Decisional Autonomy, Dependability, Interaction Ability, Manipulation Ability, Motion Ability and Perception Ability) provide an application, domain and technology independent way of characterising whole system performance and through the definition of levels identify the different abilities that robotic systems can possess.



Technologies are divided into clusters each characterised by a purpose; Systems Development: Better systems and tools; Human Robot Interaction: Better interaction; Mechatronics: Making better machines; Perception, Navigation and Cognition: Better action and awareness. Details are given of the underlying individual technical components in each cluster and of metrics and benchmarks that may be used to establish the state of the art and thus future progress. The MAR does not detail methods or techniques within these technologies instead it examines what technologies deliver to systems and the links both between technologies and between technologies and applications.



1.3.3. Technical Progression in the MAR

The MAR identifies several different types of technical progression:

- Step changes in the capability of individual technologies
- Improvements in System Ability Levels and Parameters in specific applications.
- Advancement of TRL levels applied to a particular module, system or application.

Technical step changes represent significant advances in technical capability and are likely to impact across different market domains. Step changes are either; multiplicative advances in technical capability in terms of quantifiable metric changes (for example a system being able to recognise 100 everyday objects where the state of the art is 10 objects); or a categorical step change in a technology that radically alters what can be achieved at an application level (for example moving from graphical user interfaces to more intuitive physical interaction interfaces). Step changes are expected to have an identifiable impact on applications and markets.

System Ability Levels provide a way of mapping system ability in one of the nine key system abilities The abilities are described in detail in the SRA and MAR. Each is assigned a series of levels. Ability Levels provide a progressive characterisation of what any system might be required to do. They do so without reference to the technologies that create the Ability and without reference to the application. Ability Levels provide a way of characterising systems in terms of the requirements of a particular application. They allow proposers to declare the current state of the art and the intended goal of a project in a uniform way.

The **TRL level** names follow the naming convention established within Horizon 2020. The MAR provides some examples of these level names within a robotics technology context. It is particularly important that there is a common understanding of the nature of each level as this has a significant impact on the viability of subsequent technology transfer actions.

1.3.4. Use of the MAR in Proposals

The MAR is explicitly and implicitly referenced within the Call Text. The meaning of many key phrases in the Call text are contained within the descriptive framework of the SRA and MAR. It is expected that proposals will directly refer to the relevant sections of the MAR that they impact on. By referencing this defined framework proposals should not need to detail and justify their context and impact unless their context differs from that contained within the MAR. Since the application contexts within the MAR are constructed by domain experts these represent currently held and realistic viewpoints. Specific information about the current Call can also be found within the Q&A document published alongside the Call Text.

With respect to Technical Capability Step Changes and System Ability Levels it is expected that proposals will situate themselves within this technical landscape by using the terminology of the MAR to set out both the current State of the Art and the expected achievements of the proposal. System Ability Levels provide a common framework for expressing the State of the Art within a given application with respect to the different properties of a system and expressing the intended end point of a proposal. Should a more fine grained approach be needed for a particular application area then proposers should use the current sets of Ability Levels and Ability Parameters as reference points.

Projects are expected to establish a realistic view of their current TRL level based on the key technical elements within any proposed system. Typically the TRL of a system is that of its lowest element with respect to the application target. The real world justification of TRL status and a realistic assessment of the actions and efforts needed to increment the TRL level are a key part of establishing the state of the art. It is important to establish benchmarks with respect to TRL progression. The current expectation is that within a 2-3 year timeframe there will be at least a single TRL increment achieved. Since TRL increment refers to the progress towards market it is unlikely, for the higher TRL levels and within Innovation actions, that this can be achieved without an industrial or end user partner.

1.3.5. Focus within ICT-25, ICT-27 & ICT-28

The current Horizon 2020 work programme has been developed using input from the SPARC Public Private Partnership between euRobotics aisbl, the European Robotics Association and the European Commission. This collaboration has resulted in a more focused work programme taking into account strategic directions identified in consultation with the wider European robotics community.

When writing proposals it is instructive to carefully consider the phrases used in the Call Text that are designed to establish this focus on a target by target basis. Key concepts underlie this focus notably the need to demonstrate real market impact, to take into account end user needs and to make progress beyond the state of the art. Constructing proposals and more importantly consortia to address a target with the right balance of technical and market expertise is critical to developing an excellent proposal.

A number of targets within the Call specifically focus on parts of the MAR relating to either technology capability, abilities or specific areas of technology. The current call does not focus on specific domains or on specific configurations of robot.

1.3.5.1 ICT-25

This target remains unchanged from ICT-2016, Its RIA focus is placed on cross cutting technologies that have application across multiple domains and on developing technologies that can create step changes. Its IA focus is on end-user driven application development beyond TRL 5, where it is important to generate economic and operational data to reduce future investment risk, and on application areas where technical and regulatory gaps present barriers to market.

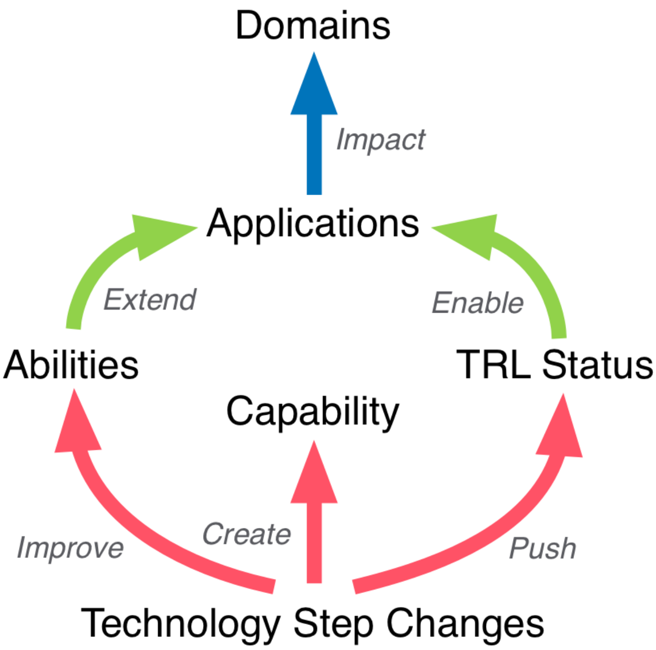
1.3.5.2 ICT-27

The first sub-target focuses on specific system abilities noted in the Call text which relate to improved dependability. The second sub-target focuses on SME based research and addresses the need for SME's to engage more fully with research to develop novel products. This is set out as a Cascade Action sometimes referred to as a Funding Support for Third Parties (FSTP) action. The final RIA target concerns the development of application relevant benchmarks and metrics that are helpful to an end user in assessing the capability of robotic systems. The IA target addresses a Cascade Action (FSTP) to develop testing protocols for safety assessment in collaborative systems and to test and disseminate these protocols.

ICT-27 also includes a Pre-Commercial Procurement action (PcP) in smart cities.

1.3.5.3 ICT-28

This target details two Coordination and Support Actions (CSA). The first covers non-technical barriers to take-up, standards and regulation, community support and the second addresses competitions.



1.3.6. Step Changes and TRLs

Technology Step Changes in capability drive up both TRL levels and System Ability Levels. The effect of any particular Step Change will depend on the application area. Step Changes in capability extend the ability of applications to achieve specific functions within an area of application. Technical Step Changes can also raise TRL levels which eventually enable new products to reach the market. While this is not a fixed rule, in general, multiplicative Step Changes will typically raise TRL levels and categorical Step Changes will typically raise System Ability Levels.

It is important to understand the difference between technical capability Step Changes, Ability Level shifts, and TRL level increments. Technical Step Changes underlie both TRL increments and System Ability Shifts and these technical steps may come from robotics technology, process technology or external technology, (e.g. a new battery chemistry). A TRL increment is very likely to require more than one step change in technology, since multiple technologies will be needed to realise a system. System Ability Level Shifts may result from single important steps in a key technology or more likely a number of steps in a key technology combination.

It is this cross dependence between technology steps and TRL and System Ability shifts that underlies the importance of stimulating and recognising Step Changes in technical capability. Recognising Step Changes and in particular recognising Step Changes in several technologies that has a combined impact will help the TRL push and the Ability improvements that are generated reach market faster.

1.3.7. MAR Summary

The SRA and MAR provide a descriptive framework for robotics in Europe. Each document is produced with the consensus of the robotics community. The SRA provides a higher level strategic overview and the MAR provides in-depth technical detail. The SRA and MAR cover both application areas and technologies. They can be seen as following a conventional Road-mapping format where market domains set requirements and technologies drive capabilities. Interspersed between domains and technologies are non-domain specific and non-technology specific System Abilities. These are used to map market requirements to technology capabilities and vice versa.

The MAR details different types of technical progression and links them to their market context. It also details the main application opportunities in each domain and provides details of the technology landscape for robotics.

These documents are not intended to be encyclopaedic but are instead designed to provide a comprehensive overview of research and innovation opportunity within a European market context to support the Horizon 2020 Calls.

2. Markets and Applications

Robotics technology can be deployed in a wide range of different market domains. Each domain has its own needs and requirements. These must be captured and assessed in order to direct R&D&I funding where it will have the greatest impact.

The robotics market place is also complex involving a diverse range of opportunities. Organisations may create value by concentrating on specific end applications, supplying different types of robot, modules, sub-systems, tools, or providing services within the market. It also includes dedicated supply chains, design services, and research and development organisations. Providing a coherent categorisation of the potential in each type of market is an important step in evaluating the potential for robotics and robotics technology.

The SRA provides an overview of the major application domains and the Roadmap provides a breakdown of the different areas of activity. This illustrates the opportunity for innovation and provides a basis for identifying linkage between current and future technology capability and market impact.

Within the Roadmap this market characterisation needs to be accessible to different observers. Observers from outside of the robotics community need to be able to understand the potential impact of robotics technology in their own market sector. Observers from the robotics community need to understand their context within the internal and external markets.

Each market domain will present barriers, both technical and non-technical. Identification of these barriers will be the key to maximising the impact of R&D&I initiatives.

In order to fully develop a viable market in Europe each possible domain where robotics technology can be applied must be fully explored so that new markets are not left undiscovered.

2.1.1. Application Domains

Markets can be presented as a series of individual market domains clustered under a set of high level categories. Each high level category representing a similar type of market opportunity.

These clusters are based on a number of common characteristics which broadly apply to a class of market domains.

These characteristics are:

- The business model used to deliver and deploy robotics within the specific market.
- The types of end user
- The broad legal infrastructure that applies to the domain.

Based on these characteristics the high level market domains are:

- Manufacturing Domain
- Healthcare
- Agriculture Domain
- Civil
- Commercial
- Transport and Logistics
- Consumer

Under each of these categories are a collection of individual sub-domains that characterise the activity within each domain.

2.2 Manufacturing Domain

2.2.1. Domain Overview

Robot technology has become the backbone of may large scale manufacturing industries. In order to compete globally manufacturing must be both competitive and agile. Robots are the key drivers of flexibility and competitiveness and will be instrumental in bringing manufacturing back to Europe.

As the pressure to automate moves beyond the traditional manufacturing industries such as automotive and electronics, the need for flexibility in these automation systems grows, particularly for SME manufacturers. Meeting these needs will require new technologies and new working practices.

As Europe strives to increase the value added by manufacturing (back to 20% of EU's GDP by 2020) it will be competing not just with low-wage economies, but also highly automated economies. Leadership in robotics will be a key differentiator in driving up the productivity of Europe's manufacturing base.

2.2.2. Current and Future Opportunity

The current market for robotics technology in manufacturing is concentrated on large scale manufacturing industries that have high levels of automation. However it is widely recognised that the impact of robotics technology on manufacturing must widen its base to address a broader range of manufacturing. For example by addressing SME manufacturing, systems able to handle soft materials and millimetre scale assembly operations amongst others.

New automation concepts such as Human Robot Collaboration (HRC) and Cyber-Physical Systems (CPS) are recognised as having the potential to impact and revolutionise the production landscape. Increasing the flexibility of industrial robots and providing automation systems that provide faster more intuitive configuration are important goals for future production systems.

Robotics technology will impact on these areas in the medium term;

- lean and agile manufacturing,
- miniaturised assembly,
- introduction of Cyber-physical production systems (CPS) for example the "Industrie 4.0" programme in Germany,
- introduction of intuitive and adaptive manufacturing systems including intuitive programming and tasking,
- deployment of Dual-arm, lightweight, low-cost compliant manipulators,
- increased cooperation with humans including physical cooperation,
- novel business models and deployment strategies.

2.2.3. Barriers to Market

The application of robotics technology to manufacturing is a dynamically developing domain. For European manufacturing industry to thrive amongst global competitors, it is necessary to overcome various barriers to growth:

- User awareness of robotics technology capabilities
- User concerns about system complexity
- Cost of ownership and return on investment
- Flexibility and adaptation of systems to changing needs.

2.2.4. Key Market Data

The annual World Robotics Report of the International Federation of Robotics (IFR) provides a comprehensive overview of the robotics business worldwide, showing breakdowns in geographical regions as well as in application areas.

2.2.5. Relationship to other Domains and Markets

Within a European context there are strong connections and synergies with the "Factories of the Future" PPP and EFFRA, the "European Factories of the Future Research Association" (www.effra.eu).

Within the market domains defined in the SRA Manufacturing will impact on the production of goods in all other domains. However the strongest linkages are with the Robot Markets and in particular the market for robot arms and the markets for Systems Development tools. With the advent of smart manufacturing robots these linkages will expand to encompass user interface systems and wide area sensing.

2.2.6. Europe's Place in the Market

Europe presently has a leading role in industrial robotics, supplying the world market,[1] but this position is vulnerable. Aside from well-established Japanese suppliers, new companies are entering the European market.

The typical business model of the established suppliers of industrial robots is to work closely together with system integrators. In this way, the suppliers concentrate on the technology of the robot manipulator and controller and the application-related know-how resides mostly with smaller companies doing the integration work.

This method of doing business works well across many market domains, ranging from food & beverage to automotive. Future markets may need to review and adapt this way of working to accommodate new boundary conditions. Examples could include application rental agreements, pay-on-production, equipment leasing arrangements, etc.

Finally, the larger of the equipment manufacturers are actually "global players", supplying not only the European markets, but also markets abroad.

2.2.7. Key Stakeholders

There are a significant number of European based companies that have a global reach in the manufacturing sector. In addition there are significant end users of large scale manufacturing systems within Europe. Europe also has a high proportion of SME manufacturer end users and there is an open market within Europe to exploit these strengths. In addition to the robotics suppliers there is also a well proven network of service companies that install and configure systems.

The strong market for manufacturing and for robotics technology has been supported by outstanding research and academic organisations distributed throughout Europe. There is a strong research base and extensive opportunity for technology transfer.

This is a well established market with a well defined structure, however there will need to be awareness of the disruptive nature of new technology in smart manufacturing such that market shares can be maintained over time.

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[1] See web site http://www.everything-robotic.com/2012/11/1000-robot-makers.html, visited 2013-09-09.

2.2.8. Current Key Projects

The following projects funded under FP7 have the potential to impact on this domain.

TAPAS	
FIRST-MM	Flexible Skill Acquisition and Intuitive Robot Tasking for Mobile Manipulation in the Real World
CustomPacker	Highly Customisable and Flexible Packaging Station for Mid-to-Upper Sized Electronic Consumer Goods Using Industrial Robots
KAP	Knowledge, Awareness and Prediction of Man, Machine, Material, and Method in Manufacturing
RoboFoot	Smart robotics for high added value footwear industry
COMET	Plug-and-Produce Components and Methods for Adaptive Control of Industrial Robots Enabling Cost Effective, High Precision Manufacturing in Factories of the Future
Dynxperts	New Machine Functionalities Through Process Dynamic Stability Control
AIMACS	Advanced Intelligent Machine Adaptive Control System
HARCO	Hierarchical and Adaptive Smart Components for Precision Production Systems Application
LOCOBOT	The Toolkit for Building Low Cost Robot Co-Workers in Assembly Lines
PopJIM	Plug and Produce Joint Interface Modules
FAB2ASM	Efficient and Precise 3D Integration of Heterogeneous Microsystems from Fabrication to Assembly
AUTORECON	AUTOnomous co-operative machines for highly RECONfigurable assembly operations of the future
PRACE	The Productive Robot Apprentice
THERMOBOT	Autonomous Robotic System for Thermo-Graphic Detection of Cracks
MiRoR	Miniaturised Robotic systems for holistic in-situ Repair and maintenance works in restrained and hazardous environments
MAINBOT	Mobile Robots for Inspection and Maintenance Activities in Extensive Industrial Plants
CableBOT	Parallel Cable Robotics for Improving Maintenance and Logistics of Large-Scale Products
PAN ROBOTS	Plug&Play robots for smart factories
MEGAROB	Development of flexible, sustainable and automated platform for high accuracy manufacturing operations in medium and large complex components using spherical robot and laser tracker on

	overhead crane
FoodManufuture	FoodManufuture.eu

2.2.9. European Products

The maturity of this market and the strength of European companies in the global market mean that there are a significant number of products designed and produced in Europe. These products are being augmented by smaller lighter more compact manufacturing solutions suited to SME manufacture.

2.2.10. Manufacturing Sub-Domains:

2.2.10.1 Production

Sub-Domain Overview

Mass production systems in the aerospace, automotive, electronics and domestic appliance sectors have been a cornerstone of the robotics market for several decades. This industrial robotics sector is an important and major source for revenue and investment. The market is mature and well understood. Sales are mainly to larger manufacturing operations and most often represent repeat orders for faster, better more efficient assembly robots.

Current Opportunity

The push to increase employment and increase competitiveness will open the market for increased automation. European companies already operate in a global market and maintaining their current market share will require R&D&I investment.

Future Opportunity

It is widely acknowledged that this sector will expand through the integration of service robotic technologies and through the deployment of robots into novel areas of manufacturing, into SME manufacturing and into areas of manufacturing that require more complex materials handling such as the food industry.

Key Market Data

The IFR report on World Robotics provides an overview of the key market sectors that use robots in production. The main markets are:

- Electronics assembly
- Automotive parts manufacture and automotive assembly
- General production of metal, rubber or plastic parts.
- Food processing

Production in SMEs now accounts for a significant proportion of the manufacturing in Europe and represents a new market for the application of robotics technology.

2.2.10.2 Food

Sub-Domain Overview

Increasing concern about food cost, traceability and security have impacted on all aspects of the food chain in the last decade. There has been considerable interest in the application of robotics technology to different aspects of the food production industry, from farming to the preparation of food for consumption.

Current Opportunity

Many applications for robotics technology have been proposed in the food preparation industry, with new applications typically concentrating on areas where there is a high level of manual labour or where there is a need for responsive production with a fast turn-round or where contamination is a significant risk.

Areas considered include deboning meat, the preparation of ready-meals and the packaging of delicate products. There is already considerable automation in many areas of the food production industry where the uniformity of product and high volumes can justify the investment. Where there is a significant variation in raw materials and a high preparation overhead, or where the speed of processing is limited by human factors these are areas that have attracted robotic solutions.

These applications often present significant manipulation and quality control challenges where exact qualities of additives and flavourings must be made to each product or where multiple items of differing shape and texture must be assembled, for example in sandwich making. The advantages to the food industry lie in higher levels of adaptation to demand, improved consistency, longer shelf life and higher levels of hygiene. For example robots can be operated in an inert atmosphere to stop oxidation, or can be consistently cleaned to avoid cross contamination.

Future Opportunity

Future opportunities in the Food industry are likely to focus on the lowering of production costs and meeting hygiene and regulatory standards. and the speeding up of processing that is currently limited by human factors. At the retail end of the market there may be niche applications for on demand food preparation, for example in the production of ready-meals (e.g. Pizza, or microwave meals) to adaptable specifications. These systems would allow a customer to specify the inclusion or exclusion of specific ingredients, for example to account for allergies or taste, this would also allow the system to individually price meals.

Much of the development in this sector comes in the form of specialised manipulation and ingredient handling technology as well as dealing with the high flexibility demands arising from short product life and the very short product runs typical of a SME food manufacturer.

Key Market Data

The European food industry can be characterised by the following:

- Largest European Manufacturing sector (14.9% of turnover and 12.9% of added value for EU manufacturing industries)
- Leading employer in EU manufacturing sector (4.25 million)
- Turnover €1,017bn
- 14.5% of household expenditure
- Exports €76.2bn
- Trade balance € 13.2bn
- 287,000 companies
- 99.1% SME
- 0.53% of turnover spent on R&D

{Source: Data and Trends of the European Food and Drink Industry 2012 – FoodDrink Europe.}

Relationship to other domains

There is linkage to the Agriculture sector specifically in the balance between the preparation of ingredients at harvest vs preparation prior to food preparation. There are also links to marketing robotics and to Domestic Appliances where the food preparation process might be split between in factory and at home.

2.2.10.3 SME Manufacturing

Sub-Domain Overview

It is widely understood that SME manufacturing is an important manufacturing sector within Europe. SMEs are the engines of innovation within Europe and represent the seed corn of industrial growth. The EC recognises this:

"What usually gets lost is that more than 99% of all European businesses are, in fact, SMEs (see definition of SMEs). They provide two out of three of the private sector jobs and contribute to more than half of the total value-added created by businesses in the EU. Moreover, SMEs are the true back-bone of the European economy, being primarily responsible for wealth and economic growth, next to their key role in innovation and R&D."

http://ec.europa.eu/enterprise/policies/sme/facts-figures-analysis/index_en.htm

Addressing the manufacturing needs of SMEs is therefore an important step change in capability for robot technology suppliers. These needs centre around the following factors:

- The need to design systems that are cost effective at lower lot sizes.
- The need to design systems that are intuitive to use and are easily adapted to changes in task without the need to use skilled systems configuration personnel.
- The ability to work safely in close physical collaboration with human operators.

In addition to these important design challenges there is also a need to address the dissemination of good practice and knowledge about automation to SMEs. This is made more difficult by the geographic spread of SMEs and the diversity of their requirements.

Current Opportunity

There are relatively few robotic systems designed specifically for the SME market. The current opportunity relies on the acceptance of robotics as a means of production within an SME environment. SME's are typically unwilling to invest unless there is a very clear benefit in terms of cost saving or revenue generation. The specialised nature of most SME manufacture means that solutions must be highly adaptable and deployment must be low cost.

There is also an opportunity for using robotics technology in the automated testing of products, emulating physical user interactions to provide life cycle data.

Future Opportunity

Future opportunity will depend on modularity and adaptability. Both adaptation to individual tasks by unskilled users and adaptation between different tasks as the manufacturing output shifts between product types.

Barriers to Market

SME uptake of new manufacturing technology will depend strongly on perceived economic benefit or competitive advantage.

2.2.10.4 Soft Products

Sub-Domain Overview

The manufacture of clothing, shoes, and goods made from flexible materials presents novel and complex problems relating to localisation and adaptation to parts. Combined with the need for precision fixing required to manufacture a product where look and feel are as important as function this area presents significant challenges.

In the wider context of bringing manufacturing back to Europe the garment and shoe industries while still strong within Europe no longer have a mass production base in Europe.

The presence of leading global brands in Europe should provide an incentive to investigate how robotics technology can impact on this type of production.

Current Opportunity

There is limited deployment of robotics technology in the manufacture of products that involve soft materials. Most notably the food and garment industries are currently labour intensive. While there is limited deployment of robots within the food industry the garment industry is still dominated by hand assembly.

Future Opportunity

Particular opportunities exist for specialised soft materials handling processing both in terms of mass production and bespoke production. There are also opportunities in the mixed processing of soft and hard materials where one is used as a coating, fixed by gluing or defined pressure.

Barriers to Market

The ability to predict the behaviour of flexible materials while being handled and grasping technology are the main technical limitations. In mass market applications the loss of capacity to the far east has reduced the manufacturing base within Europe from which adoption of robotics technology might seed.

2.2.10.5 Craft and Bespoke

Sub-Domain Overview

There is an increasing market trend to use the internet to allow customers to customise and adapt products prior to purchase. Robotics technology may be able to increase the levels of customisation while retaining low costs, and may also be able to reduce time to delivery by allowing cost effective manufacture to take place closer to the customer.

Similarly there are many areas of high value production which rely on craft skills. If robotics technology is able to lower the cost of manufacture the high value margins may present an opportunity.

2.2.11. Key System Ability Targets

2.2.11.1 Configurability

The main requirement is being able to reconfigure industrial robots and their applications with regard to both software and hardware. The hardware may include peripheral devices, such as sensors, but may also include the kinematic chain of the manipulator itself. Software configuration may take place during or prior to installation or as a result of the end user selection of operating parameters. An important step change in usability will come with the adoption of Intuitive programming

Within certain environments systems are at TRL9 for Level 3 (Run-time self configuration) for limited mechatronic reconfiguration such as tool changing.

Mechatronic Kit (modular set up for robots):	Configurability Level 2 - User Run-time Configuration for a wider range of mechatronic options that are user configurable.
Introduction of Intuitive programming methods:	Configurability Level 2 - User Run-time Configuration

Standardised interfaces for modular controller software:	Configurability Level 3 - Run-time Self Configuration for software configuration in plug and play architectures.
Autonomous configuration of safeguarding strategies:	Configurability Level 4 - Autonomous Configuration coupled to Safety Interaction ability at Level 3/4.

2.2.11.2 Adaptability

The requirement is for the robot to respond to changes in the operating environment include the ability to self-learn and apply auto-configuration strategies.

Adaptive control systems are deployed in some large scale manufacturing systems (Level 1/2).

Self-learning robot with prepared strategies provided in Knowledge Databases:	Component Adaptability Level 3 - Process chain adaptation.
Self-learning robot utilising reasoning algorithms:	Task Adaptability Level 2 – Single task adaptation coupled to Cognitive reasoning ability Level 3 - Basic Environmental Reasoning.

2.2.11.3 Interaction Ability

In manufacturing applications robots need to be able to interact with operators, other robots and other systems within a production environment. The main requirement is for these interactions to be safe, intuitive and appropriate. A step change in ability will occur with the adoption of intuitive tasking interfaces.

Systems are deployed at TRL9 for Human Robot Interactions at Level 2, some limited deployment exists in particular applications at Level 3 - Direct Physical Interaction. Most current systems are at Level 2 - Basic Operator Safety for Safety Interaction ability.

Safe physical interaction.	Human-Robot Interaction Safety Levels 3-6 depending on the level of operator risk.
Autonomous interaction with other robots:	Robot to Robot Interaction Level 4 - Team communication.
Human-robot collaborative manipulation, load-sharing:	Level 3-5 of Human-Robot Interaction .

2.2.11.4 Dependability

Today, the state of the art is a Mean Time To Failure (MTTF) of approximately 10 years for the robot only. The limiting factor for current applications is very often the periphery and integration environment. The relevant interpretation of “dependability” in this case is both maintaining uninterrupted productivity, minimising necessary downtime, and intelligent recovery procedures.

The majority of deployed systems have dependability at Level 2 - Fails Safe.

Capability of detecting upcoming failures enabling preventive maintenance:	Dependability Level 5 - Task dependability

Self-maintenance between robots.	Dependability Level 5/6 - Task/Mission dependability coupled to Robot Robot Interaction Level 5 - Team coordination.
Maintenance performed on robots in hazardous places:	Cognitive Action Ability Level 7 - Dynamic planning coupled to Robot Robot Interaction Level 5 - Team Coordination.

2.2.11.5 Motion Ability

The primary requirements for motion ability relate to the kinematics and dynamics of manipulators as well as the positioning and navigation of autonomous platforms in a manufacturing context as well as mobile manipulation for logistics tasks and for advanced reconfigurable work cells.

Current deployed systems are TRL 9 for Level 3 - Open path motion.

Mode Switching, from flexible motion (Human Interaction) to fixed motion (Autonomous), e.g. variable stiffness, controllable stiffness:	Constrained Motion : Level 2 - Reactive motion

2.2.11.6 Manipulation Ability

The requirement concerns the ability to handle material objects and tools in a manufacturing context. Adaptability and robustness are primary goals along with the need for accuracy and repeatability.

Currently deployed systems are at TRL 9 are typically at Level 3 - Tolerant grasp.

Some systems exist at Level 4 - Tolerant grasp with sensors but without wide deployment.

Manipulation of flexible objects:	Cognitive Object Interaction Level 2 - Property Identification coupled to Level 8/9 of Object Recognition, and Level 5 - Flexible object interaction.
Free-form, shape-adaptable manipulators and grippers:	A combination of: Level 4 – Dynamic holding of modelled object, Level 5 - Location unknown pick, Level 4 - Compliant placement

2.2.11.7 Perception Ability

In this domain perception ability requirements vary significantly with application domain. Of primary concern are a suitable choice of sensing modality, efficient signal and data analysis, as well as generating the maximum information output from the data at hand. Guaranteed safe perception is also a key requirement.

Most deployed systems are at Level 2 – Low Level processing parameter sensing, a limited number are at Level 3 - Multi-Parameter Perception.

Accurate positioning of mobile systems, fast calibration, self-calibration; consistency of coordinate systems in sensors, platform, end-effector, fixturing, etc:	Location Perception at Level 2 - External beacons provides external reference points for position, level 4/5 provides for mobile platform localisation where there is an

	integrated arm.
Integration of multiple sensors:	Perception Ability Level 3 - Multi-Parameter Perception.
Classification of status of perceived information, e.g. quality information, error conditions, etc:	Dependability Level 5 - Task dependability.
Context-aware perception to reduce uncertainties	Perception: Object Recognition Level 6 - Context based recognition

2.2.11.8 Decisional Autonomy

The primary goal is to increase the level of responsibility in the control processes of the production system. The resulting autonomy is focused on reducing energy consumption, increasing throughput, and providing context aware task control in the interaction with operators.

Current deployed systems are TRL 9 for Level 4 - Simple autonomy without environment model

Reacting to perceived status of application (error condition, production conditions, etc.)	Decisional Autonomy Level 7 - Constrained task autonomy.
Online rescheduling of tasks in HRI scenarios based on task, ergonomic and safety information.	Decisional Autonomy Level 7 - Constrained task autonomy coupled to Safety Interaction Level 4 - Work space detection.
Energy efficiency criteria for path planning:	Decisional Autonomy Level 7 - Constrained task autonomy
Decentralised production knowledge and decision-making instances to augment robustness of manufacturing task:	Decisional Autonomy Level 11 - Distributed autonomy and Human-Robot Interaction Levels 3-6 depending on system complexity.
Self-evolving systems capable of autonomous manufacturing decision making:	Decisional Autonomy Level 11 - Distributed autonomy coupled to Cognitive Reasoning Ability Level 8 - Task hypothesis, and Acquired Knowledge levels 9-11.

2.2.11.9 Cognitive Abilities

In the context of manufacturing, the greatest potential is for functions that contribute to a reduction of programming and configuration requirements in deployed systems. There are clear benefits for small lot size systems in reducing the time and skill needed to reconfigure an adapt systems to new processes.

Current Deployed systems are at TRL 9 for Level 1 - Sense data knowledge of Acquired Knowledge, Level 2 - Task context interaction for Cognitive Human Interaction, Level 1/2 for Interpretive ability , Level 3 - Sense driven action for Action ability, Level 1/2 for Envisioning ability, Level 2 - Pre-defined reasoning for Reasoning.

On the fly exchange of hardware (robot)	Mechatronic Configuration Level 3/4 coupled

(enabled by abstracted task representation with context-aware self-configuration).	to Decisional Autonomy levels 5-7
Intuitive Human Robot Interfaces for use and configuration, teach or specify task using domain specific terminology:	Human Interaction Level 2 - Task context interaction.
Standardised data model for robot, application, environment, etc:	Cognitive Knowledge Acquisition Level 6 - Knowledge scaffolding.
Motion planning for HRI vs. motion planning for autonomous operation, plus orderly transitions between the two:	Action Ability Level 4 - Optimised action or Level 5 - Knowledge driven action.
Robustness in the face of uncertainties.	Cognitive Reasoning Level 4 - Reasoning with conflicts.
Verification of contextual expectations against current data, leading to modifications of motion strategy (supervisory control):	Cognitive interpretation Ability Level 5 - Structural interpretation coupled with Decisional Autonomy Level 5 - Simple autonomy with environment model.
Learning through human-robot and robot-robot interaction.	Human Interaction Level 2 – Task Context Interaction, Knowledge Acquisition at Level 6 - Knowledge scaffolding, and Robot Robot Interaction at Level 5 - Team Co-ordination for Communicated Adaptation between systems.
Autonomous interpretation of situation, constraints and relevant part of production plan:	Cognitive Knowledge Acquisition Level 4 - Deliberate Acquisition coupled to Interpretation ability level 5/6.
Situation interpretation through heterogeneous sensors to enforce a correct safety behaviour in HRI:	Safety Interaction ability Levels 4-7 depending on work context.
Human-robot interaction with open-end learning process; robot apprentice learning from experience, from various workers, abstraction, etc:	Human Interaction Level 2 – Task Context Interaction coupled to Knowledge Acquisition Level 4-6.
Cloud-based cognition with access to remote robot experience and ability:	Cognitive Acquired Knowledge Level 8 - Distributed Knowledge.
Information perception, management and interaction of individual robots within the overall manufacturing environment (sort of along the cloud manufacturing idea in dealing with digital resource management):	Cognitive Acquired Knowledge Level 8 - Distributed Knowledge

2.2.12. Key Technology Targets

The key technology targets for the application of robotics technology in manufacturing need to concentrate on systems with the following properties:

- intuitive handling,
- easy to use,
- easy to (re-)configure,
- adaptable,
- provide safe perception and safe actuation with certified components and systems,
- provide an ergonomic design for human interaction
- are energy efficiency, provide energy autonomy and short charging cycles
- provide privacy for personal data gathered during human interaction.

2.2.12.1 Systems Development

There is a strong relationship between the manufacturing sector and the Systems Development technologies. Large productions facilities involving multiple robots and multiple types of robot, for example part delivery AGV systems and robot arms used in assembly, are highly complex. There is a strong imperative to manage this complexity as efficiently as possible and the Systems Development technologies that impact systems integration and deployment are a key part of the delivery of robot manufacturing. The challenges of additional flexibility, and the increase in collaborative working present a challenge to systems development technologies that must be addressed if the expected deployment of smart manufacturing systems is to be cost effective.

Systems Integration

Multi human – multi robot stations with seamless integration of humans and robots in the same production line.

Modelling and Knowledge Engineering

Modelling technologies are a central aspect for modern application development. They avoid premature investment and unnecessary changes to hardware aspects of the application. Advances in the degree of realism will further contribute to this gain of application development efficiency.

Mid term

- Standard software for modelling environment / robot cell / robot line, including sensors and actuated components.
- Physics engine for real-time information on physical quantities in robot application.

Long term

- Multi-physics enabled model of robot application, including all relevant effects (e.g. solid, fluid, electrical, magnetic, thermal, etc.)
- Real-time availability of all relevant physical information on environment and application, to be used as a basis for real-time adaptive motion planning, prediction and control.
- Domain-specific ontologies for application description

2.2.12.2 Mechatronics

Mechanical Systems

The goals for mechanical systems design can be summed up as "smaller, lighter, faster stronger".

- Appropriate design for physical interaction, design principles for safe interaction
- Zero cable robot
- High performance robot based on low-cost / low-accuracy components
- Appropriate design of drive components and kinematic structures for physical interaction, design principles for safe interaction

Actuators

- Low-cost, modular drive systems with integrated sensing (e.g., position, torques)
- Low-power consuming drives and control methodologies
- Multi-fingered industrially proven robust grippers
- Safe components (SIL / performance level D)
- Light-weight, intelligent structures (with sensors integrated)
- Lightweight actuation principles, high power density, low-friction gears with high transmission ratio
- Direct drives for high loads

Sensors

- New safety-rated sensors for Physical Human Robot Interaction (e.g. Capable of returning positions of objects / operators in scene)
- Sensor redundancy for safety-rated applications, e.g. Information fusion from diverse sensing types
- General 3D Work/Object scan and monitoring for real-time path correction
- Use of information available in the area from distributed sensors, e.g. to treat occlusions and lift perspective redundancy of 3D perception

Control

- New control paradigms with constraint-based optimisation and use of task redundancy for best trade-off among different objectives (e.g. productivity, manipulability, safety, ergonomics...)
- Sensor-based control with adaptation to unforeseen situations (e.g. obstacles, humans...)
- Online control-based dynamic path re-planning (e.g. from sensor information)

Increasing sophistication of control approaches can serve to increase the level of robustness of applications, particularly in the event of uncertainties.

Sensors and Sensing

One essential ingredient of any approach to add more and new functionality to control, motion planning, application adaptivity, etc. is always the availability of an increased level of information on the environment and on the application. Therefore, advances in sensors and sensing are a basic enabler for such progress.

Power Supply and Management

Wireless power transmission

2.2.12.3 Human Computer Interaction

Safety

To avoid additional hardware such as fences and fixed guards, future applications will rely more heavily on sensor-based support for safety functions as well as safe behaviour of industrial robots. While this can make possible various degrees of direct human-robot interaction, it also can serve to make application layout more compact and cost-efficient.

- Methods and tools to adapt robot motion to injury risk knowledge (see TG pHRI)
- Intelligence and decision-making capability for autonomously generating dynamic safety zones based on live robot movements (as opposed to pre-programmed motions).

2.2.12.4 Perception

Sensing

- Use sensor information redundancy to detect faulty situations (e.g. sensor failures, control failures, etc.)
- Combination of various sensing technologies to achieve safety-rating of the information
- Bringing new sensing capabilities into routine industrial use as safety-rated systems

Long Term

- Self-calibrating safety sensors

Interpretation

- Combination of various sensing technologies to achieve safety-rating of the information
- Integrate new sensing capabilities into existing systems as safety-rated systems

2.2.12.5 Navigation

Localisation

- Task appropriate indoor positioning in industrial environment, e.g. combination of platform + manipulator

Motion Planning

- Capability to autonomously generate alternate motions to avoid collisions (safety rated algorithms)
- Autonomous path planning with obstacle avoidance in cluttered environments
- Reactive motion planning, i.e. online planning revision, based on current sensor information

2.2.12.6 Cognition

Learning Development and Adaptation

- Learning Affordances for Robot Object Interaction.
- Task learning by demonstration, human-robot and robot-robot interaction

Natural Interaction

- Passive and Active Safety of Mobile Manipulation in Human Workspace
- Ergonomic Evaluation, Analysis of Workspace Sharing Systems
- Instruction and Assistance in Semi-Automated Assembly Processes
- Intelligence and decision-making capability for autonomously generating dynamic safety zones based on live robot movements (as opposed to pre-programmed motions)

2.2.13. Technology Combinations

Flexible Grasping

Systems which are able to grasp arbitrary objects of varying geometry and weight while requiring only few to no user input. The grasping system will be able to generalise knowledge from previously learned grasping tasks to novel grasping situations. It will be able to handle objects, unknown objects similar to previously known objects, and also flexible parts. This capability is brought forth by a combination of grasp planning + cognitive abilities + sophisticated sensing means.

Model Driven Engineering of Complex Systems:

Providing an engineering environment for a robot designer that dramatically improves the time and effort required to program and design a robotic system to tackle a new task. The robot designer will be empowered to efficiently reuse components in new and creative ways, while at the same time most engineering tasks like robot program generation will be performed automatically by the underlying framework. The robot designer can therefore concentrate on the creative tasks while many engineering tasks are automatically handled by the software framework. Here, we see a combination of systems engineering and integration + modelling + knowledge representation.

Mobile Manipulation:

The goal is to develop systems which can support a human worker with manipulation tasks. For seamless and flexible operation, the system has to be able to execute complex manipulation tasks in unstructured and dynamic environments. This brings together technology targets in motion planning + safety + collaboration and interaction + learning and adaptation.

Passive and Active Safety of Mobile Manipulation in Human Workspace:

Seamless and safe human-robot interaction on the work floor. The development of new safety concepts for human-robot interaction is based on existing industrial standards and regulations. The realised safety will conclude as well avoiding static obstacles (e.g. tables, etc.) as well as reacting actively to dynamic obstacles (e.g. humans and other robotic systems) that are moving around in the environment. With active safety the robot will avoid the human operator, thereby trying to continue to fulfil its assignment. New planning and control paradigms, where different objectives are concurrently optimised, need to be addressed. Here, we draw on the technology targets of motion planning + safety + collaboration and interaction + learning and adaptation.

Ergonomic Evaluation, Analysis of Workspace Sharing Systems:

Define ergonomics requirements for a safe human-robot interaction. These requirements will function as guidance for the development of the mobile manipulator and the workspace for collaborative manufacturing. The design process will be validated against the defined requirements and updated to uphold the ergonomics principles. Ergonomics requirements will also serve as one of the objectives to be optimised with motion planning, through e.g. use of intrinsic kinematic redundancy or task redundancy of the manipulator arm. Relevant technology targets are collaboration and interaction + cognitive abilities + sophisticated sensing.

Instruction and Assistance in Semi-Automated Assembly Processes:

Holistically improvement and facilitate a flexible development of the robot systems in co-existence with the human. These cooperative processes have to address safety issues, and the robot system has to be highly flexible to be able to fulfil new tasks. Thus the main goal is the development of a system interface that provides an intuitive way to teach a robot's behaviour in assembly sequences without the need of professional trained robot programmers. Important technology targets for this objective are collaboration and interaction + safety + motion planning + sophisticated sensing + cognitive abilities.

Rapid Deployment in Realistic Industrial Environments

A key capability is the ability to quickly deploy robotic systems in realistic industrial environments. A large portion of the cost of automation solutions is spent on deploying solutions to new customers and under slightly varying requirements. Current deployment strategies rely on a long set-up process by experienced system operators and are generally not automated. A key mid-term goal will thus be reducing the time and effort spent by operators in configuring a perception system to operate in a new application domain or a new operational environment. The major technological advance in this respect is expected to come from better learning capabilities and more robust solutions for interpretation, as well as synergies with more robust mapping and localisation systems in semi-structured dynamic environments. Important directions to investigate include limiting dependence on costly infrastructure solutions, increased transferability of experience, life-long learning as well as learning by demonstration.

2.2.14. Product Visions

There are a number of different product visions in the manufacturing sector, these relate to the breadth of the sector and the different driving forces in the market. On the one hand systems need to be developed that improve cost vs performance in the traditional manufacturing sectors so that Europe can retain its current market position. On the other hand new markets based on increasing human interaction and more flexible adaptation and configuration suited to SME manufacturing processes represent an important and growing new market.

The key product vision in manufacturing is of a robot able to safely operate in an semi-structured environment in physical collaboration with human operators. To be configured using intuitive interfaces by operators rather than by specialised programmers. These new systems need to have flexibility not only with respect to the user interface but also with respect to the task. Generic grippers, gripping strategies and planning and control systems able to adapt to different optimisation parameters, and to dynamic environments without compromising safety.

This vision involves the integration of a much broader range of sensing and interpretation technologies with advanced systems development and human robot interaction technologies.

As with all technology related to manufacturing the R&D&I activity must result in deployable systems that provide an economic advantage.

2.3 Healthcare

2.3.1. Domain Overview

Healthcare and Robots

Due to demographic changes in many countries healthcare systems will come under increasing pressure as they deliver healthcare to an aging population. In addition demand for care is increasing as improved procedures lead to better outcomes over a wider range of medical conditions. Costs are similarly increasing while the proportion of human caregivers will decrease over time.

The application of technology, including robotics, is generally seen as part of the solution. For the purpose of this document healthcare is seen as a combination of three sub-domains:

Clinical Robotics: defined as robotic systems that support "care" and "cure" processes. Primarily in diagnosis, treatment, surgical intervention and medication, but also emergency healthcare. These robots are operated by clinical staff or other trained care personnel.

Rehabilitation: covers post-operative or post injury care where direct physical interaction with a robot system will either enhance recovery or act as a replacement for lost function (e.g.: prosthetic hand or leg).

Assistive robotics: this covers other aspects of robotics within the healthcare process where the primary function of the robotic system is to provide assistive help either to carers or directly to patients either in hospital or in a specialist care facility.

All of these sub-domains are characterised by the need to provide safe systems that take into account the clinical needs of patients. They will typically be operated or set up by clinically qualified staff.

Healthcare Robotics; more than just technology

Besides the development of the robot technology itself, it is crucial that these robots are deployed as part of a clinical or care process. System requirements should be driven by clearly identified User and End User needs. During system development the demonstration of added value is crucial for eventual market success. Achieving added value requires direct engagement with care professionals and Users during both the design and deployment stages of development. Developing systems in the context of their final use gains the commitment of stakeholders. A clear understanding of current care practice, the eventual need for clinical staff training and the wider aspects of information handling that these applications may require is important for the creation of a deployable system. The introduction of robots into healthcare will require adaptations to be made to care provisioning. This adaptation is a delicate process in which technology and care practices influence and shape one another in both directions. Therefore, from the start of technical development this mutual dependency needs to be carefully taken into account.

The development of healthcare robotics covers a very wide range of different potential applications. These are set out below in the context of the three sectors identified above.

Clinical robotics:

Within the context of Clinical Robots there are multiple application areas. These can be categorised into:

- Systems that directly extend surgical dexterity and efficacy,

- Systems that enable remote diagnosis and intervention, both over long distances and in intra-corporeal settings.
- Systems that assist during diagnostic procedures
- Systems that assist during surgical procedures.

In addition to these direct clinical applications there are a number of auxiliary clinical applications such as sample taking, laboratory tissue handling and testing as well as related clinical services.

Rehabilitation robotics

Rehabilitation robotics covers prosthesis and devices such as robotic exoskeletons or orthoses that train, support or replace impaired activities or impaired body functions and structures. Such devices may be used in a clinical or non-clinical setting but are likely to involve clinical input to parameter setting and progress monitoring. Post-operative care particularly in orthopaedics is projected to be a major area of application.

Specialist support and assistive robotics

This covers clinically based assistive robotics that are designed to help perform routine functions. While assistive robots can be found in both specialist and domestic healthcare settings. There are significant differences in the design and deployment of robot systems in these two different environments. In a specialist healthcare context, such as a hospital or care home for the elderly robots will be operated by professional staff and will need to conform to clinical and healthcare standards and certification. These robots will support employees of these healthcare institutions in their work, specifically caregivers. Such robotic systems have the potential to enable caregivers to spend more time with their patients, to reduce physical demands, for example in patient lifting and to provide assistance in routine services.

2.3.2. Current and Future Opportunity

Robotics for healthcare presents a major research challenge due to its multi-disciplinary nature and the strong requirement to deal with and in many cases physically interact with humans who may also be in a vulnerable state. Users may also have varying levels of expertise and capability which must also be taken into account. The following sections overview the main opportunities that exist in the three healthcare sectors.

2.3.2.1 Clinical Robots

This covers robotics for surgery, diagnosis and therapeutic processes. The potential market for surgical robotics has high value. Robot-assisted capabilities could be used in virtually all pathologies and medical specialities, ranging through cardiac, vascular, orthopaedics, oncology and neurology.

On the other hand the technical constraints are numerous and multi-faceted including constraints on size, capacity, constraints following from the hostile environment and the limited number of technologies that are currently available off-the-shelf for clinical use.

Apart from technological challenges there are also major commercial hurdles as the US holds a firm monopoly in the field with a broad coverage of IP. This situation can only be circumvented by developing radically new hardware, software and control concepts together with financial instruments to support costly but necessary developments and associated clinical validation. Typical areas of opportunity are:

Minimal Invasive Surgery (MIS)

Gains can be made by designing systems able to improve dexterity, increase efficiency or augment procedures with additional feedback (e.g. force) or data presented during the procedure. Market deployment will also depend on cost effectiveness, reduced set-up times and a reduction in the level of additional training needed to use the system. Any system must show a clear added value within a surgical context. Validation of clinical outcome is essential as is acceptance by surgeons.

Compared to other minimally invasive surgery approaches, robot-assisted surgery potentially gives the surgeon better control over the surgical instruments as well as a better view of the surgical site. Surgeons no longer have to stand throughout the surgery and do not tire as quickly. Hand tremors can be filtered out largely by the robot's software, this is particularly important in micro scale MIS such as eye surgery. In theory the surgical robot can be used 24 hours a day by rotating surgery teams.

Robotics can offer faster recovery, reduced scaring and trauma, less tissue damage and lower exposure to radiation. Robotic surgical tools can help lower the mental load, reduce the learning curve and improving the ergonomics for the surgeon. Therapies that lie beyond the borders of human capabilities may also become possible through robotic technology. For example a new generation of flexible robots and instruments allowing access to sites deep in the human body reducing further the diameter of the entry point into the body or requiring no artificial entry port at all.

In the longer term cognitive assistance during surgery may reduce complications by increasing the flow of appropriate information to the surgeon. Other potential benefits include the up-skilling of paramedic staff through the robotic implementation of standard clinical emergency procedures in the field and the delivery of tele-surgery to remote sites.

Specific opportunities can be identified:

- Novel compliant instruments that provide an inherent level of safety yet achieve manipulation capabilities approaching those of rigid instruments. Through novel control techniques or dedicated mechanical means (which can be embedded inside the instruments or provided externally) the behaviour of these instruments can be adjusted in real-time so as to exhibit compliancy or stability when needed.
- The introduction of advanced assistive technology that guides and warns the surgeon during surgery could simplify surgical tasks and reduce medical errors. Such 'cognitive assistance' should ensure compatibility with the surgeon so that it is intuitive and unambiguous in use.
- The application of appropriate levels of autonomy in surgical tasks up to the fully autonomous implementation of specific well-determined procedures: Application examples are: autonomous autopsy, blood sampling (Veebot), biopsy, automation of parts of surgery/surgical tasks (knot tying, camera holding…). All these have the potential to improve efficiency.
- Smart surgical instruments directly controlled conventionally by the surgeons. These tools are in direct contact with the tissue and they up-skill a surgeon's dexterity and manipulation. Miniaturization and simplification of future surgical instruments as well as availability of the surgical procedures inside and outside of the operating theatre are the main drivers of such technologies

Training: Providing physically accurate models delivered through haptic tools to the surgeon have the potential to improve training both at an early stage and as a means to assess consistent performance. The ability to simulate a wide variety of conditions and complications can also enhance the effectiveness of this type of training. Current limitations centre on the quality of haptic feedback, and the resulting difficulty that this has in demonstrating performance gains from of this type of training.

Clinical sampling: There are numerous areas of application for autonomous sample taking from blood and biopsy samples to less invasive autopsy analysis.

2.3.2.2 Rehabilitation robotics and prosthetics

Rehabilitation robotics covers a range of different forms of rehabilitation and can be divided into distinct sub-sectors. Europe has strong industries working in this sector and improved engagement with these will enhance technology transfer.

Rehabilitation aids

These are aids that can be used post-trauma or post-surgery to train and support recovery. Their role is to promote healing and enable faster recovery while protecting and assessing the user. Such systems may be used within a clinical setting under supervision or through self motivated exercise where the device controls motion or restricts motion as appropriate. Such systems are also able to provide valuable feedback on progress and monitor outcomes more directly than clinical observation.

Functional replacement aids

The function of these robotic systems is to replace lost function. This may be as a result of aging or traumatic injury. These devices are designed to improve mobility and motor skills. They may be worn as a prosthesis or as an exo-skeletal or orthotic device.

In developing rehabilitation systems it is critically important that existing European manufacturers are engaged as market stakeholders and that relevant clinical and clinical delivery partners are engaged in the development process. Europe has world leading manufacturers in this area.

Neuro-rehabilitation[2]

A limited number of Neuro-rehabilitation robotic devices are currently used, whereas widespread use has not yet been achieved. Robotics is proposed for post-stroke rehabilitation in the post-acute phase and in other neuro-motor pathologies, such as Parkinson disease, Multiple Sclerosis, and Ataxia. Positive outcomes using a robotic approach (equal or better than traditional therapy) in rehabilitation are starting to be confirmed by studies on functional assessment and, recently also by some studies on brain plasticity by neuro-imaging. Integration with FES has been proven as an amplifier of positive outcomes (both for the muscular, peripheral conditioning and for central motor re-learning facilitation). Immersive exercises with biofeedback and gaming interfaces are beginning to be considered for deployable solutions but these systems are at an early stage of development.

In order to develop workable systems a number of issues must be addressed. These are; lower device cost, proven clinical utility, a well defined patient assessment process. The ability of systems to correctly identify user intent and thus prevent injury is currently limiting their effectiveness. Control and mechatronics integrated to match human performance capability, including cognitive load, are at an early stage of development. Improvements in dependability and working time must be increased before deployable systems can be developed. Acceptance by therapists and reduced setup times are also key design goals.

Prosthetics

Considerable progress has been made in the production of smart prosthesis able to adapt to the user’s gait and the environment. Robotics has the potential to combine improved cognitive awareness and increased dexterity and control particularly in upper limb and hand prosthesis and in controlling foot placement. Particular areas of development include adaptability to the individual, semi-autonomous control, provision of artificial sensory feedback, improved validation, improved energy efficiency and self power recovery and

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[2] The COST network TD1006, European Network on Robotics for Neuro-rehabilitation provides a platform for exchanging standardisation of definitions and approaches across Europe.

improved myoelectric signal processing. Smart actively driven prosthetic and orthotic devices will enable a larger end user group to utilize the benefits of such systems.

Mobility support systems

Patients with reduced physical function, either permanent or temporary, can benefit from increased mobility. Robotic systems can provide the support and exercise needed to increase mobility. There is already some early stage deployment of such systems.

In the future it is possible that such systems may be capable of compensating for cognitive impairment preventing falls and accidents. Limitations as to end cost and dependability currently exist as do the practical wear-ability of current systems for long term use.

In many rehabilitation application areas there is the possibility of using natural interfaces such a myoelectric sensing, brain signal detection or interfaces based on speech and gesture.

2.3.2.3 Specialist support and assistive robots

Specialist support and assistive robotics can be divided up into a number of different areas of application:

Carer support systems: Support systems used by carers interacting with patients or systems used by patients. This may include robot systems that deliver medication, take samples, improve hygiene or the recovery process.

Lifting and displacing aids: Patient lifting and positioning systems have wide ranging utility from precise positioning during surgery and radio therapy to assistants for care staff in getting people in and out of bed and in transporting them through hospitals. Such systems can be designed to configure to specific patient conditions and can be used to provide patients with a degree of control over their own position. Limitations are caused by the need for full safety certification and the safe control of forces sufficient to move patients without causing injury. Energy efficient structures and space saving designs will be critical to effective deployment.

In developing assistive robotics it is important to adhere to a number of basic principles. Development should focus on support for functional deficit rather than specific conditions. Solutions must be practical within the context of use and provide clinically valid benefits to the User. This may include the use of technology to motivate patients to do as much as they can for themselves while ensuring safety. The deployment of such systems will not be viable unless they reduce the burden on care staff, provide an economic case for deployment and are reliable and safe in operation.

Biomedical laboratory robots for medical investigation

Robots are already used within biomedical laboratories to sort and manipulate samples during testing. The applications for complex robotic systems extends beyond this to improved cell screening and manipulation for cell based therapies and selective cell sorting.

2.3.2.4 Medium Term Requirements

The following list provides a snapshot of the expected progress points in Healthcare robotics that are expected in the medium term.

- Leg exoskeletons that adjust behaviour to the individual behaviour and/or properties and optimize their support according to the user or environment. Systems can be adapted by the user for different environments or tasks. Application areas: neuro-rehabilitation and worker support
- Robots to be used in autonomous rehabilitation (e.g., game-based rehabilitation, upper limb post-stroke rehabilitation) should understand the user needs and reactions and adapt the therapy to them.
- Robots to assist mobility and manipulation should be able to interface naturally with people and guarantee safety and operability in “natural” environments.

- Rehabilitation robots designed to promote sensory-motor integration by providing bidirectional communication, including multimodal command input (myoelectric signals, inertial sensing) and multimodal feedback (e.g., electro-tactile, vibro-tactile and/or visual).
- Arm/wrist/hand prostheses which automatically adapt to the patient, enjoying single fingers flexion/extension, thumb rotation, wrist DOFs. These should be coupled with multiple sensors and pattern matching algorithms to enforce natural control (continuous force control) over the available DOFs. Application areas: restoration of hand functions in amputees.
- Prostheses and rehabilitation robots enhanced with semi-autonomous control to improve performance and/or decrease the cognitive burden to the user. The systems should be capable of sensing and interpreting the environment with some level of reasoning to allow for autonomous decision-making.
- Prostheses and rehabilitation robots that exploit vast online resources (information, storage, processing power) through Cloud Computing to implement advanced functions that are far beyond the capabilities of the on-board electronics and/or direct user control.
- Low-cost prosthetics and robotics designed through new additive or generative manufacturing methods (3D printing).
- An at-home therapy relieving the intensity of neuropathic pain or phantom limb pain by means of advanced interpretation of the residual muscle signals, and with the aid of a robotic hand (less dexterity needed than in the previous case) and/or a VR environment.
- Biomimetic control for physical surgeon robot interaction.
- Adequate mechanical actuation and sensing technologies for the design of dexterous force-feedback miniature robots and instruments for advanced and enlarged Mini-invasive surgery application.
- Power harvesting for implantable micro-robots.
- To get a biomimetic control of rehabilitative exercise: integration of volitional residual subject motion, eventually supported by FES to enhance motor relearning, with robot control
- Development of clinically applicable methods for movement restoration that reach beyond the commonly used state-machine, manually-tuned paradigms. This includes closed-loop model-based control utilizing identifiable real-time neuro-musculoskeletal models.

At low TRL

- Automated (cognitive) understanding of intended task in actual environment. Seamless physical human/robot cooperation in “regular” environments directed by an additional control interface. Fully-fledged, non-supervised adaptability to the patient. Reliability of intention detection.
- Development of energy efficient driving mechanisms for actively powered prosthetic and orthotic devices.

2.3.2.5 Future impact and dependence

The current picture arising from the prevalence and incident rate of many impairment and disabling conditions combined with our increasing age clearly indicate a potential crisis point where available human resources will become insufficient to aid a large number of elderly individuals at high risk of stroke, traumatic brain injury and so on. This deficiency will impact care and rehabilitation. As robot technologies develop improved capability, there is an opportunity to utilise them within the care and support network to alleviate these shortages.

To date uptake has been slow, but also the technology has not reached a tipping point where it is able to cost effectively fulfil functional requirements. Further work is needed to ensure that European care professions can utilise the most advanced technologies, including complex prostheses (dexterous hands, full-arms) and other upper-limb robots (hand and arm exoskeletons), walking and rehabilitation robots, as well as using clinical robots to their best advantage. In considering provisioning an additional dimension focusing on care and rehabilitation at home present a substantial opportunity. Coordinated effort in this area is required to ensure support technologies can be used at home thus reducing hospital stays and reducing pressure on long-term bed occupancy, while also considering the potency of these technologies for prevention in the ageing well.

The market for robotics in healthcare has a huge potential and Europe is well placed to build a global industry both because of its strong interdisciplinary research base and because of its publically funded healthcare systems.

2.3.3. Relationship to other Domains and Markets

There is a strong relationship between Healthcare and Assistive Technology in the Consumer Domain. The dividing line between these two areas relates to the user. In a clinical setting robot systems will be controlled or set up by clinically trained staff for use by an individual. In a Consumer, or more specifically a domestic setting, the robot systems will be set up and used by untrained users and will not require clinical expertise to operate.

Within specific areas of Healthcare there are relationships to other areas of robotics based on manipulation ability. However in general the Healthcare domain has specialised requirements with respect to materials, certification and safety that are not replicated in other Domains.

2.3.4. Unknowns

Standards, regulations and ELS issues are not taken into account in this document. The consideration regarding these issues are addressed in the section on standardization, and in sections relating to Ethical, Legal and Socio-Economic issues..

There are specific areas where Healthcare Robotics may have unknowns:

There are significant differences in the legal frameworks and financing models for providing care in individual European countries, and in the provision of assistive devices and technology at home and in residential care facilities. There is a possibility that these differences could become more diverse as each national system adapts to the provision of autonomous systems. This may require European wide harmonisation to ensure the market does not become fragmented.

The implementation of robots in a health care context concerns much more than "just" the technical development. Tailored development, driven by care needs is the first step but after technological realisation it is the demonstration of added value that is crucial for success. This added value cannot be shown without involvement of care professionals and End Users. It is also likely that the modification of current care practise will be essential in order for the robot to be effective this in turn will require training and education of clinical and care staff.

Demonstration/verification of cost effectiveness in terms of added value but also of cost-benefit will be required before large scale financial commitment will be made. However it is unclear how novel and inventive products can be trialled and proved without initial commitment.

2.3.5. Key Market Data

2.3.5.1 Surgical robots for surgery, diagnosis and therapeutic processes

Surgical care is an integral part of health care throughout the world, with an estimated 234 million operations performed annually. Each year, approximately four millions minimally invasive procedures performed worldwide are candidates for use with a robot.

The surgical robot device market estimated at $2.4bn in 2011 is anticipated to reach $8.5bn by 2018 as next generation devices, systems, and instruments are introduced.

The surgical robot market is heavily dominated by the US. The main US provider is Intuitive Surgical however a limited number of US companies also show growth potential such as Hansen Medical, Accuray, Stereotaxis and Restoration Robotics. A handful of European companies are active in the field. The most well-known European company was the UK-based Acrobot, however it has now been acquired by its main US competitor. Other systems include the ROSA system (MedTech), the iSYS robot (iSYS MedizinTechnik), the Freehand (Freehand 2010 Ltd), Novalis (Brainlab) the Viky endoscope holder and the Jaimy robotic handheld instrument (Endocontrol) and Neuromate (Renishaw).

The surgical robotic market is also dominated by the US where 70% of the installed base is present. Europe has about 20% of the installed base, the remaining 10% can be found in the Near and Middle East regions.

The financial results of Intuitive Surgical are impressive and demonstrate the importance of the market for surgical robots, but also the importance of a carefully managed patent portfolio. In 2012 revenues were $2.1bn, up 24% from 2011, and the operating profit was of $878m, up 26% from 2011, 40.3% of sales. In 2013, the revenues of the first half are $1.9bn, up 15% from the first half of 2012. There are 2,799 da Vinci robots installed worldwide, of which 2001 in the United States, 443 in Europe, and 355 in the Rest of the World. These robots performed approximately 450,000 procedures in 2012, up 25% from 2011.

Some specific market figures are listed below.

- The estimated annual market of robotic surgery is predicted to exceed the $4bn in 2016: robotic surgery was first commercially introduced in the year 2000. In only ten years it has grown to a one billion USD industry.
- Image-guided surgery and intra-operative use of imaging techniques forms a compound market of nearly $1.3bn in 2013 in Europe. The market is expected to increase with an annual growth factor of approximately 5% in the next few years. Of such market, interventional imaging systems account for an estimated 85% of the sales. Surgical navigation systems occupy the remaining 15%.
- The surgical robot device market is at $3.2bn in 2012 and is anticipated to reach $19.96bn by 2019 as next generation devices, systems, and instruments are introduced to manage surgery through small ports in the body instead of large open wounds.
- Renishaw Mayfield (CH) has made 40 installations worldwide of the NeuroMate system for neurosurgery. The turnover of the Renishaw healthcare division is around £29m for 2012 fiscal year, the market share in the special field is approximately 80%.
- Endocontrol (FR) has installed more than 120 ViKY endocoscope holders worldwide and the company has today 20 employees.
- MedTech (FR) has installed 20 ROSA systems for neurosurgery worldwide. The company has today 20 employees.
- The running cost of the Mazor (IL) commercial system (SpineAssist) is €550 per case plus €50,000 for maintenance, In total 40 systems are installed.

2.3.5.2 Rehabilitation robotics and prosthetics

Robotics in neuro-rehabilitation (from COST MoU): It is estimated that in the EU the proportion of the population aged over 65 will rise from 17.1% in 2008 to 30% in 2060 and that the proportion of persons aged over 80 will rise from 4.4% to 12.1% over the same period (EUROSTAT population projections). Neurological conditions, especially stroke, are a major cause of disability among older people. Incidence of a first stroke in Europe is about 1.1 million and prevalence about 6 million. Currently, about 75% of stroke sufferers survive one year after. This proportion will increase in the coming years due to steadily increasing quality in hyper-acute lifesaving practice, follow-up acute and sub-acute care, and life-long management of these conditions. Despite these positive developments in stroke care, approximately 80% of stroke patients experience long-term reduced manual dexterity and half of all patients with neurological conditions are unable to perform everyday tasks. In addition, Cerebral Palsy (CP), mainly due to congenital brain damage, is the commonest cause of motor disability in early childhood and its rate is between 2 and 3 per 1000 live births. This rate increases to 40–100 per 1000 live births among babies born very early or with very low birth weight and therefore they represent the population with highest rate of neurological disorders. Diagnosis and management of stroke in childhood can be difficult because of the diversity of underlying risk factors and the absence of a uniform treatment approach.

Spinal Cord Injury: 1,200 new injured persons in France per year with 39% tetraplegia (21% complète) and 61 % paraplegia (complète, 48 %; incomplète 13 %) and a current population of about 20,000 persons.

[Friggeri 2006; from TétrAfigap enquiry
http://www.paratetra.apf.asso.fr/IMG/pdf/Portrait_chiffre_des_blesses_medullaires.pdf].

In US approximately 12,000 new cases each year, population having SCI estimated to be approximately 273,000 persons. Since 2010, the most frequent neurologic category is incomplete tetraplegia (40.6%), followed by incomplete paraplegia (18.7%), complete paraplegia (18.0%) and complete tetraplegia (11.6%). Less than 1% of persons experienced complete neurologic recovery by hospital discharge.

(US data:
https://www.nscisc.uab.edu/PublicDocuments/fact_figures_docs/Facts%202013.pdf).

Post-stroke rehabilitation robotics. Each year approximately 500,000 people experience a stroke in US and about 1,1 million in Europe. Stroke has been identified by the World Health Organization in 2008 as one of the five main chronic diseases and its incidence is amplified by ageing. Consequences of stroke are often related to impairment of upper- and/or lower limb motion. In the ideal scenario that all of the stroke patients shall be extensively treated in clinical canters with robotic machines (either end-point manipulators, cable suspensions or exoskeleton robots) - we can estimate the market turnover based on the following assumptions:

It is possible to estimate that a rehabilitation centre can treat around 200 new patients every year; each centre will have at least 10 devices for lower-limb rehabilitation (reasonable cost: €150k for each device), 10 robotic trainers for upper-limb (reasonable cost: €50k for each device) and 10 robotic trainers for the hand (reasonable cost: €50k for each device);

The average life of each robotic device is about 10 years. This provides an estimate that every year this market has a potential turnover of about €2bn Limitations of this estimate do not consider that most of the market opportunities will derive from the fact that these devices will be continuously updated so clinical canters will stimulate development of new software, human-robot interfaces and sensory apparatus for monitoring patient bio-signals.

Robotic treatment of special diseases such as autism in children has been successfully tested in EU and national projects. There are more than 60 million persons affected by autism in the world, presently treated, when treated, only by human therapists.

Lower-limb prostheses. Incidence of all-cause lower-limb amputations changes significantly among countries, races and genders. For instance, all-cause lower extremity amputation incidence in Japan is about 0.4 over 10,000 (ten thousands) inhabitants per year, while in UK is about 2 over 10,000, and in US, it can reach peak values of 10 over 10,000 per year, To better quantify the incidence of lower-limb amputations and have a dimension of the problem, we should realize that every year – only in US – about 150,000 people undertake a lower-limb amputation caused by a vascular disease (http://www.amputee-coalition.org).

In order to estimate the potential market for robotic lower-limb prostheses, the following assumptions can be made:

- *in Europe and US, there are every year 300,000 new potential users;*
- *majority of users will be trans-tibial amputees (80%);*
- *the smallest fraction (20%) will be trans-femoral;*
- *a reasonable estimate of a robotized ankle-foot prosthesis can be €10k*
- *a reasonable estimate of a robotized knee-ankle-foot prosthesis can be €15k.*

Upper-limb prostheses. There are some new 50 to 270 new upper-limb amputees every year in Europe, making it for a stable population estimated around 1900 traumatic upper-limb amputees and 94 000 total upper-limb amputees. Trans-radial level (below-elbow) amputations account for 57% of this figure, while trans-humeral (above-elbow) for 23% [Micera et al., IEEE Rew. Biomed. Eng 2010].

The price of, e.g., the average self-powered hand prosthesis is extremely hard to estimate, mainly since such devices range from one-degree-of-freedom open/close artefacts (e.g., Otto Bock's Sensorhand Speed) to poly-articulated, multi-fingered mechanical hands equipped with wrist motions. It is expected that the latter kind of devices will be the major players in the mid- to long-term future, as they go towards the reinstatement of a significant fraction of the lost functionality of the human hand/arm. Each such device (even at the market-production level, e.g., RSL Steeper's BeBionic or Touch Bionics's i-LIMB models) might cost in the range of €20,000 to €40,000.

Even if only the cost of the hand prosthesis is considered, that is, neglecting the associated care, hospitalisation and maintenance costs, a potential initial market value of about 1B€ upfront and 21M€ every subsequent year. This is only considering the European market.

Neuropathic pain. In 82% of amputees, *phantom-limb pain* appears soon after the operation, and persists after six months in 65% of the cases and after two years in 59% of them. Levels of pain described as "severe, disabling" is reported in 10% to 25% of the cases after several years, independently of age, gender, level of amputation or age after 8 years old. It is sometimes reported in individuals born without a limb (agenics), and it is so far essentially untreatable, since there is no application place for drugs. *Complex Regional Pain Syndrome* appears, on the other hand, after the healing of trivial operations (e.g., bone fracture) or associated with peripheral nerve injury (2-5% of the cases) and hemiplegia (13-70%). CRPS is a highly disabling, untreatable, unbearable for of pain whose aetiology is still unknown.

CRPS incidence was estimated in 2007 as of 26.2 per 100,000 person years; combining this figure with phantom-limb pain figures, restricted to the case of upper-limb amputations, yields about 34.000 patients in Germany only every year.

2.3.5.3 Assistive robotics for caregivers or patients

Robots to support caregivers in their work.

The World population aging 2013 study (United Nation) clearly demonstrate the need to structure a silver economy (senior people, retirement houses, hospitals, home with a minimalistic medical infrastructure -government incitation for old people to stay at home to reduce budgets- medical institutions) that encompasses the society aging phenomenon coupled to the need of reducing costs in medical and para-medical institutions. On a global and European level the aging population opens an alley for companion robots dedicated to wellbeing/telepresence/personal care robots.

Care personnel are increasing in average age, e.g. in Germany number of care workers above 50 years old almost doubled between the years 2000 and 2009

Care workers are among the professions with the highest numbers of sick days – in Germany on average 25 days per year,

{see http://www.spiegel.de/wirtschaft/soziales/0,1518,705576,00.html }.

Cannot work continuously in their job, frequent interruptions of working periods can be observed that add up to 47% of their possible working time, {see http://www.iwak-frankfurt.de/projansprech/Berufsverbleib.htm. }.

Average time of care worker in one job is only 8.4 years. One of the reasons is frequent number of ergonomically unsuitable movements, e.g. bending upper body up to 1300 times per shift[3], 1 in 10 nurses suffers from chronic back pain through handling patients. 33% of US population are obese. Carer injuries in the US cost an estimated $20bn per year.

The only "robotic" devices supporting care staff are transport systems operating in large hospitals with more than 600 beds. However, these systems usually don't navigate in the corridors or provide required care utensils in or close to the patients' rooms.

Robots for people with medical conditions or handicaps

EU-SILC Data from 2006 to 2008 show that on average over 30% of people aged over 75 say they are restricted to some extent, and over 20% describe themselves as severely restricted. In the 85-and-over age group, 'severe limitation' is more common than 'some limitation'.

An estimated 9 million people in the EU need help getting out of bed.

Current products for end users are mainly dedicated to supporting handicapped people: e.g. wheelchair mounted manipulators or feeding devices. However, also larger person groups e.g. elderly can profit from such devices. The deterioration of functions caused by ageing frequently leads to diminished sensory motor functions. The ability to reach and grasp, especially above shoulder level, is often reduced due to muscular weakness or the effects of motor control problems.

The World robotics study 2013 registered only around 150 units for elderly and handicap assistance sold in 2012; however, more than 6,000 are predicted for 2013-2016.

Market estimation for robotic wheelchairs (mobility assistance) is here reported. "Medicare allowed an average of $11,507 for complex rehabilitation power wheelchair packages that cost suppliers an average of $5,880 in the first half of 2007 " http://oig.hhs.gov/oei/reports/oei-04-07-00400.pdf

Over 200,000 people in the United States use electric-powered wheelchairs (EPWs) as their primary means of mobility 3.3 million wheelchairs are used daily in USA. Fehr et al reported that 18%– 26% of their patients that used a manual wheelchair could not safely operate an EPW. Furthermore, a report using data from the United States emergency departments stated that in 2003 over 100,000 wheelchairs related accidents were treated with 65–80 percent of the accidents being tips and fall http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2811532/ This brings to estimate the worldwide market for assisted, powered wheelchairs as more than 1 million units at a cost between $5,000 and $10,000 each.

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[3] see http://www.bgw-online.de/internet/generator/Navi-bgw-online/NavigationLinks/Kundenzentrum/Grundlagen__und__Forschung/Ergonomie/CUELA/

The WHO just launched the new GATE initiative aiming to support people after initial medical prevention and treatment has been taken care of. This involves assistive technology including assistive robots.[4]

2.3.5.4 Europe's Place in the Market

Europe has considerable expertise in Healthcare robotics[5] as is clearly highlighted in the EuroSurge CA results. Europe has pioneered this application area with first assistive robots (e.g. Spartacus in the 1980's, first Care-O-bot prototype introduced in 1998), primary rehabilitation robots and early surgical robotics experiments. The first surgical robot used on more than 100 patients was the robot designed in 1989 in Grenoble by TIMC-IMAG for stereotactic neurosurgery. This was also the first robot to be able to work in an operating room. The first patient was treated in 1989. Since then more than 1000 patients were treated with this first prototype. This first system was the direct ancestor of Neuromate®. Some of the first tele surgery experiments were performed in Europe, e.g. with the Artemis surgical system developed by Karlsruhe Institute of Technology, Germany in 1990-1994. Also, the first transatlantic surgery the so-called "Lindbergh operation" took place in 2001 between Strasbourg and New York. It was conducted by a team of French surgeons.

However European industry despite having global medical companies has not to date followed this pioneering work and still lacks visibility. Therefore it is crucial that Europe dramatically raises efforts to ensure that European Healthcare robotics research is actually transferred into products so that European citizens and the economy in general can benefit from this.

Clinical Robotics

There is extensive research activity and expertise present in European academics. Also, several European companies such as Storz, Philips and Siemens are involved in the supply/value chain. In addition, there is a participation in the surgical robotic field by some European SME's such as Endocontrol, iSYS and MedTech. It is therefore of critical importance that on the short to mid-term a high potential niche of robotic surgery is found *and* occupied by a European company.

Some of the largest providers of self-powered upper- and lower-limb prostheses are located in Europe – examples are Otto Bock, RSL Steeper, Touch Bionics and Ossür. Research in Europe on prosthetics is world leading and establishing links between the academic community and these current market leaders will help to simulate technology transfer.

Rehabilitation Robotics

In rehabilitation robotics Europe is well positioned with key players in the market such as Hocoma, (market leader), Reha Technology, Tyromotion, and many others. However, US, Israel and Japan are currently dominating other specific areas as e.g. the lower extremities exoskeletons market. Here, despite a number of strong research projects running in FP7, a stronger commitment by the industry needs to be facilitated by the H2020 PPP. The area of domestic/tele-rehabilitation needs to be strengthened both on the research and the commercial side, following the policies on e-health and e-inclusion. There is a clear potential for lowering societal challenges and increasing accessibility to modern and impactful rehabilitation.

Some of the largest providers of self-powered upper- and lower-limb prostheses are located in Europe – examples are Otto Bock, RSL Steeper, Touch Bionics and Ossür. Research in Europe on prosthetics is world leading and establishing links between the academic community and these current market leaders will help to simulate technology transfer.

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[4] http://newsletter.aaate.net/?q=node/43

[5] http://www.eurosurge.eu/eurosurge/

Assistive robotics

Robots supporting care personnel: AGVs are used in some large hospitals and many of the manufacturers come from Europe. However, also new products from the US such as the TUGs manufactured by Aethon, are starting to be introduced to European hospitals. Initiatives to reduce the size of currently used AGVs and enhance them towards more flexible and compact systems able to navigate not only in separate but also in public areas can be observed in several European countries. Some Japanese developments of robots operating in public buildings can be observed as well, e.g. for cleaning and transportation. Some of them, e.g. the hospital delivery robot "Hospi" by Panasonic, are based on European technology.

Additional support systems for care staff are currently being developed in Japan, e.g. a robotic lifter by Muscle Corp. or a standing up assistant by Toyota. Emotional support robots such as Paro had their origins in Japan can be found in use in Europe.

Robots supporting people with medical conditions: There are a number of companies providing assistive robots for the handicapped in Europe. For example the first robot-mounted manipulator, Manus, was a European product now being followed by iArm in the Netherlands. Additional solutions come from Canada (Jaco) and are also sold in Europe. Feeding robots have until now been mainly a Japanese product, but new European systems are now getting introduced, e.g. Bestic in Sweden. Similarly, tele-presence robots have made their way from the US. More advanced communication and interaction robots as well as socially assistive robots able to interact with their user in an intuitive way are a strong research topic in Europe.

2.3.6. Key System Abilities

Summary

Intuitive user interfaces, efficient and effective operation, high functional dependability, good sensing and interpretation of the working environment.

The following tables describe abilities for Healthcare robotics applications and the levels (performance) required for these abilities. Levels are defined in the chapter 3 of the MAR ("*System Abilities*"). The levels defined

2.3.6.1 Configurability

Description of the ability	**Domain** *Assistive (A), Surgery (S) Rehabilitation (R)*	**System Abilities level required**
Intuitive configuration mechanisms and modular systems. Minimal user knowledge requirement.	A, R	Level 2 to 3
	S	Levels 0 to 4 - Intuitive and Minimal user knowledge requirement
Automatic system configuration based on learning	A, R	Level 3
	S	Levels 3 and 4
Tools to identify suitable configuration of the robot based on required functionality	A, S, R	Level 0

2.3.6.2 Adaptability

Description of the ability	Domain Assistive (A), Surgery (S) Rehabilitation (R)	System Abilities level required
Adaptation to users (patient, surgeon, caregivers) and environment	A, R	Levels 2 to 3
	S	Levels 1 to 3 – for automatic procedures or tasks Levels 4 – patient anatomy or movement adaptation/compensation Level 4, support surgical situation awareness
Auto-adaptation to user learnt profile	A, R	Levels 4 to 5
	S	Levels 3 to 5

2.3.6.3 Interaction Ability

Description of the ability	**Domain** *Assistive (A),* *Surgery (S)* *Rehabilitation (R)*	**System Abilities level required**
High performance capacities to interact with user and environment	R	Level 2
	A	Level 4 (e.g. semi-autonomous operation of assistive devices)
	S	HRI Level 2 – real time force feedback Levels 3 to 6
Transparency of the interaction between the user, the robot and the environment.	A, S, R	Level 2
Multimodal feedback (including force tactile, vision, sound, olfaction, etc.)	A, S, R	Level 2
Interaction among robots committed to an overall procedure	A, S	
Integration with residual volitional user control of the motion, eventually enhance by Functional Electrical Stimulation	S, R	Level 2 and 4

2.3.6.4 Dependability

Description of the ability	**Domain** *Assistive (A),* *Surgery (S)* *Rehabilitation (R)*	**System Abilities level required**
Intrinsically safe systems	A, S, R	Levels 1 and 2
Resilience/Robustness to sensor failure	A, S, R	Levels 5 and 6
Prediction and identification of future failures to inform the user and activate maintenance	A, R, S	Level 5 and 6

2.3.6.5 Motion Ability

Description of the ability	**Domain** *Assistive (A),* *Surgery (S)* *Rehabilitation (R)*	**System Abilities level required**
Ability to follow human dynamics and perturbing physiological motion.	A, S, R	Levels 4 to 5 of Constrained Motion
Capable to produce smooth human-like motion integrated with residual user controlled volitional movements	S, R	Levels 5, 6 and 1 to 5 of Constrained Motion

2.3.6.6 Manipulation Ability

Description of the ability	**Domain** *Assistive (A),* *Surgery (S)* *Rehabilitation (R)*	**System Abilities level required**
Increased dexterity in narrow spaces	A, S, R	Unconstrained Motion Level 4
Dexterous manipulation with limited encumbrance device.	S	Unconstrained motion Level 7
Versatile and polyvalent tools recognition and objects manipulation	A, R	Handling Ability Level 4/5
Grasping / manipulation of soft and delicate objects	A, S, R	Handling Ability Level 4/5

2.3.6.7 Perception Ability

Description of the ability	**Domain** *Assistive (A),* *Surgery (S)* *Rehabilitation (R)*	**System Abilities level required**
Detection and tracking of typical household or care utensils	A, R	Levels 1 to 8 - perception ability Levels 1 to 4 - Tracking Ability Levels 2 to 12 - Object Recognition
Real time perception and following of patient state (movement, metabolism, fluid flow, etc.)	A, S, R	Levels 3 to 5 - Tracking ability Levels 4 to 13 - Object recognition
Real time situation monitoring (person in conjunction with environment and objects)	A, R	Levels 2 to 8 - perception ability Levels 1 to 4 - Tracking Ability Levels 2 to 12 - Object Recognition Levels 3 to 6 - Scene perception
Multimodal perception, fusion of heterogeneous sensor information	A, S, R	Levels 1 to 5 – perception ability Levels 1 to 7 - Location perception

2.3.6.8 Decisional Autonomy

Description of the ability	**Domain** *Assistive (A),* *Surgery (S)* *Rehabilitation (R)*	**System Abilities level required**
Situation recognition, capacities to accommodate uncertain environments and make autonomous decisions according to preferences	A, S, R	Level 6 to 9
Adjust training to optimize outcome for specific user	R	Levels 7 to 10
User/environment automatic recognition to allow a appropriate/diminishing support	A, R	Levels 8 to 10
Safe response in emergency	A, R, S	Level 3 to 9

2.3.6.9 Cognitive Abilities

Description of the ability	**Domain** *Assistive (A),* *Surgery (S)* *Rehabilitation (R)*	**System Abilities level required**
Online patient state analysis	A, S, R	
Context or situation understanding	A, S, R	
Flexibility of assistance solution on learned experience by integration of robotic support with residual user capability and support	R	Action ability: Level 2, 5, 8 Interpretive ability: Level 3 to 6 Envisioning ability: Levels 1 to 5 Acquiring knowledge: Levels 1 to 4, Levels 9 to 11, Levels 13 to 15 Reasoning: Levels 7 and 8 Object Interaction: levels 3 to 5 Human Interaction: Levels 2 to 4
Online/real time patient state diagnostics	S, R	
Online environment analysis and take up	A, S, R	
Full task and environment understanding (in gait)	A	
Automatic assistance merging robotic support with residual user capability and action	A	
Intention anticipation	A, S	

2.3.7. Key Technology Targets

2.3.7.1 Systems Development

Systems Architecture

Assistive and Rehabilitation

- Definition of standards allowing enhanced interoperability of multimodal components including haptic force and tactile components and plug and play interfaces.
- Standardised system architecture, also including interfaces with home electronics, health care / hospital IT infrastructure and AAL systems
- Surgery
- Real-time OS and dedicated surgical robotic middleware
- Plug and play interoperable surgical robotic standardized middleware
- Workflow and ontology based procedure guidance and control
- Architecture for linking real-time image processing and reconstruction to robotic middleware
- Medically certified real-time OS and robotic middleware

Systems Integration

Surgery

- Fully integrated force/tactile feedback devices, self-sensing
- Medically certified sensors, hardware components and software libraries for composing of new (procedure-specific) surgical robots and devices
- Vision-integrated surgical robot control, stereo-displays
- Standardized surgical cockpit for multiple disciplines

Rehabilitation

- Systems combining force and tactile feedback
- Wearable systems with open interfaces for establishing collaborative body area networks, including assistive systems (e.g., prostheses) and other general-purpose sensing and communication devices (e.g., smartphones, smartwatches).

Modelling and Knowledge Engineering

Assistive

- Extension of object modelling through computer vision through other forms of sensing (infrared, tactile)
- Database of typical motion and interaction patterns during care processes, format should allow care personnel to verify correctness of learnt models
- From ontological learning to phylogenetic and social learning. Formal methods for knowledge integration also on a collaborative way with other robots (internet of things for problem solving)
- Models for safety verification, specifically taking into account (all) possible environment structures, human postures and motion etc. the robot could come into contact with
- Modelling of specific care processes that should be supported by the robot (carer interacting with environment and patient)

Surgery

- Surgical knowledge database and means for retrieval of relevant context-dependent knowledge for online feedback and guidance (suggesting optimal procedure or intervention approaches).
- Ontology to structure the knowledge of surgical procedures
- Use of atomic surgical steps and their composition to generate patient specific intervention plans
- Rules for robotic surgery planning
- Interaction of learning and modelling paradigms
- Real-time FEM soft tissue modelling,
- Modelling of tissue damage for damage detection and prevention

- Online reconstruction of anatomic structures
- Modelling of intervention on tissue, muscles, organs
- Modelling of physiological and biological functions
- Intra operative tissue deformation modelling
- Compliant robots modelling, flexible robot-tissue interaction modelling
- Online identification of human motor control
- Task and surgical workflow modelling
- Flexible robots-tissues interaction modelling
- Task and surgical workflow modelling

Rehabilitation

- Better models of human motor control
- Guidance cues through overlay technology, library with expert procedure execution samples
- Semi-autonomous prosthetic reaching, grasping and manipulation
- Interfaces for exploiting the vast knowledge resources that are available online (object model repositories and know-how instructions)
- Afferent/natural feedback in prosthetics

Assistive

- Standardized methods such as Wizard-of-OZ to verify target functionality with end users before starting new hardware and software developments
- Use of existing research platforms to verify functionality before building dedicated assistive device
- Design concept to adjust robot hardware and functionality to individual user requirements
- Methods to create functional robot design, i.e. visual appearance that mirrors the robot's abilities

Surgery

- Specific design methodologies for sterilise-able and safe surgical robots
- Intra-corporeal robotic system design methods
- Multimodal VR training platforms design and validation methods
- Public databases of surgical procedures (images, forces, physiological parameters and other data sources) for requirement distillation.
- Guidelines, equipment and algorithms for setting up a Smart OR that gathers all relevant data for requirement distillation or validation.
- Principled methods for analysis of the workspace, surgical workflow, surgical tasks and surgical skill for requirement distillation.
- Reproducible artificial mock-ups that replicate the behaviour of the relevant properties of real organs or body parts for use in requirement distillation, benchmarking and validation.

Rehabilitation

- Specific partial design strategies for system in direct interaction with human limbs or human organs.
- Wearable robotic system design methods

Systems Engineering

Assistive, Surgery, Rehabilitation

- Methodologies for modular and rapid prototyping and benchmarking

- Software environment for rapid, easy and intuitive simulation and testing
- Modular system concepts allowing the re-use of hardware components for different functionalities and users
- Automatic safety verification for modular robots

2.3.7.2 Human Machine Interface

Assistive

- System integrated control interface, easy to use even by non-technical personnel
- (Natural) Dexterous interaction with haptic feedback
- Co-manipulation
- Hands-free operation (speech, body posture, etc.)
- Novel kinds of interfaces; sensor data fusion allowing to “propose” assistive activities to the user based on observed situation

Surgery

- Force/tactile and haptic feedback with transparency and stability guarantees
- Human-machine interaction e.g. in hands-on-mode and virtual fixtures
- Situation reactive human-machine interfaces
- Touchless interaction techniques for sterilized environment
- Haptic interfaces offering intuitive operation and dexterity similar to open surgery. Interfaces and technology for rendering palpation interaction in more natural way
- Augmented reality environment for full immersion of the surgeon and medical staff, summarizing information from the surgical field and providing guidance for efficient human-robot collaboration.

Rehabilitation

- Natural haptic interaction
- Implicit interaction; wearable robot as interface
- User accepted BCI interface for robot control
- Wearable multi-sensory platforms
- Integrating automatic functions with the manual control of the user (shared control)
- Support for bimanual tasks
- Bidirectional human-machine interfacing to promote sensory-motor integration

Safety

All

- Safety certified OS
- Safety certification procedure for software

Assistive

- Intrinsically safe systems (mechanical systems and actuators)
- 3D supervision systems to ensure collision free manipulation, for robots in direct touch with the human: to ensure that contact and / or motion applied to the user will bring him no harm
- Semantic analysis of situation allowing to avoid critical situations in advance
- Hardware safety concept including redundant sensing, processing devices and certified safety controllers
- Safety verification procedures to comply with ISO 13482 and medical guidelines

Surgery

- Intrinsically safe systems (electro-mechanical systems and actuators)

- Shared control with safety features
- Safe physical human robot interaction guaranteed by an attentive/monitored environment (avoid blocking surgical site by robot for human surgeon emergency access).
- Definition of no-go regions to allow safety during interventions.
- Cognitive assistance during entire surgical task execution
- Safety hardware and backup systems

Rehabilitation

- Human capacity needed to avoid falls and accidents
- Shared control with safety features
- Passive auto-adaptive restrictions (surgery, exoskeleton)
- Intrinsically safe systems (mechanical systems and actuators)
- Exoskeleton robot providing gait and balance safety
- Cognitive capabilities for the modelling of situations and action/hazard prediction
- Automatic compensatory/recovery reactions to hazardous events

2.3.7.3 Mechatronics

Mechanical Systems

Assistive and Rehabilitation

- Light weight, energy optimized design
- Modular design allowing to adapt robot to user requirements
- Concepts for safely moving / manipulating heavy objects in human environments
- Sizeable and comfortable interactive systems
- High performance capacities to interact with user and environment
- Dexterous device with limited encumbrance
- Practically usable force control and impedance control
- Intrinsically safe mechatronic systems
- Development of energy efficient actively driven systems

Surgery

- Modular surgical robotic systems (rapid prototyping techniques)
- Passive elements to build intrinsically safe mechanical systems
- Miniaturized (and micro- nano-) robots to decrease surgical or diagnostic interventions invasiveness
- High mobility degree (e.g.: highly redundant or large stroke) mechanisms
- Low-cost robots specialized in their functionality – preferably for application scenarios already approved in practice
- Reconfigurable and easy to deploy robots
- Soft and stiffness controllable robots
- Implantable miniaturized robots for diagnosis and therapy
- Body mounted robots

Sensors

Assistive

- Safety certified 3D sensors, tactile sensors for collision detection etc.
- High resolution 3D sensors, low-cost 3D sensors
- Multi-modal sensing and sensors with integrated processing (e.g. environment modelling, person detection) functions

- Miniaturized/wearable sensors

Surgery

- Environment / bio-compatible sensors and electronics (subject to intra-corporal constraints, imaging constraints) – either low-cost and disposable or sterilise-able
- Miniaturised sensors, force sensing, high-resolution tactile skin
- 3D-sensing and multi-spectral vision sensing
- Multi-modal sensing
- Sensors for localizing untethered robots inside the body
- Vision through blood
- Sensors for tumour detection
- Wire-less, self-powered sensors
- Body/organ motion trackers
- Miniaturized/wearable sensors
- Environmental compatible sensors and electronics (intra-corporal constraints, imaging constraints)

Rehabilitation

- Foot-sole interaction force measurement (exoskeleton)
- Intention detection through tactile sensing, pressure sensing, optical recognition, ultrasound images (prostheses)
- Sensors for detecting residual volitional control of user
- Detailed and continuous sensing of human-robot interaction forces
- Online, smooth sensor fusion
- Miniaturized/wearable sensors
- Environmental compatible sensors and electronics (intra-corporal constraints, imaging constraints)
- Wearable high-density myoelectric interfaces
- Comprehensive sensing of the robot state (embedded sensors), user movements (wearable sensors) and external environment (3D sensors), with sensor data fusion

Actuators

- High power to volume ratio actuators
- High power miniaturized actuators
- Self-sensing actuators
- Human safe actuators
- Low-noise actuators
- Energy efficient actuators

Assistive

- Low-cost actuators with limited accuracy and speed (for many applications low accuracy might be compensated by Software or by user interaction)

Surgery

- Further reduction of weight, optimization of intrinsic compliance.
- Further increase of static and dynamic performances (e.g. large displacement over large bandwidth)
- Environmental compatible high power to volume ratio actuators (intra-corporal constraints, imaging physical principle constraints)
- Ubiquitous MRI-compatible actuation, sterilise-able/disposable actuation, micro hydraulic actuation, variable impedance actuators…

- High power to volume ratio actuators, high power miniaturized actuators
- Large stroke miniaturized actuators
- Disposable actuators/robots
- High power/consumption ratio actuators and mechanical concepts

Rehabilitation

- Integrated single-finger and wrist control for highly dexterous hand prostheses
- Integration of hybrid assistive devices including Functional Electrical Stimulation
- Specific actuation technologies for wearable robotics
- Human muscle level force capabilities
- Integration of functional electrical stimulation multi-electrodes systems, combining multiple actuators and multiple stimulation sites to get natural task execution
- Specific actuation technologies for wearable robotics, such as under-actuated mechanisms
- Prosthetics with compliant properties and back-drivable operation, allowing precise and consistent control, which would promote effective utilization of sensory feedback to the user.

Power Supply and Management

Assistive

- Energy-flows optimized design
- Fuel cells using biological fluids

Surgery

- Wireless power supply (US, IR, EM) for micro-systems
- Self-supplied (power harvesting/scavenging from patient body) systems

Rehabilitation

- Power harvesting in the body (RF, EM, movement…)
- Energy harvesting
- Fuel cells using biological fluids

Communications

Assistive

- Interface to home infrastructure / hospital IT

Surgery

- Tele-surgery over internet/dedicated lines
- Real time communication technologies

Rehabilitation

- Communication between prosthetic devices, direct point-to-point connections or through Internet of Things infrastructure, to support cooperation during collaborative tasks

Materials

Assistive

- Soft, natural materials, easy to wash and clean
- Possibility to adapt appearance of the robot to user preferences
- Resistant, yet easy to manufacture

Surgery

- Highest stiffness and resistance materials
- Advanced materials (rigid, soft, adaptable or deformable, active)
- Bio compatible disposable materials

Rehabilitation

- Higher stiffness and resistance
- Bio-compatible tactile sheets, adhesive glues, tissue engineering
- Environmental compatible structural material (e.g. bio or MRI compatibility)
- Light weight materials
- Wearable high-density myoelectric interfaces (e.g. conductive textile and silicone)
- Self-degradable instruments, hysteresis free materials, human-friendly contrast agents,

Control

Assistive

- User controlled device providing assistive functionalities for collision avoidance of enhancing ease of use
- Integration of cognition and control paradigms
- Direct control through physical interaction or person detection / motion adaptation
- Compensation of perturbing physiological movements (tremors,…)
- Active, and safe sensing for environment reconstruction and recognition

Surgery

- Bilateral tele-operation over (long)distance, guaranteed robust performance, variable-scaled control
- Compensation of perturbing physiological movements (heartbeat, breathing,…)
- Control of flexible/compliant structures
- Shared control & autonomous task execution
- Active, and safe sensing for environment reconstruction and recognition
- Control of an integrated OR including robots (workflow controller)
- Master control for an integrated OR including robots (workflow controller)
- Integration of cognition and control paradigms

Rehabilitation

- Dynamic estimation of workspace impedance during interactions and automatic feedback gain adaptation for maximum performance and guaranteed stability
- Compensation of perturbing physiological movements
- Shared control & autonomous and semi-autonomous task execution
- Control based on real-time neuro-musculoskeletal modelling and identification

2.3.7.4 Perception

Sensing

Assistive

- High resolution multimodal perception and interpretation of objects, environments, persons and scenes
- Reliable application in changing lighting conditions, indoor and outdoor environments

Surgery

- Improved interaction force sensing
- tactile sensing, stereo chip-on-tip, high S/N US, vision through blood
- Real time perception, following of patient state and full-patient monitoring

- Fusion of heterogeneous sensor information
- 3D models reconstruction from images in unstructured environments as body organs
- SLAM of inner body cavities and organs
- High resolution multimodal perception
- OCT integration

Rehabilitation

- Improved interaction force sensing
- Distributed interaction force sensing
- Condition-independent sensing technology (temp/pressure)

Interpretation

- Emergency detection and handling

Assistive

- Situation / activity monitoring allowing to "propose" assistive activities to the user
- Learning and detection of objects and / or environment to be manipulated
- Recognition of more than 10000 objects indoor and outdoor.

Surgery

- Assessment of clinical state of patient in specific procedures
- Episode segmentation (workflow) by OR perception
- Assessment of clinical state of patient during training or use

Rehabilitation

- Assessment of clinical state of patient in specific procedures
- Perform clinical assessment of user based on defined procedures and sensors
- Semantic analysis of the scene and actions, using on-board processing as well as online resources (Cloud computing)

2.3.7.5 Navigation

Mapping

Assistive

- Indoor / outdoor 3D mapping
- Indoor / outdoor 3D mapping and remapping with changes in the environment
- Local real-time mapping for safe manipulation close to humans

Surgery

- Real-time 3D organ reconstruction from cameras, flexible registration, real-time 3DUS fusion
- 3D non-invasive scene mapping including dynamics
- Multi-modal registration
- Registration of intra and pre-operative maps
- Microscope 3D imaging
- Master/Slave mapping

Rehabilitation

- Real-time 3D reconstruction of moving structures while under process

Localisation

Assistive

- Optimal understanding of and interaction with environment

Surgery

- Shape estimation of flexible, continuum robots, contact / force detection over whole internal part of surgical robot
- High frequency 3D position measurement of patient, organs and robot / effector
- Flexible registration and mapping, automatic segmentation of whole patient
- True real-time 3D positioning of patient, organs and robot / effector
- Anatomical localization of instruments in the patient body
- Intra operative imaging for organ motion tracking and organ deformation tracking
- Medical imaging registration (intra operative Imaging)

Rehabilitation

- Sense of verticality and balance

Motion Planning

Assistive

- Collision-free navigation and manipulation in dynamic environments
- Adaptation of motion target (e.g. approach human, individual preferences)
- Smooth, human-like trajectory planning and motion execution for specific tasks
- Semi-automatic path planning merging visual and robot sensors information
- Automatic path planning merging visual, robot sensors information and knowledge-based medical information

Surgery

- Collision-free multi-arm coordination
- simulation-based prediction of flexible instrument motion, interaction, contact estimation
- Safe motion inside the human body
- Collision-free motion between robotized instruments and organs
- Virtual fixtures

Rehabilitation

- Basic generation of steps, and assuring postural balance, for walking in structured environments
- Smooth, human-like trajectory planning and motion execution for specific tasks
- Full generation of gait adequate to task and environment
- Natural human-like motion automatically planned on target spatial identification

2.3.7.6 Cognition

Cognitive Architectures

Assistive

- Context understanding, situation awareness
- Written text interpretation

Surgery

- Self-aware instruments, Intelligent instrumentation with inherent safety operational limits, self-exploratory devices
- surgeon and OR personnel attention detection
- Ontologies based workflows

Learning Development and Adaptation

Assistive

- Supervised learning from experience of new behaviour, of user preferences
- Learning by expert supervision, Intention recognition, emergency detection, safety constraints
- Reliable object learning, search and recognition
- Unsupervised learning from experience of new behaviour, of user preferences

Surgery

- The system stores a database of previous sessions and is able to change control parameters according to the user (e.g. the surgeon/ patient/ physician) intentions, characteristics and habits
- The system stores a database of previous sessions and is able to infer the user (e.g. the surgeon/ patient/ physician) intentions, characteristics and habits in order to learn skills and sub tasks
- Procedure ontology dynamic update

Rehabilitation

- Automatic adaptation according assist-as-needed training approaches
- Online learning; flexible learning (new patterns added upon the patient's request)
- Previous data are stored to allow the best integration between robot assistance and volitional residual control, with or without FES
- Automatic adaptation to individual needs for support or training.
- Acquisition of stable models of environment and user behaviour to be used for context-dependent control and prediction of user intentions

Knowledge Representation and Reasoning

Assistive

- "Good practice" in care processes, individual differences to be used for scene analysis and pre-active assistance
- Basic understanding of tasks and environments

Surgery

- Uniform procedure description and classification, online skill assessment and warning generation
- Automatic deduction of measures of success and benchmarks
- Object modelling and optimal grasp detection

Action Planning

Assistive

- Workflow planning (sequence of tasks)
- Accurate and secure grasping of all sort of material and objects of different shape, texture, size and weight
- Real-time deformable object modelling
- Automatic set of grasping posture in daily activities, making the system disappearing.
- Multi-system, user procedure planning and task allocation, online procedure evaluation, re-planning and instructing, multi-expert diagnosis

Surgery

- Automatic translation from pre-operation patient-data, description of surgical procedure, symptoms and treatment to robot programs

- Operation and workflow planning (sequence of tasks)
- Realistic patient-specific pre-operative procedure training, surgical skill assessment
- Image guided semi-autonomous robotic surgery
- Robotic suturing, multi-instrument grasp/handing down
- Semi-automatic grasp planning merging visual and robot sensors information

Rehabilitation

- Basic understanding of tasks and environments (in walking, reaching, grasping and manipulation)
- Understanding of tasks and environments (in walking, reaching, grasping and manipulation)
- Multiple grasping posture automatically set for some objects manipulation without direct manual control
- Automatic grasp planning merging visual, robot sensors information and knowledge-based medical information (surgery)
- Semi-autonomous grasping enforced on a dexterous prosthesis
- Multi-disciplinary/multi-institution procedure planning

Natural Interaction

Assistive

- Multi modal emotion understanding

Surgery

- Multi-user tele-surgery, fully immersive operation
- Emotion monitoring for confusing and alert situations
- Hybrid human-robot-team tele-surgical procedures

2.3.8. Key Technology Combinations

In most healthcare applications it is the successful integration of all of the different technologies that forms the most important technology combination. This mist often centres on the integration of materials, mechanisms, sensing, control and planning. Clinical healthcare is a highly constrained problem and creating viable systems is a long and complex process because there are numerous stakeholders in the design.

Particularly important for exoskeletons is the combination of Power Management – Human Machine Interface – Sensing – Control – Perception – Motion Planning (involves probably Systems Engineering – Learning – Localization). Such integrated systems can be characterised as “human/robot physical task sharing” or “human/robot motor cooperation” or “shared autonomy systems”. The close coupling of human and machine creates a specific technical challenge.

Of maximum importance for prostheses: advanced sensor capabilities in order to combine different human interfaces into a single reliable decision process is a complex challenge. The need to adapt the system also requires advanced machine learning capabilities to adapt to the subject, re-learn from failures and involves machine learning methods that can operate in embedded devices. Tactile feedback is also an important technology where novel devices to give touch and force feedback to the patient. Finally, enhancing the manual control (myoelectric interfacing) with intelligent automatic functions can decrease the burden for the user as well as improve the performance, especially with complex devices (e.g., dexterous hands, full-arm prostheses).

For assistive robotics it is important to provide solutions that are cost effective for end users as well as for institutions. This requires extensive field trials and collaborative design processes as well as certification and testing protocols.

Attentive Operating Room (Smart OR)

Sophisticated Operating Rooms, so called Hybrid Operating Rooms, combine imaging with advanced surgical procedures. This leads to a complex technical environment which could result in hazardous situations for the patient and the surgical team. Robot technology can be used in different tasks: for the flexible and accurate positioning of the imaging modalities (e.g. robotized C-arm), also being involved directly in the surgical procedure (e.g. milling, laser ablation) or as endoscope holder. An attentive Operating Room will monitor all actions of the surgical procedure, will identify the current status of the operation plan and delivers the best support for the surgeon at the right time. This will prevent a cognitive overload of the surgeon and her/his team. Here, we see a combination of robot integration + human-machine interfaces + surgical workflow + perception + cognition.

2.3.9. Current Key Projects

Assistive Robotics

Project	Funded by	Website	Start date
WiMi-Care	BMBF	http://www.wimi-care.de/eng/	2008
SRS	ICT	www.srs-project.eu	2010
ACCOMPANY	CT-2011.5.4 ICT for Ageing and Wellbeing	http://accompanyproject.eu/	2011
Companionable	ICT	www.companionable.net	2008
AALias	AAL-2009-2	http://www.aal-alias.eu	2010
Florence	ICT-2009.7.1. ICT & Aging: service robotics for aging well	http://www.florence-project.eu/	2010
Patient@home		http://www.patientathome.dk/	2013
HOBBIT		http://hobbit-project.eu/	2011
SERROGA	ESF + Thuringian Research Ministry	http://www.serroga.de	2012
ALMA	AAL Joint program	http://www.aal-europe.eu/projects/alma/	2013
STIFF	European 7th framework program	http://stiff-project.eu/2/	2008-31-12
DEXMART	European Community's 7th Framework Program		2008-02-01
Smart Hand		http://www.elmat.lth.se/~smarthand/index.html	2007
RAPP	RAPP FP7-ICT-2013-10	http://rapp-project.eu	2013
ERimAlter	BMBF	https://www.frankfurt-university.de/fachbereiche/	2013-2014

		fb4/projektefb4/emotionalerobotikimalter.html	
ORTAS	BMBF	http://www.mtidw.de/ueberblick-bekanntmachungen/mit-60-mitten-im-arbeitsleben/ortas-orthetisch-bionisches-assistenzsystem	2014-08-01
RoPaRa	BMBF	http://www.b-e-c.de/forschung/	2013-10-01
TEMSAM	ICT		2016

Rehabilitation Robotics

Project	Funded by	Website	Start date
ADCOMP	Marie Curie Actions (MCA) - FP6-2004-MOBILITY-5		2006-04-01
BALANCE	ICT-2011.2.1 Cognitive Systems and Robotics (a), (d)	http://balance-fp7.eu	2013-01-01
MOBOT	ICT-2011.2.1 Cognitive Systems and Robotics (a), (d)	http://www.mobot-project.eu	2013-02-01
WAY	FP7-ICT ICT for smart and personalised inclusion	http://www.wayproject.eu	2011-10-01
NINAPRO	Swiss National Science Foundation	http://www.idiap.ch/project/ninapro	2011-01-01
SCRIPT	ICT-2011.5.1 Personal Health Systems	http://scriptproject.eu	2011-11-01
CORBYS	ICT-2009.2.1 Cognitive Systems and Robotics	http://www.corbys.eu	2011-02-01
BETTER	BNCI-driven robotic physical therapies in stroke rehabilitation of Gait disorders	http://www.car.upm-csic.es/bioingenieria/better	2010-02-01
PATCH	ERC-AG-PE7 ERC Advanced Grant - Systems and communication engineering	http://www.upmc.fr/fr/recherche/europe/7e_pcrd/patch.html	2010-08-01
EVRYON	ICT-2007.8.5 Embodied intelligence	http://www.evryon.eu	2009-02-01
HUMOUR	ICT-2007.2.2 Cognitive systems, interaction, robotics (ICT-2007.2.2)	http://www.humourproject.eu	2009-01-01
VIACTORS	ICT-2007.8.5 Embodied intelligence	http://www.viactors.org/	2009-02-01

STROKEBACK	ICT-2011.5.1 Personal Health Systems	http://www.strokeback.eu	2011-10-01
REWIRE	ICT-2011.5.1 Personal Health Systems	http://www.rewire-project.eu	2011-10-01
REHAB4LIFE	HEALTH.2012.3.2-3 Social innovation for active and healthy ageing	http://www.rehabathome-project.eu	2012-10-01
ROREAS	BMBF	http://www.roreas.com	2013
MUNDUS		www.mundus-project.eu	
CaReToy	ICT-2011.5.1 Personal Health Systems	www.caretoy.eu	2011-2014
CYBERLEGs	FP7-ICT-2011-7	www.cyberlegs.eu	
SYMBITRON	ICT-2013-10	www.symbitron.eu	2013-10-01
BIOMOT	ICT-2013-10	www.biomotproject.eu/	2013-10-01
inRehaRob	BMBF	http://inreharob.de	2016-04-01

Surgical Robotics

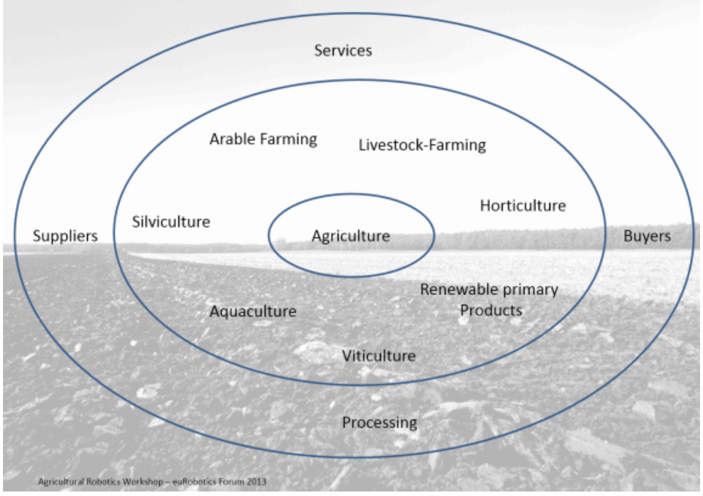
Project	Funded by	Website	Start date
MIRO Lab	Helmholtz Validation Fund		2011-10-01
ACTIVE	ICT-2009.2.1 Cognitive Systems and Robotics	www.active-fp7.eu	2011-04-01
EUROSURGE	ICT-2009.2.1 Cognitive Systems and Robotics	www.eurosurge.eu	2011-10-01
ARAKNES	ICT-2007.3.6 Micro/nanosystems	http://www.araknes.org/	2008-05-01
CASCADE	ICT-2011.2.1 Cognitive Systems and Robotics	http://www.cascade-fp7.eu	2013-02-01
HIPHAD	PEOPLE-2007-4-3.IRG Marie Curie Action: "International Reintegration Grants"		2009-04-06
HEARTSURGERYROBOT	FP7-PEOPLE-2012-CIG Marie-Curie Action: "Career Integration Grants"		2013-07-01
iRAMIS	BMBF	http://www6.in.tum.de/Main/ResearchiRAM!S	
SCATH	ICT-2009.5.2 ICT for Patient Safety	http://www.scath.net/	2010-02-01
I-SUR	ICT-2009.2.1 Cognitive Systems and Robotics	http://www.isur.eu/isur/	2011-03-01
SAFROS	ICT-2009.5.2 ICT for Patient Safety	http://www.safros.eu/safros/	2010-04-01

TELEPRESENCE SURGERY	FP7-PEOPLE-2011-IOF Marie Curie Action: "International Outgoing Fellowships for Career Development"		2012-08-01
OPTIMISE	ERC-SG-LS7		2009-12-01
URALP	ICT-2011.2.1 Cognitive Systems and Robotics	http://www.microralp.eu	2012-01-16
STREAM	PEOPLE-2007-4-3.IRG Marie Curie Action: "International Reintegration Grants"		2008-09-01
STIFF-FLOP	ICT-2011.2.1 Cognitive Systems and Robotics	http://www.stiff-flop.eu/	2012-01-01
ROBOCAST	ICT-2007.2.1 Cognitive Systems, Interaction, Robotics	www.robocast.eu	2008-01-01
LABEX CAMI	Agence Nationale de la Recherche (FR)	http://cami-labex.fr	
EQUIPEX ROBOTEX	Agence Nationale de la Recherche	http://equipex-robotex.fr/	
IHU MIXSURG	Agence Nationale de la Recherche	http://www.ircad.fr/ihu/	
AccuRobAs	FP6-2005-IST-6 (045201)	http://wwwipr.ira.uka.de/accurobas/	2006-10-01

2.4 Agriculture Domain

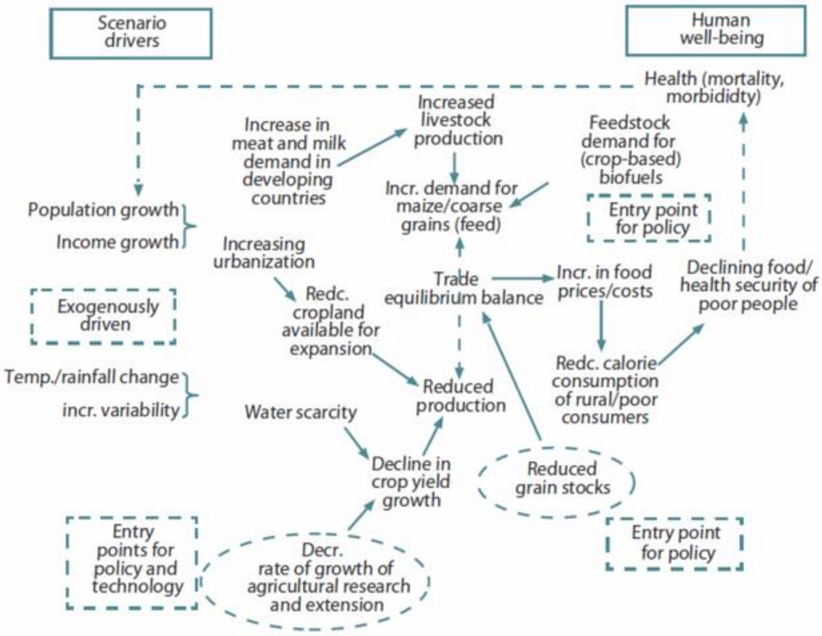
2.4.1. Domain Overview

Agriculture is a general term for production of plants and animals by use of paramount natural resources (air, water, soil, minerals, organics, energy, information). Products are used in a large variety – nutrition, renewable energy and renewable materials. Agriculture can be divided into subcategories like shown in Figure 1. As in every other industry and part of an entire system this domain has relationships to suppliers, buyers, processing, services, administration and end-“users”.



Simplified structure of agricultural production categories

Several interrelated drivers make agriculture a challenging business:

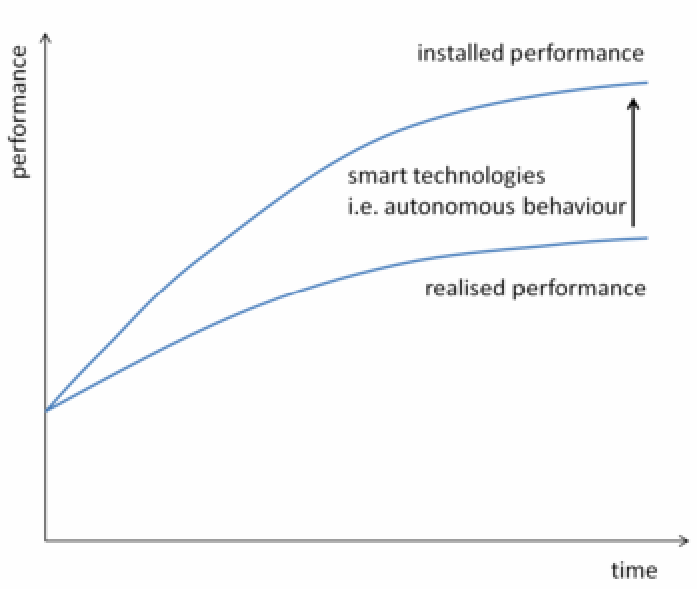


Interrelationships among key drivers of change in food systems, and their connection to human well-being {Source: FAO - IFPI's long-term outlook for food and agriculture}

With reference to the key European Societal Challenges. The following major conflicting trends can be seen:

- World population is growing from todays figure of 7Bn. to an estimated 10Bn. in 2050.
- The available agricultural area (4.9 Bn. ha) is limited and can only be increased marginally. In effect it decreases by degradation. 1/3 of 1.4Bn ha. arable land is degraded.
- Expected climate change has negative impacts on soil productivity
- Consumer habits in emerging countries are rapidly changing. Producing 1 kg of meat needs up to 16 kg of grain.
- The growth in land based renewable energy and renewable materials production conflict with food production.
- Land and agricultural products become the subject of speculation reducing stability.
- In highly developed countries agricultural machines are reaching their capability limits. Additional productivity has to be achieved in other ways.
- FAO expects that by 2050 only 0.15 ha of arable land will be available per person.

Within Europe agricultural machines are typically equipped with a high level of installed performance. Analysing tasks carried out with these machines it can be observed that realised performance differs significant (Figure 3).



Gap between installed and realised performance

The gap can be reduced by enhancing single machine capabilities i.e. with assistance systems or autonomous functions on one side and by improving the entire process performance – the interrelation to other machines – on the other side. In the context of agriculture robotics autonomous capabilities should not only should focus on single machines but whole processes (self-organising machines and self-organising processes).

Introducing robot systems significant advantages:

- Increase precision and quality in the process
- Extend operation time
- Provide a quantitative decision base
- Improve interoperability and coordination
- Reduce unit costs

These advantages are counterbalanced by several barriers:

- safety: Large and heavy machines in accessible environment, Robots on public roads

- privacy: data capture, processing and communication in 3rd party environments (contractor vs. farmer)
- cooperation: behaviour of autonomous machines in low-deterministic environment
- organisation: control in mixed environments, how to get a robot to the field and the driver back home?

2.4.2. Current and Future Opportunity

The prime opportunity in the application of Robotics Technology to farming is to increase farm efficiency while maintaining economic and ecological standards. Robotics technology has the potential to transform all types of farming while significantly increasing data gathering to enable better decision making. Key to these improvements is the interoperability and communication both between machines working on the farm and to organisations outside of the farm. Such connections allow improvements in the processing of harvested crops, efficient transport and faster time to market. The increasing use of technology will also impact on the life quality of farm workers and may also attract a younger generation back into farming. Robotics technology has the potential to make ecological targets for the use of pesticides, fungicides etc. achievable at lower levels, as well as contributing to good soil management.

Farming has an important place within the European community but is also a global opportunity to export machinery and expertise. Europe has taken a strong lead in a number of areas where robotics technology can be applied and it is important that this progressive approach is promoted and supported through R&D&I actions.

The following are important impact points for the application of robotics technology:

- Improving interoperability through standardisation (for example: ISOBUS)
- Moving processes from a batch oriented 'factory' to a flow oriented, continuous process (24h milking, 8 times feeding by robots)
- Applying path strategies to reduce soil compaction
- Interconnecting multiple autonomous systems to improve quality and efficiency
- Interoperability of machines with different degrees of autonomy. Such a feature will allow replacing the classic tools step by step with intelligent ones (e.g. an intelligent tractor will still work with a simple plough).
- Development of driver assistance systems suggesting corrective actions, leaving the responsibility with the farmer. In the future provided there is legal proof of dependability corrective actions can be taken directly by the system.
- Possibility of increased communications enabling tele-operation.
- Increased energy efficiency through optimised use of machines.
- Develop systems and strategies that reduce the use of antibiotics and *icides. Boosting ecologically sound farming.

As robotics technology develops the extent to which farming tasks and processes can be automated will increase. While current systems act in an advisory capacity, or provide limited automation it is anticipated that levels of autonomy will gradually increase. This increase in autonomy will be driven by greater data collection and built-in knowledge about each farm and the preferences of the farmer and staff, for example improved soil analysis driving more effective crop distribution.

Specific areas of future opportunity are:

- Utilisation of sensing and data processing on autonomous machines operating on the farm to gain more fine grained data about the land and crops. This data can then be utilised to improve decision making and in driving increasingly accurate simulations of the farm. This presents a number of different opportunities:

- Using "Big Data" methods to provide the farmer with access to broader data analysis, including comparative analysis.
- Driving crop distribution patterns to maximise land use and yield year on year.
- Provide data about livestock feed stuff vs yield.
- Allow better land and equipment utilisation.
- Maintain ecological standards.

Improved data will also allow the development of more realistic farm simulations of the actual farm (with all its fields, barns, animals etc.). Giving a tool to develop and test new tools, machines or work strategies and provide the basis for a fully automated farm.

- Investigate the possibility that multiple smaller machines allow more flexibility than one large machine, the opportunity to reduce soil compression could be cost-effective even on very small fields, and the combined reliability may be higher.
- Development of modular machines where a core autonomous machine is usable on multiple tasks during the year with changeable tools.
- The progressive development of greater levels of autonomy, particularly the development of systems able to assess risk and impact. Highly autonomous systems would allow the farmer leaving the farm for a longer period. Leaving the farmer able to access data via the internet once or twice a day to provide high level supervision. Such high levels of automation might allow "part time farming" by supporting liveability and managing land in rural communities.
- Develop energy systems able to utilise the natural energy sources (e.g. by-products from the current process) and provide continuous operation.

2.4.3. Barriers to Market

There are numerous barriers to market:

- The legal framework for the operation of autonomous systems does not yet exist. This means that systems must remain "human in the loop" for safety and liability reasons.
- There are potential issues with Cross-Contamination (grain, weeds, bacteria etc) where autonomous machines operate across the whole farm.
- Within farms there are issues about the storage and maintenance of autonomous systems, storage facilities will often need to be upgraded and new skills acquired. Support infrastructure, power, communications, supplies etc. will also present an additional cost.
- Interface standards between machines and to the wider community will need to be developed and the adoption of extensive autonomy will depend on this.
- The privacy of data about the farm also needs to be assured as this will be extremely valuable to third parties.

2.4.4. Key Market Data

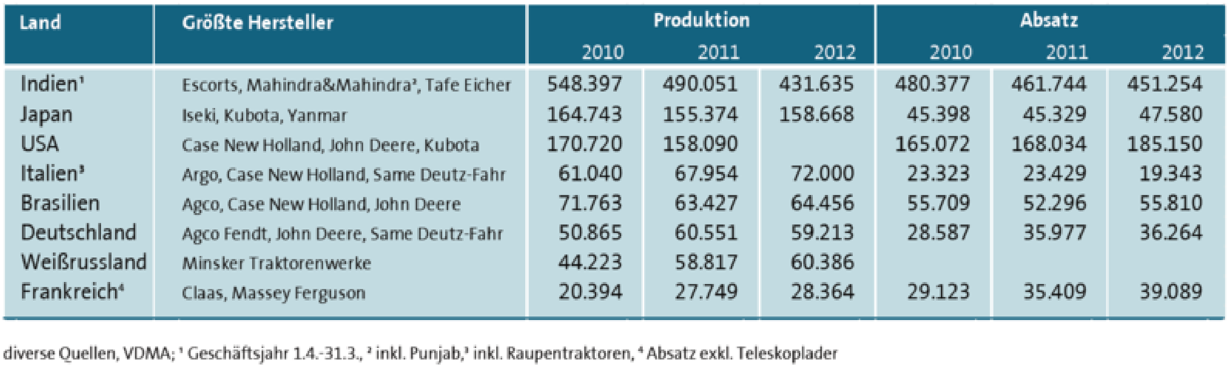
In 2007, gross value added in the agriculture sector amounted to €16.0bn. (production value €46.3bn; intermediate inputs €30.3bn). Some 370.5 thousand enterprises farmed around 17 million hectares of agricultural land and had 1.251 million employees (of whom 336.3 thousand were seasonal workers). Actual work done corresponded to 529.7 thousand full-time equivalents. Approximately 95% of agricultural businesses are family-run farms, which farm less than one-quarter of agricultural land. At 55% of farms, activity in the agricultural sector is only a side-line. The dominant legal form is the sole proprietorship, which accounts for 93.5% of all farming businesses, followed by partnerships (5.1%) and legal persons (1.4%).

Based on area farmed, legal persons farmed an average of 561.6 hectares, with partnerships farming an average of 125.7 hectares and sole proprietorships farming an average of 33.1 hectares.

According to a VDMA market research in 2013 agricultural machinery valued at €96bn. will be produced (estimated). Europe's share is at about 30%. Considering the introduction of mobile agricultural service robots as an evolving process an increasing share of €30bn can be assigned to the robotic market.

World production agricultural machines (VDMA, 2013 estimated)	€96bn.
Investment €/ha Germany 2012 (VDMA)	324 €/ha
Investment €/ha Netherlands 2012 (VDMA)	599 €/ha
Investment €/ha Spain 2012 (VDMA)	36 €/ha
Investment €/ha EU 2012 (VDMA)	150 €/ha
Agricultural area ha EU	170m. ha

Some key market data



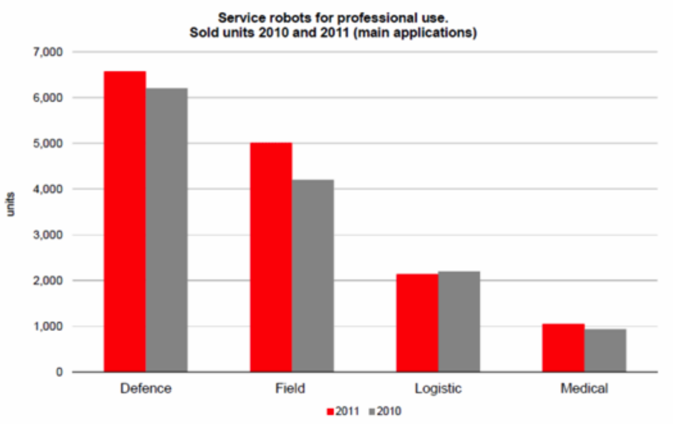
Land	Größte Hersteller	Produktion			Absatz		
		2010	2011	2012	2010	2011	2012
Indien[1]	Escorts, Mahindra&Mahindra[2], Tafe Eicher	548.397	490.051	431.635	480.377	461.744	451.254
Japan	Iseki, Kubota, Yanmar	164.743	155.374	158.668	45.398	45.329	47.580
USA	Case New Holland, John Deere, Kubota	170.720	158.090		165.072	168.034	185.150
Italien[3]	Argo, Case New Holland, Same Deutz-Fahr	61.040	67.954	72.000	23.323	23.429	19.343
Brasilien	Agco, Case New Holland, John Deere	71.763	63.427	64.456	55.709	52.296	55.810
Deutschland	Agco Fendt, John Deere, Same Deutz-Fahr	50.865	60.551	59.213	28.587	35.977	36.264
Weißrussland	Minsker Traktorenwerke	44.223	58.817	60.386			
Frankreich[4]	Claas, Massey Ferguson	20.394	27.749	28.364	29.123	35.409	39.089

diverse Quellen, VDMA; [1] Geschäftsjahr 1.4.-31.3., [2] inkl. Punjab,[3] inkl. Raupentraktoren, [4] Absatz exkl. Teleskoplader

Number produced and sold in leading countries

Compared to the number of agricultural machines produced (see table 2) the number of mobile service robotics (5,000 see Figure below “field”) is comparably small. This number mainly results from milking robots.

Note that in these figures autonomous in-door service robots for farms (mainly barn-floor cleaners) are not included. This markets currently has a growth rate of approximately 3000 units annually.



Source IFR statistical department

The term “robot” in an agricultural context requires proper definition if the extent of the market is to be properly established. For example auto-guidance is often available as a retrofit to manual equipment. It is expected that as the market develops its exact nature will become clearer.

2.4.5. Relationship to other domains and markets

There is a strong link between the agriculture domain and other markets. There are possible synergies with the automotive sector. Autonomous driving and safety are for example needed technologies in both application domains. Furthermore autonomous feeding systems in livestock farming have a large technology overlap with automated guided vehicles in logistics and logistic support systems in the manufacturing industry.

The need for robustness of autonomous agriculture machines is similarly needed for autonomous systems in the construction and mining industry.

There are possible synergies regarding technologies such as system design, power management and safety.

There are strong links to the component supply industry because of the need to drive the down the cost of robot parts, mechanisms, sensors and associated sub-assemblies through mass production. There are also links to more consumer driven markets such as smart phones and tablet computers as these are most commonly used as interface devices to farm systems.

As the food processing industry is a direct successor of the agriculture domain it has the strongest link of all to the above named markets. The transfer of robotic technology into the agriculture domain might lead to more efficient agriculture processes with, for example, new timing constraints. The food processing industry also has to adopt these processes by responding to changes in farm practice brought about by increased use of robotics technology.

2.4.6. Europe’s Place in the Market

The value of agricultural machines in Europe is €28bn. which is 30% of worldwide production. Whereas the worldwide export rate averages 50% it is significant higher in Europe (estimated 70%).

Compared to other markets Europe’s agricultural machinery industry consists of numerous well known and highly specialised manufacturers providing high-end solutions to their customers. Unlike America European agriculture machine fleets primarily consist of a large variety of brands. Interoperability has been a long held tradition.

Robotic developments can mainly be seen in Europe (dairy), the US (high value crops) and Japan (high value crops).

Considering the engineering strength of European manufacturers and high market shares worldwide, there is considerable potential for future development within Europe feeding a global market for autonomous agricultural machines.

The global market is also changing. China is being forced to modernise its economy and to correct the lag in its machinery base. China may therefore become in important producer of agricultural machines. The construction machine domain can be seen as a blueprint for this expansion. In 2010 China became the worlds largest manufacturer of construction machines. In 2010/11 600,000 tractors were sold in China spending €1.5bn. (For comparison: Germany 28,000 tractors). It is highly likely, as with other industries, that China will try to enter the European market. It is important that Europe has a secure technological leadership in advance of this happening.

2.4.7. Key Stakeholders

Europe has an extensive agricultural machinery business. It contains significant global players and has a strong innovation mentality. Agriculture has a very broad range of stakeholders that reflect both the diversity of products and the diversity of farm management strategies. Europe's wide geographic spread means that almost every aspect of farming can be found within Europe from large arable farms, where many farms are managed as a conglomerate, to individual family run farms specialising in unique products.

In addition to the end users and manufacturers there are suppliers of consumables, fertiliser, feedstuff, livestock, seeds etc. As well as energy suppliers, legal services, analytical services and veterinary practices. Government departments and standards bodies are also significant stakeholders in agriculture.

CEMA is the European association representing the agricultural machinery industry. In the agricultural machinery sector, there are some 4,500 manufacturers, that generated a turnover of around €28bn. in 2008. 135,000 people work in this sector and a further 125,000 people work in distribution and maintenance. A significant number of the larger manufacturers are already engaged in the design, development and production of robotics technology based products. EurAgEng is the European Society of Agricultural Engineers (EurAgEng) exists to promote the profession of Agricultural and Bio-systems Engineering. It lists Research Institutes all over Europe. http://www.eurageng.eu/engage-insts

In addition to these industrial organisations there are a number of academic and research organisations that have significant facilities for the development of autonomous agricultural machines. These organisations, some of which are dedicated to agricultural research, are spread across the main farming nations within Europe and have an extensive base of research on which to draw.

2.4.8. Current Key Projects

HUBRINA (HUman-roBot co-woRking IN Agricultural master-slave systems) - Tyker Technology (NL), Wageningen University (NL) - ECHORD. Master-slave robot control for agricultural activities. Advance the research to master-slave systems in agriculture beyond just the level of simulation and prove the feasibility of a fully automated master-slave system.

FutureFarm (WP6: Influences of robotics and bio-fuels on economic and energetic efficiencies of farm production) - University of Wageningen (NL) and 14 more - ERA-NET ICT Agri. Typify current and new robot technology and their potential tasks in farming. Single and multiple machine fleet management in view of energy usage and costs will be optimized. Demonstrate current research robotic platforms for agriculture.

CROPS (Clever Robots for Crops) - University of Wageningen (NL) and 13 more - ERA-NET ICT Agri. Intelligent sensing and manipulation for sustainable production and harvesting of high value crops

RHEA (Robot Fleets for Highly Effective Agriculture and Forestry management) - CSIC (ES) and 18 more - ERA-NET ICT Agri. Design, development, and testing of a new generation of automatic and robotic systems for both chemical and physical –mechanical and thermal– effective weed management focused on both agriculture and forestry.

GEOPAL (GNSS-based Planning system for Agricultural Logistics) - Aarhus University (DK), LACOS (D), CLAAS-Agrosystems (D), LEE Engineering & Construction Company (UK?). Research on Technologies for improving cooperation: Fleet Radar, Infield Route Planning with background of renewable energies.

QUAD-AV (Ambient Awareness for Autonomous Agricultural Vehicles) - Fraunhofer IAIS (D), Cemagref (F), University of Salento (I), Claas (D/DK) - ERA-NET ICT Agri. Enhancing Safety-Level of autonomous agricultural vehicles during process in terms of threads to humans, animals and tangible goods. 4 different types of sensors are combined. these are Stereo Vision, Radar LADAR and Thermal Imaging.

SmartBot - (here: Subproject AgroBot) - INTERREG. Develop basic technologies needed for constructing multiple, agriculture, robotic demonstration models with different application

2.4.9. European Products

European products in terms of agricultural autonomous machines can be divided in mainly three categories: Arable Farming, Livestock Farming and Special Crops.

Milking robots, with an installed base of approximately 30,000 world wide, is dominated by European companies. In some countries up to 50% of newly built barns nowadays have milking robots instead of milking parlours. Milking robots can milk cows more than 2 or 3 times per day, hence increasing the udder health of the cow, and creating less stress for the animals. The farmers are released from having to do a heavy task at set times each day, 7 days per week.

Mobile autonomous barn cleaning robots, typically used for barn floor cleaning & feed pushing have an installed base of between 10,000 and 15,000 units. Cleaning barn floors frequently has a positive effect on NH3 emissions, and on the hoof health of livestock.

Mobile autonomous feeding robots. This is a new development, replacing the manually operated mixer feeding wagons. For example cows can now be fed 6 to 8 times per day, instead of twice per day, giving the animals a more natural eating pattern. The feeding robot can also provide more balanced rations to specific groups of animals within the barn.

Arable Farming and High Value Crops: The Robotics & Automation Society lists manufacturers of agricultural mobile service robots. All companies are engaged in the domain of livestock farming (http://www.service-robots.org). Opposite from livestock farming where most robotic systems are developed from scratch, arable farming uses an incrementally enhances existing machines with autonomous capabilities. This results in a threefold situation:

- Prototypes: BoniRob (Amazone), Demeter (University of Illinois;), HortiBot, Kinze Grain Auger,
- Traditional Machines with autonomous capabilities like Autoguidance and Master-/Slave-Procedures: John Deere, CNH, AGCO, CLAAS
- Robots for high value crops (planting, pruning, harvesting): Harvest Automation, Robotic Harvesting, AGROBOT,

Agriculture Sub-Domains:

2.4.10. Agriculture

2.4.10.1 Domain Overview

There has been considerable progress in recent years in the deployment of agricultural robotic systems. Dairy heard milking can now be fully automated with improved milk yields and lower infection rates. Automated ploughing is becoming increasingly used and systems are being trialled for selective weeding and harvesting.

Primary concerns in this market are the optimal use of resources, improvement in yields, and minimisation of environmental impact for example soil erosion and compaction, pesticide and fertiliser use. The automation of source tagging for livestock and arable crops, the inspection of fields and livestock and the monitoring of crop condition all drive the development of fully integrated systems.

The industry traditionally has long service life from its equipment and there will be an expectation that robotic products will give similarly long life cycles. Cost effectiveness is a driving concern.

2.4.10.2 Current and Future Opportunity

Current opportunities in agriculture and forestry are extensive. There is a strong collaborative relationship between research organisations and the agriculture equipment companies. Opportunities are well understood in the industry and this is supported by growing level of deployed systems.

The domain is ripe for technology transfer in terms of sensing and manipulation. Future developments are likely to concentrate on systems able to selectively harvest ripe produce and those able to recognise the early signs of pest infestation or disease and selectively respond. Systems able to work with high value delicate crops and those that currently require hand harvesting will provide exploitation opportunities provided that the cost benefit analysis can be proved.

2.4.10.3 Relationship to other markets

There is an interface relationship with the Food domain. In terms of crop assessment there will be linkages to other service robot domains such as Civil Infrastructure and Service and Utilities.

2.4.10.4 Europe's Place in the Market

Europe has a leading position in this market with a large number of agriculture equipment companies located in Europe.

2.4.11. Forestry

2.4.11.1 Domain Overview

Europe has considerable forestry resources that cover very large areas of land. Managing this resource both in terms of monitoring it and felling trees can be automated to a certain degree. Historically there has been significant interest in forestry robotics within Europe. The automation of felling per tree is now at a high level where a felling machine can fell and process a tree without much human intervention. The use of robotics technology to monitor forests is still in its infancy because of the large areas of terrain that need to be covered and the limitations of current UAV usage regulation.

2.4.12. Fisheries

2.4.12.1 Domain Overview

There are numerous applications for robotics technology in fisheries. Primarily applications focus on the monitoring of fish stocks and water condition. The use of autonomous systems to monitor both shoal size and type, as well as longer term trends have the potential to alter the application of fisheries policy. Robotics technology may also contribute to the implementation of fisheries policy through the monitoring of fishing practices.

2.4.13. Key System Ability Targets

2.4.13.1 Configurability

All farms are different both in terms of their product mix and physical characteristics. Farmers will want to be able to use the best machine for each task and these will come from different

OEMs. The mechatronic configuration of different agricultural machines to enable inter-operation is a critical part of “plug and Play” technologies in agriculture. Similarly the dynamic configuration of software don physical interfaces during missions as machinery enters and leaves each task is an important part of raising autonomy levels.

Configuring systems to each farm and to the specific needs of each farmer is critical to the wider market adoption of robotics technology.

Optimal configurations for different farm sizes.	Mechatronic Configuration: Level 2 User Run-time Configuration
Configuration to specific crops, harvesting parameters, crop size etc.	Mechatronic Configuration: Level 3 Run-time Self Configuration
Self configuration of groups of machines.	Mechatronic Configuration: Level 4 Autonomous Configuration

2.4.13.2 Adaptability

As the growing season progresses, as crops are grown, as boundaries are altered and feed and pesticides are used the autonomous systems on the farm will need to adapt to provide optimal output from each task.

Adaptation to farm layout and crop and field patterns.	Task Adaptation Level 3 – Multiple Task Adaptation
Adapt to the long term dynamics in the farm cycle.	Component Adaptation Level 3 – Process chain adaptation
Adaptation to crops, new crops or sizes.	Parameter Adaptation Level 3 – Multiple Parameter adaptation

2.4.13.3 Interaction Ability

Interaction between different agricultural machines and their inter-operation is critical to many of the task visions for agriculture. The need for certifiable decision making also requires close collaboration between human and autonomous machine.

Machines aware of each other’s status.	Robot Robot Interaction: Level 2 Communication of Task Status
Interaction between machines to establish capability.	Robot Robot Interaction: Level 2 Communication of Task Status
Human machine interfaces appropriate to farm environment.	Human Robot Interaction:
Safe human interaction with large machines.	Human Robot Interaction Safety:
Machine to machine knowledge transfer.	Robot Robot Interaction: Level 4-5

2.4.13.4 Dependability

Farming requires high levels of dependability for fully autonomous operation. Livestock and crops have high value and in many cases decision making needs to be certifiable and traceable.

Safety guarantee under all operating conditions.	Level 2 - Certification and Classification of Safety Levels {Note: This requires environmental safety guarantees}
Proof of dependability	Dependability parameters: Failure criticality and Task or Mission risk. Level 5 – Task Dependability

2.4.13.5 Motion Ability

Agricultural machines are designed to endure the harsh conditions on the farm. The ability to maintain location and control on sloping surfaces and in poor ground conditions without impacting on the environment or compromising safety guarantees presents a significant challenge.

Safe motion on difficult and dynamic terrain	Constrained motion Level 4/5 and Cognitive Interpretive Ability: Level 9 Environmental Affordance
Track and path planning to optimise energy and ecological parameters such as ground compaction.	Motion Capability: Level 6 Parameterised Motion

2.4.13.6 Manipulation Ability

Harvesting and crop handling, particularly of soft items, will require robust and dependable manipulation solutions.

Ability to control force and manipulate crops.	Unconstrained Motion: Level 5 Force constrained motion
Livestock manipulation	Manipulation parameters – Object Dynamics and Object Properties
Handling of soft and delicate items e.g. Fruit harvesting.	Manipulation parameters – Object Dynamics and Object Properties +. Handling Ability Level 6 – Generic positioning for placement. Holding Ability Level 4 – Dynamic Holding of modelled object.

2.4.13.7 Perception Ability

While farms contain a subset of objects that will need to be recognised the ability to correctly interpret novelty and more importantly condition, particularly of livestock and crops will presents a challenge to perception abilities. Detecting field and crop boundaries throughout the growing season, minimising wastage and reducing environmental impact will all require advances in perception ability.

Ability to identify boundaries, crop condition, objects including animate objects in fields, distinguish plant types and pests.	Perception Ability: Level 5-7 combined with Object Recognition Level 7: Novelty Recognition and Scene Perception: Level 4-5.
Maintain perception ability in extreme weather conditions, rain, fog, snow, ice.	Object Recognition Parameter: Environment Perception Ability Target: Immunity to natural variations.
Perceive other machines and farm products and objects (e.g. hay bales, feed bags etc.).	Scene Perception: Level 2-6 Object Recognition Levels 4-6
Perception of people and other animates obscured or partly obscured by crops.	Object Recognition: Level 12 Animate Objects

2.4.13.8 Decisional Autonomy

Higher level decisional autonomy will be critical to increased levels of autonomy in the application of robotics technology to agriculture.

Self or co-repair of machines.	Decisional Autonomy: Level 8 Multiple Task Autonomy.

2.4.13.9 Cognitive Abilities

The variability both in the short and long term coupled to the long term data gathering on the farm combined with external knowledge sources means that agriculture will require advances in cognitive ability to enable autonomous operation and optimally manage tasks.

Ability to Semantically map the farm.	Action Ability: Level 6 Plan Driven Actions combined with Acquired Knowledge: Level 5
Farmers assistant based on deep knowledge of historic farm operation.	Acquired Knowledge: Level 5 Place Knowledge Acquired Knowledge: Level 6 Knowledge scaffolding
Ability to learn successful strategies from machines, other farms or external experts.	Acquired Knowledge: Level 9 Interaction acquisition
Goal based task planning, including weather and ground conditions.	Action Ability: Level 5 Knowledge driven actions
Overall and long term strategic planning based on Farmers Assistant.	Action Ability: Level 6 Plan driven actions
Autonomous experimentation with new strategies.	Acton Ability: Level 7 Dynamic planning

2.4.14. Key Technology Targets

2.4.14.1 Systems Development

High level requirements for dependability and safety will drive system development methods. The need for standardised interfaces and certified systems will also impact on the design of both mechanical and software systems. Many of solutions for robotics in agriculture are only achievable if they are completely manufacturer independent.

System Architecture

- Cross platform architectures, common interface standards and interoperability.

Systems Integration

- Interoperability of systems from different original equipment manufacturers

Modelling and Knowledge Engineering

- Key to the development of better farm management and optimisation is the development of better models based on captured data. The use of simulation in the loop decision making is a key technology in strategic decision making.
- Development of farm models based on data gathered from the farm by autonomous systems.
- Development of semantic representations of agricultural information, for communication and within decision systems.

System of Systems

- Farms will become a integrated system of diverse devices cooperating to carry out the work and assess results. Farms will become an important exemplar for System of Systems research and development.

2.4.14.2 Mechatronics

The agriculture industry has a long history in the design of large mechatronic structures and mechanisms and control systems are well understood. However autonomous systems will create new opportunities for design and in particular in the interactions between machines where material and crops need to be transferred during operation. There are also opportunities in developing mechatronic systems that operate where high dexterity and fine control are needed, for example in fruit harvesting.

Mechanical Systems

- Systems for easy maintenance.
- Retrofit autonomy for existing machines.

Actuators

- Miniaturised actuation

Power Supply and Management

- Power systems for continuous operation.

Communications

- Machine to machine communications in-field, with no infrastructure.

Control

- Control strategies that require minimal calibration.

2.4.14.3 Human Computer Interaction

It is important that existing farm workers are able to continue to operate autonomous equipment as well as manual machines. This requires intuitive and interactive user interfaces. The value resting on specific decisions in the agricultural environment can be high so it is important to ensure that interfaces present information in a clear and intelligible way for all types of operator.

Human Machine Interface

- Operation of complex machines by multiple users with different skill levels.

Safety

- Certification of systems, including certification of sensing and decision systems.
- Analysis of safety in large autonomous machines in unstructured environments.

2.4.14.4 Perception

Perception is critically important to the operation of many applications of robotics technology in agriculture. Perception ranges from the application of multiple sensing modalities for the assessment of crops to the detection of crop and field boundaries and the identification of novel events in the agricultural environment. The wide range of operating conditions and the need for certifiable performance present significant challenges to the development of workable solutions.

Sensing

Develop all weather processing of sense data.

Interpretation

- Detection of novelty in agricultural context. From detection of crop condition, e.g. Early detection of infections and infestations, to the identification of unexpected animates in a scene.

2.4.14.5 Navigation

The agricultural environment presents numerous difficulties in terms of 3D navigation. The weather creates a dynamic environment as do the changing seasons and crop growth and rotation.

Mapping

- Semantic mapping within a agricultural context.

Localisation

- Fine grained localisation in 3D for harvesting.

Motion Planning

- Motion planning accounting for vehicle condition and ground conditions to minimise soil/crop impact.
- Motion planning against dynamically changing weather conditions.

2.4.14.6 Cognition

Aspects of decision making and perception in agriculture involve a cognitive element where long term strategic planning, learning or task optimisation are critical. The optimisation of yield, and the identification of trends an patterns in data gathered from the environment all require cognitive processing.

Learning Development and Adaptation

- Learning with low rates of repetition
- Learning from simulation

Knowledge Representation and Reasoning

- Knowledge acquisition during normal operation

Action Planning

- Planning the optimal use of multiple machines during a process.

2.4.15. Technology Combinations

Cooperating (autonomous) agricultural machines

Many processes in the agricultural domain depend on the cooperation of machines. If autonomous machines are to impact on farm processes then each process must be automated and this requires a set of machines to cooperate. To co-ordinate such collaboration will require a distributed planning system because individual machines often enter and leave a process dynamically. Such a planning system has to consider the abilities, for example the motion ability, of all participating machines (autonomous or not) and needs to find an overall process optimum for all machines. Subsequently the missions/tasks have to be distributed to the machines. The development of such distributed planning processes will increase the impact of autonomous systems within farming.

Safety design and certification

Safe interaction of humans and agriculture machines is one of the central preconditions for the market introduction of autonomous agriculture. As with industrial robots for some applications ti may be sufficient to protect the work area and ensure safety by excluding people form the working environment. However many applications will require greater levels of safety because of the direct physical interaction either with people or livestock. Safety will need to be embedded in the physical human machine interface. This interface needs to be able too operate in diverse conditions.

Similarly the safety inherent in the machine's ability to detect its environment will need to be enhanced by developing optimal combinations of sensors, sensing, obstacle detection and obstacle avoidance strategies. Of equal importance is the certification of safe operation. Lack of certification will present a barrier to many farm applications of robotics.

Hardware in the Loop

Testing agriculture scenarios in simulation is important. Especially in arable farming realistic tests are often only possible once a year during harvest. This can be mitigated by high quality simulation. A planning system that coordinates multiple cooperating machines can use the simulation in the development phase but can also use the simulation in the loop during the real scenario. The building of farm models both in terms of developmental models that allow systems to be designed and in terms of providing models of individual farms based on gathered data are critical to the long term deployment of robotics technology.

Semantic Environment Awareness

A significant step ahead is possible in many robotic applications if the robot has a semantic representation of its environment and is able to keep this representation up to date in a dynamic unstructured environment. This enables the system to reason about the tasks it has to do to achieve a high level goal or work within task level constraints. In the agriculture domain this means for example that a robot that today follows a wire in the ground and pushes feed to livestock would progress to a system that is able to fulfil a range of tasks driven by the farmer for example: “Please feed my cows in all my barns and keep my farm clean!”

“Plug and Play” Systems and Architectures

Since the agriculture domain has various constraints (field size, weather, ground conditions…) it is impossible for a single agriculture machine to fit all these constraints. Machines therefore need to be easily configured or adapt to the current application conditions. This implies the need for a “Plug and Play” type architecture for agriculture robotic systems where sensors, power supplies, communications can be adjusted (by a non-expert user) to the current needs.

2.4.16. Product Visions

There are numerous product visions that are already elaborated for farming. From harvesting to livestock handling. The issue in agriculture is not about vision but about technology, and in particular dependable safe technology where performance can be certified and guaranteed. This market his therefore driven by the availability of technical solutions at high TRL levels and R&D&I activity will need to focus on its delivery to market.

Near Market Activities

A primary enabling activity will be manufacturer independent evaluation of new machines. Stimulating common testing standards and enabling national organisations to conduct standardised tests and providing reports and certificates will significantly help to reduce market barriers.

These tests will have different scopes. R&D&I activity needs to focus on developing new, or extend existing, methods towards evaluating autonomous systems. Subjects of evaluation could be:

- Functionality and performance metrics
- Safety certification and operating procedures.
- Confirmation of adherence to standards
- Suitability and usability parameters to allow assessment of compatibility with particular farm characteristics
- integration/interoperability of different machines and systems.
- Assessment of cooperation between machines, and between humans and machines.
- Assessment of the expected economy benefits from utilising the technology.

2.5 Civil Domain

2.5.1. Domain Overview

The Civil domain covers applications managed by civil authorities, national and local government and robots operated by regional and national agencies or by contractors engaged in public works. Many applications for robotics technology exist within the services provided by national and local government. These range from support for the civil infrastructure, roads, sewers, public buildings, rivers, rubbish collection etc to support for law enforcement and the emergency services. These public services are most often managed by civil authorities, city councils, local governments and national government departments and agencies. The protection of the public and the efficient maintenance of services mean that the basis for the purchase of services must show either cost saving or an enhancement of service delivery in order to justify public expenditure.

These robots will be operated/supervised by trained personnel and may be operating in hazardous, contaminated or extreme environments where people may be at risk. Certification and validation of operation will be important elements in the deployment of this type of robot system.

The legal and ethical operation framework will be that of the civil authorities. This market is broadly characterised by Business to Government (B2G) business models.

Applications in the Civil domain cover the provision of services related to national civilian infrastructure these services are typically non-commercial services provided to, or on behalf of, the public, these services are not specified or purchased directly by the public and are often provided on a non-competitive basis.

Typical applications include civil infrastructure services, such as:

- Urban maintenance and cleaning;
- Civil security services (police services or boarder security agencies; including tasks such as border and site surveillance, law enfacement, and crowd management;
- Emergency services (fire service, ambulance and coast guard) involved in disaster management including Search and Rescue for both rural and marine environments;
- Environmental services such as surveillance of rivers, air quality, and pollution.

The Civil Domain also covers the broader area of Scientific Support covering robotics technology used in scientific investigations such as oceanic survey, volcanology and geological survey.

These tasks may be carried out by a wide variety of different types of robot and operating modality ranging from single robots or small fleets of homogeneous or heterogeneous robots. Often robot teams will need to cooperate to span a large workspace, for example in urban rubbish collection, and range over all environments; in air, ground, sea surface, underwater or space. These systems are also likely have extensive interaction with people and their environments.

Civil robots are typically purchased and operated by organisations with high levels of technical and operational skill. In some of the proposed Civil applications robotic systems would be deployed in hostile and complex conditions where they may need to integrate into mixed teams of manned, unmanned and tele-operated vehicles.

In terms of the primary domain needs these can be summarised as follows:

- Improvements in academic and industrial research in the fields of algorithms, sensors and platforms creating greater levels of autonomy for Civil domain applications;

- Demonstrations and trials of higher technological maturity of domain applications and functions. In particular; all terrain motion and sensing; all weather performance; and the autonomous navigation and coordination of teams of heterogeneous robots;
- Progressively lower system, subsystem and component costs through increased use of commercial-off-the-shelf components rather than custom development of systems, while providing increased robustness and dependability;
- Formulation of laws and regulations concerning unmanned systems for example the ability to over-fly populated areas, or allow terrestrial vehicles to share the same roads with manned vehicles and pedestrians;
- Development of standards for interfaces / protocols / function, to improve: system interoperability, payload/mission reuse and diversification. Particularly within the different areas of the Civil domain and related domains in order to reduce costs and establish a vibrant component market.
- Raising of user awareness of the availability of robotics technologies to drive the market;
- Availability of high performance ad-hoc communications networks which are critical for the effective integration of multiple robots.

2.5.2. Current and Future Opportunity

Compared with the other fields of application, Civil Robotics is characterised by having a unique combination of environments and end users. It is also characterised by the heterogeneity of the involved agents (i.e., heterogeneous types of robot, with heterogeneous capabilities and equipped with different sensors or effectors, operating in mixed teams with humans).

Typical purchasers/operators of civil robots are likely to include:

- Civil authorities running or contracting services that can be augmented by robotics technology.
- National governments or agencies contracting services for national projects
- Public institutions, at regional, national or transnational level;
- Private companies operating under contract within the Civil domain.
- Organisations entrusted to public functions, such as airport or harbour authorities, environmental monitoring agencies, airborne and space agencies;
- Organisations with high levels of technical and operational skill deploying robotics technology in hostile and complex conditions;
- Organisations providing civil services where it is difficult to deploy people (either due to safety risks, budgetary constraints, or unpopularity of the tasks to be performed).

Some examples of Civil applications for Robotics Technology are:

- Provision of civil authority services in urban areas. (e.g. Road maintenance, rubbish collection, etc).
- Monitoring and maintenance of the civil infrastructure (roads, dams, bridges, tunnels ...);
- To provide assistance in decommissioning tasks.
- Environmental quality monitoring of industrial sites, harbours, rivers, lakes and sea (monitoring air, water and ground quality);
- Security monitoring of strategically important sites. (e.g., airports, energy plants, nuclear plants, pipelines, railways, industrial sites)
- Monitoring of urban environments - residential & commercial zones, civil buildings, streets, pedestrian areas, parks, entertainment/recreation areas, tourist sites;

- Monitoring of crops and forests against fires and other natural events;
- Surveillance and intervention in areas characterised by flows of people and goods (national borders, maritime areas);
- Support to human officers in operations to uphold civil law;
- Surveillance and inspection of areas of historical and artistic importance;
- Monitoring and intervention in disaster areas (large destroyed areas, e.g. due to earthquake, partly collapsed buildings or sites that are dangerous to enter by humans);
- Assistance in training of personnel working in the civil sector. (e.g. Law enforcement, emergency services, hazardous environment operations etc.).
- Space operations (Earth orbit and planet surface).
- Ocean science exploration.

There exist compelling opportunities in the current market in environment monitoring, surveillance and emergency services where there are already commercial products able to satisfy some applications.

In many inspection and maintenance applications robots will need to become intuitively integrated with human operators. Systems will be designed to complement and act as an aid to a human mission expert. The envisioned paradigm is an easily deployable system, able to provide the relevant information (e.g. the map of a workspace) to the mission expert, while seamlessly and autonomously performing the tasks that do not require operator input in the background.

This domain is also driven by changes in legislation resting to services, such legislation is often itself influenced by advances in technical capability. For example the European Marine Strategy, that commits each Member State to provide a detailed assessment of the state of the environment, a definition of "good environmental status" at regional level and the establishment of clear environmental targets and monitoring programmes. It is possible that robotics technology offers the opportunity of developing and marketing unmanned robots for the environmental monitoring of coastal zones allowing nation states to implement the strategy.

Examples of future opportunity markets are for instance the long term large scale ocean monitoring, both for security and search and rescue operations, the use of integrated teams of multiple small autonomous aerial robots for terrestrial surveillance (fire detection, site and border surveillance, etc.) or human activity support (such as real time observation, communication link establishment and others).

It is widely recognised that robotics technology has a key role to play in the decommissioning of a wide variety of civil infrastructures, most notably in the nuclear and oil and gas industries. Out of the 437 worldwide nuclear plants catalogued by the IAEA, 162 have been in operation for more than 30 years and although their life expectancy has been extended through maintenance the problem of decommissioning still remains. Robotics technology has a key role to play both in extended life maintenance programmes, in the decommissioning of legacy facilities and in the eventual decommissioning of currently active reactors.

The Fukushima disaster has also shown that it is extremely complex, risky and costly to have human workers performing tasks in such environments. It is expected that robotics technology can be more cost effective and safer than current methods in this type of emergency decommissioning and containment activity.

As technology progresses in its capability systems dedicated to surveillance and inspection will expand their function to intervene in the environment and start to carry out maintenance and manipulation tasks. For example cleaning or decontaminating surfaces, or effecting repairs.

2.5.3. Barriers to Market

The major barriers to market are divided between technical and non-technical barriers. In certain areas of application within the Civil domain the non-technical barriers are the most significant. For example until recently it has not been possible to fly autonomous vehicles in public air space and the use of autonomous ground vehicles on public roads is still not permitted. These areas of regulation are currently under review however it is highly likely that restrictions imposed by civil authorities will be limiting on the applications that are proposed. The establishment of clear compliance goals and testing regimes and the early demonstration of compliance and adherence will help to progress the deployment of applications on a wide scale.

Critical to opening up public spaces to autonomous vehicles will be the execution of large scale demonstrators able to show real world deployment of robotics technology, firstly to prove compliance and secondly to show capability. It will also be important to ensure that common legislation is enacted widely across Europe to maximise the potential market, and to ensure that the cost of certification is not prohibitive as may early operators are SMEs.

In particular regulations will need to address the significant differences between conventional aircraft or road vehicles and autonomous ones. Autonomous systems often enable different modes of operation, for example collective and cooperative operation, and that decision making may not involve a human in the loop. It may also be important for any regulation to define smaller zones of permitted operation where the regulatory requirements are reduced in proportion to the risk.

Closely tied to the issues of regulation are issues of liability. The risk levels will be determined by the application and by the type of vehicle being deployed. Insurance solutions will need to be developed that match the application and market sectors within the Civil domain.

With respect to the operation of autonomous ground vehicles there is an additional barrier in terms of public acceptance. While robots operating in public spaces can be seen as novel and interesting simply because of their rarity there has been no real assessment of public attitudes towards wide spread deployment. The lack of deployable systems makes the assessment of current public attitude problematic. Public acceptability and the development of regulation will have to be addressed within the deployment process if there is to be a wide scale use of robotics technology. In the interim systems will need to be deployed in limited and controlled circumstances where the risk can be more easily managed.

In nearly all Civil areas of application safe operation will need to be certified to predefined levels prior to deployment. Both public and operator safety will need to be at a high level in order to maintain a positive public perception of robotic deployment.

The use of robotics technology in the marine environment is more well established and the barriers to market are significantly lower than other Civil areas of application. However the treatment of autonomous surface vehicles close to the coast or in rivers may require review but there is some acceptance of them as either floating wrecks or piloted craft within current regulations.

In addition to these significant non-technical barriers there are also a number of significant technical barriers to the deployment of robotics technology in the Civil domain. These barriers range across the technology spectrum from limitations on operation time caused by insufficient on-board power storage, to the need to correctly interpret scenes and human actions in order to make the correct autonomous decisions. It is expected that these limitations will shape the early market for Civil applications but that despite these technical limitations there are a number of application areas that can be impact on by 2020.

The lack of regulations for small aircraft has restricted the development of the aerial robotics market. New regulations for Light Unmanned Aerial Systems (LUAS) or Very Light Aerial Robotic Systems (VLUAS) already developed or being developed in many countries are starting to remove this barrier. In Europe, the United Kingdom Civil Aviation Authority published in 2002 the CAP722, the UK policy for the certification and operation of UAV Systems, both military and civil. Since publishing CAP722, the CAA has further reviewed and developed its UAV policy, both in the light of recent experiences and as a result of changes in regulatory responsibilities since the formation of the European Aviation Safety Agency (EASA). CAP722 last issue was published in 2012 (5th edition), taking into account legal, certification, spectrum and security issues. Several other countries have developed similar regulations.

2.5.4. Key Market Data

The application of robotics technology to the Civil domain is still at an early stage and it is therefore difficult to estimate eventual market size. Its is likely that technology limitations will restrict early deployment to well controlled areas of application where robots are operated by skilled personnel for example in nuclear and environmental inspection tasks, including marine inspection.

In the case of marine robots, the Remotely Operated Vehicles (ROV) market is expected to grow at near 14% CAGR (compound annual grow rate) in the period 2011-2015 up to a value of about $1.5bn in 2015. ROVs sales for defence & security and scientific research equalled 25% of the total market for each sector. In the meantime, also the Autonomous Unmanned Vehicles (AUV) market is expected to grow in the defence and scientific research sectors with a CAGR equal to 12% and 8% respectively by 2016.

It is often the case that unmanned vehicles are cheaper and faster to produce than manned vehicles. Global Unmanned Marine and Ground Vehicles market is foreseen to reach $1.96bn by 2017. The potential market in Europe for Unmanned Aerial Vehicles over the next 10 years could amount to about €11bn. In the short to medium term demand is likely to be driven by monitoring and surveillance applications.

The coming decade will probably witness the rapid expansion of decommissioning activity, costing tens of billions of dollars. The decommissioning industry's performance will be critical to the future of nuclear power generation.

The decommissioning sector has been steadily forming over a few years but it is expected to see some major progress over the next five to ten years. Hundreds of offshore oil and gas platforms will be recovered from the North Sea over the coming years. Analysis by industry body Oil and Gas UK and decommissioning agency Decom North Sea put the value of this work at £30bn. over the next 25 years.

Key Market drivers are:

- Growing interest in UAS not only by US and European countries but also by emerging countries.
- Potential for improved coverage of large areas for environmental monitoring.
- Increase in quality of monitoring data and regularity of monitoring due to lower cost per task.
- Reduction of total operational costs with respect to existing manned systems.
- Increasing acceptance of robotics technology.

2.5.5. Relationship to other Domains and Markets

The Civil Robotics domain, has many relationships with the following domains listed in the SRA:

- Commercial Robots
- Logistics and Transportation

- Military Robots (note: it is not intended that programmes developed under the PPP or Horizon 2020 will specifically address this area).

In a number of application areas these domains share key abilities targets and technology requirements. There are also common requirements in terms of systems design technologies and safety certification in particular.

In addition, Civil domain applications may provide added value to robotic systems serving other domains. For instance, an agriculture robot (Commercial domain) may use terrain data built by a network of UAVs operated by a national mapping agency (Civil domain).

In terms of relationships to robotics markets there are strong links to the marine robotics market, to tele-operated robotics, aerial and space robotics markets.

2.5.6. Europe's Place in the Market

In maritime applications Europe has an established position in the market, in particular for underwater systems. The global market is currently dominated by US companies, although European companies have leadership and good market positions both in specific robot development or in the supply of subsystems (as an example one can cite the UK's SMD leading in deep ocean trenching robots or Norway's based Kongsberg with AUVs and subsystems).

If Europe is to gain a greater share of this market then the “dual use” position of the US government agencies must be echoed within Europe to ensure that technology transfer into the Civil domain is fully enabled.

In ground based robotic vehicles Europe represents a growing market despite a strong US market lead. As in the marine domain investment is needed to establish and grow the European industry.

In aerial vehicles there are a large number of SME’s operating within Europe providing a wide range of small to medium scale systems. For example The Hearing on Light Unmanned Aircraft Systems (LUAS) (Brussels, October 2009) listed 252 unmanned aerial systems with a Maximum Take-off Mass lower than 150kg.

There is also good progress towards the opening of airspace to remote operation and it is expected that this sector will expand significantly to 2020. R&D&I investment is needed to enhance the existing technology produced within Europe and secure a slice of the global market.

2.5.7. Key Stakeholders

Europe has a number of well established companies contributing to the growth of the Civil domain across all areas of application. In many cases the larger organisations have a strong background in either the military energy sectors, which is where the majority of historical expenditure has been. There are a growing number of SMEs operating in this sector specifically in the small scale aerial surveillance sector addressing environmental monitoring and surveying applications from agriculture to building inspection and growth in these sectors is expected to be strong.

Within Europe there is strong expertise in the nuclear industry and in civil infrastructure applications of robotics with a strong bias towards the marine industry.

This commercial market is also served by various research centres and university laboratories dedicated to Civil application areas, with a historic bias towards marine applications.

With the development of certification programmes, particularly in the Aerial sector, regulatory authorities are becoming key stakeholders and gate keepers for the growing industry.

2.5.8. Current Key Projects

The following is a non-exhaustive alphabetical summary of important research projects and initiatives related to the Civil Robotics market. Due to space limitations, details of each project are not included; they can be readily found on the Internet.

ARROWS	
BEE SAFE	
CADDY	Cognitive Autonomous Diving Buddy
CART	Cooperative Autonomous Robotic Towing system
CFD OctoProp	Computational Fluid Dynamics Aided Design of the Propulsion and Locomotion Systems of a Bioinspired Robot Octopus
CLAM	CoLlAborative eMbedded networks for submarine surveillance
Co3AUVs	Cooperative Cognitive Control for Autonomous Underwater Vehicles
COMAS	COnservazione programmata, in situ, dei Manufatti Archeologici Sommersi (Planned conservation, “in situ”, of underwater archaeological artefacts)
CON4COORD	Control for Coordination of Distributed Systems
DARIUS	
EURATHLON	
EUROFLEETS2	
FILOSE	Robotic FIsh LOcomotion and SEnsing
HydroNet	Floating Sensorised Networked Robots for Water Monitoring
ICARUS	Integrated Components For Assisted Rescue and Unmanned Search Operations
MARIS	Marine Autonomous Robotics for InterventionS
MINOAS	Marine INspection rObotic Assistant System
MORPH	Marine robotic system of self organizing, logically linked physical nodes
NIFTI	
NOPTILUS	autoNomous, self Learning, OPTImal and compLete Underwater Systems
PANDORA	Persistent Autonomy through Learning, Adaptation, Observation and Replanning
PETROBOT	

PICMAR	Intelligent Platform for Multimodal Characterization of the Seafloor and Submerged Structures
RITMARE	
ROBOCADEMY	
SHERPA	Smart collaboration between Humans and ground-aErial Robots for imProving rescuing activities in Alpine environments
SHOAL	Search and monitoring of Harmful contaminants, other pollutants and leaks in vessels in port using a swarm of robotic fish
SUNNY	Smart Unmanned aerial vehicle sensor Network for detection of border crossing and illegal entrY
TRIDENT	Marine Robots and Dexterous Manipulation for Enabling Autonomous Underwater Multipurpose Intervention Missions
TRITON	
UAN	Underwater acoustic networks
V-FIDES	Veicolo Filoguidabile per l'Ispezione, la Detezione e l'Esplorazione Subacquea) Underwater vehicle, optionally wireguided, for inspection, detection and exploration)

2.5.9. European Products

There are a wide range of both marine, ground and air systems produced within Europe. However many of these are low volume or bespoke products developed to meet specific needs. The global market is not yet established for mid to small scale aerial systems and the variation in legislation makes compliance approvals on a global scale difficult to achieve. In the marine sector there are some significant products with good commercial track records, particularly in the oil and gas sector. In nuclear decommissioning there is considerable potential within Europe and a number of SME's are engaged with specific projects, however the global market is not yet established.

Civil Sub-Domains:

2.5.10. Civil Infrastructure

2.5.10.1 Sub-Domain Overview

This sub-domain represents a large and growing area of application for robotics technology. There are currently two primary areas of application that have attracted interest over the past decade; Decommissioning and environmental monitoring. The decommissioning and inspection of hazardous infrastructure notably in the energy supply sectors is a primary area of application for robotics technology.

2.5.10.2 Current Opportunity

In the near term the use of autonomous inspection systems has the potential to both reduce costs and increase the thoroughness of inspections particularly of tall industrial structures such as chimneys by reducing the need to scaffold them. Historic building inspection should also benefit from reduced closures and quicker inspections.

Bridges and tunnels require continuous monitoring much of which is carried out using built-in infrastructure however older structures need regular inspection and this can result in closure and subsequent transport disruption. The use of autonomous systems may reduce closure times, or provide better early warning of issues within structures, allowing better long term planning.

The same technology can also be used for environmental monitoring ensuring pollution targets are met, monitoring the source of pollutants and inspecting water and air quality. There is an opportunity to provide services to survey installations both in terms of assessing physical infrastructure but also in terms of resource usage, for example the effectiveness of heat insulation, or the assessment of raw material quantities, for example by accurately assessing roof area, or the area of a surface to be coated.

The civil infrastructure now extends into space and communication satellites and earth observation satellites are part of a vital communication and monitoring infrastructure. Robotics has the potential to provide maintenance and decommissioning services in this domain.

Robots have been deployed in the nuclear industry for internal reactor inspection in hazardous environments reducing human risk levels.

2.5.10.3 Future Opportunity

Future opportunities lie in the development of control and user interface systems that allow rapid data gathering and assessment. The full autonomous inspection of external infrastructure may become a possibility in the near future. It is expected that future systems will be able to enter hazardous environments and carry out maintenance and repair tasks that maintain the operation of existing infrastructure and reduce unknown risks. Ultimately the goal is to use robot systems as a significant element in the safe decommissioning of hazardous infrastructure.

Across Europe there are plans to close up to 80 civilian nuclear power reactors in the next ten years. While many of these reactors are likely to have their operating licenses extended, they will eventually be decommissioned. Under a recent EU Directive establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, all Member States are to ensure that funding resources are available for decommissioning. At a global level the need to have adequate resources available for decommissioning is being addressed by the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.

2.5.10.4 Key Market Data

Annual exploitation costs for the 58 French reactors were estimated to €8.9bn in 2010. At the same date, dismantling costs were estimated to €18.4bn. In 2013, Europe had 185 nuclear reactors taken both operating reactors and those under construction. Cost estimates for decommissioning in the UK are currently estimated at £50bn over an extended time period. Germany also has similar nuclear infrastructure that required decommissioning. While these costs cover the whole process of decommissioning the potential utilisation of robotics technology may represent some 10-15% of these costs.

The Brent North Sea oil field was one of the UK's earliest and largest oil & gas development projects, with all four platforms (Alpha, Bravo, Charlie and Delta) coming on-stream in 1975-76. Brent Delta ceased production at the end of 2011 Decommissioning of all four platforms could take as long as ten years. Decommissioning is also taking place in the Ekofisk field, off Norway.

2.5.10.5 Relationship to other domains

Close relationship to the commercial sector and in particular the Service and Utilities domain. There is also strong linkage to energy supply companies and to national regulatory bodies.

The decommissioning of infrastructure provides a close linkage to the Construction and Demolition domain.

With regard to the transport infrastructure there is linkage to the large civil engineering companies and to the dedicated inspection services, to the national transport authorities, both road and rail, and to companies maintaining the transport infrastructure.

The application of robotics technology in the maintenance of space based systems and satellites provides linkage to trans-national space agencies and to the organisations engaged in the commercial and scientific use of space technology.

2.5.11. Search and Rescue

2.5.11.1 Sub-Domain Overview

The use of robots in search and rescue, both over wide areas such as at sea, or in closed spaces such as buildings is widely seen as providing a significant increase in the likelihood of success in locating trapped or missing people. The effectiveness of a single helicopter carrying out a wide area sea search can be scaled through the use of multiple coordinated guided search systems both at sea and in the air. A single operator will be able to monitor a more extensive search area in a shorter time at lower risk with autonomous assistance to search for assets and personnel, particularly in hazardous conditions.

2.5.11.2 Current and Future Opportunity

Experimental systems have been deployed to carry out search operations after natural disasters. The deployment of undersea systems has had notable success. The uptake of search systems has, to date, been low and the potential to deploy robot systems requires further investigation and exploitation.

The scaling up to high TRL levels of collaborative systems able to autonomously scan large areas during search and rescue operations, and the ability to create maps of spaces and identify voids in collapsed buildings will significantly improve search and rescue outcomes.

The use of multiple robots providing coordinated search in unknown and dynamic environments that are typical of disaster zones could provide enhanced safety to rescue workers and increase the likelihood of discovering victims and identifying threats and hazards. However investment in the development of these systems may depend on other market domains developing the initial technology, notably the civil infrastructure and military domains.

There are potentially significant safety gains that may occur with a one to one collaboration between a searcher and a tele-operated semi-autonomous robot used to enter buildings and carry out search and possibly rescue tasks. The search function alone can have significant impact in that the robot will be able to reach spaces and regions of a building that a human operator may not, and it may be able to move faster and with significantly lower risk. On finding a person its internal map of the space can be used to plot the optimal route to effect a recovery. In more advanced systems the robot may be able to provide basic medical assessments and even basic medication (for example pain relief) increasing survivability. Even simple tasks such as delivering water to earthquake victims trapped in inaccessible spaces could significantly increase survivability chances.

2.5.11.3 Relationship to other markets

There are strong links to similar functions in the military domain and to other emergency services functions. There will be links to equipment suppliers and considerable shared technology with civil sector companies engaged in environmental monitoring.

2.5.11.4 Europe's Place in the Market

Europe has a number of experimental systems and the rescue equipment industry needed to support their eventual exploitation.

2.5.12. Environment

2.5.12.1 Sub-Domain Overview

Monitoring the environment and providing up to date information about changes can provide early warnings that allow faster and more effective responses to hazards, and to long term changes in the environment. The ability of robotics technology to provide multi-modal data accurately mapped to terrain data makes it a valuable data collection tool. This data often has value in its own right, to farmers, civil authorities and utility supply companies. The potentially low cost of performing this type of environmental monitoring will accelerate the development and deployment of such systems and enhance those services that rely on this data.

2.5.12.2 Current and Future Opportunity

Potential applications range form crop monitoring to building inspection, pollution control to water quality monitoring. Almost all aspects of the environment can be monitored by using robotics technology as the main means of mapping an area.

2.5.12.3 Barriers to Market

The main barriers to market are regulatory based on the restrictions on the use of autonomous vehicles in public spaces and in the air.

2.5.13. Law Enforcement

2.5.13.1 Sub-Domain Overview

Using robots for law enforcement is an area of application that will require extensive ethical and legal debate. For this reason it is not seen as a short term area of application with the exception of tracking and monitoring. There are clear benefits in the use of autonomous systems for the pursuit and tracking of people using multi modal systems just as there are in search and rescue and in environmental monitoring. Some civil security forces are experimenting with remotely guided air vehicles for information gathering.

2.5.13.2 Current and Future Opportunity

The use of multiple aerial vehicles as surveillance platforms that can monitor ground movements often without attracting attention, and the use of water based border patrols augmented by fleets of monitors and ground patrol robots on boarders are obvious application areas.

These applications carry ethical and legal issues related to privacy, legal rights and the admittance of automatically collected data in law.

At some point in the future a critical boundary will be crossed where a robot is designed to physically engage a subject in much the same way that dogs are currently trained to do. The impact on civil rights and the establishing of legal control over the robot will require wide spread and careful analysis in order to avoid the controversy that military drones are currently undergoing. These robots have the potential to negatively alter the perception of robotics technology in the public eye.

2.5.13.3 Relationship to other domains

There will be shared technology between this domain and the Search and Rescue domain and Civil infrastructure domain. There are strong links to the emergency services domain. There is likely to be significant technology transfer from the military domain.

2.5.14. Emergency Services

2.5.14.1 Sub-Domain Overview

While some aspects of the emergency service use of robots is covered in other sub-domains, notably law enforcement and search and rescue there are a number of application areas that do not fall into these other categories. In particular fire fighting, hazard reduction, pollution control, and the provision of emergency aid and assistance.

2.5.14.2 Current and Future Opportunity

Tele-operated fire hoses may be able to reach closer to a fire than a human and may be able to sustain operation for longer at higher temperatures, or in situations where there are other hazards such as the risk of building collapse, or toxic fumes.

In pollution control autonomous systems may be able to deploy barriers, dispersants and absorbers more quickly by exploiting multi modal collaboration to both monitor and deploy dynamically as a disaster unfolds. Early intervention has the potential to reduce disaster impact and cleanup costs.

In the medium term emergency service workers may also benefit from “buddy” systems, either exo-skeletons that increase lift capability, reach, or companions that jointly perform collaborative tasks.

In the future the use of remote surgical robots may provide immediate assistance for traumatic injury. Ultimately Robots may also be deployed to lift and support accident victims during extraction from accident sites.

2.5.14.3 Relationship to other markets

Clear and strong links to search and rescue domain and to law enforcement. Eventual possible links to the Healthcare domain.

2.5.15. Science Support

2.5.15.1 Sub-Domain Overview

The domain of science support covers a wide range of different activities that relate to scientific enquiry. Robots in this domain are often highly specialised research tools designed for a specific purpose. These robots are often made singly and may be regularly upgraded during their life time. This is the domain where the public are most likely to have encountered robots. The Mars rovers, and deep sea explorers such as Alvin have high public profiles and act as technical ambassadors for science.

While these robots may have a degree of semi-autonomy they are typically tele-operated. The requirements for extremely high levels of dependability and the high cost of replacement means that control strategies are extremely cautious.

2.5.15.2 Current Opportunity

This is a mature market with well established suppliers and its roadmap is driven by large scale research funding, for example trans-national space or marine research programmes.

The use of robots for long term environmental monitoring is still in its infancy. The use of robots for the monitoring of pollution and resources carried out for research purposes is still at an early stage of development.

A secondary area of scientific support robotics is in the supply of research robots to the robotics community itself. These can take the form of kits, modules or whole systems including software and development infrastructure. This is a growing market.

2.5.15.3 Future Opportunity

There are numerous areas of application for science support notably in:

- Wildlife monitoring
- Deep space exploration
- Planetary rovers
- Deep sea exploration

2.5.15.4 Relationship to other markets

The developments in this domain often feed other more commercial domains. The uniqueness of the robots means that almost every aspect of them has to be specially developed.

2.5.16. Key System Ability Targets

The system abilities for Civil Robotics are those that enable a robot or a team of robots to endure loosely supervised missions in large unstructured scenarios: interaction, dependability, perception, autonomy, navigation, motion capabilities, cooperation with other robots or humans and, to an increasing extent, cognition.

2.5.16.1 Adaptability

Real time real-world learning	Task Adaptability: Level 2 - Single Task adaptation

2.5.16.2 Interaction Capability

Cooperative behaviour limited to specific tasks;	Cognitive Human Interaction: Level 2 Task context interaction.
Robot and human-robot teams, full cooperative behaviour	Cognitive Human Interaction: Level 3 Object and location interaction combined with Human robot Interaction Level 4-6 and Robot robot interaction Level 4-5.
Collaborative robot-robot and human-robot manipulation (e.g., load sharing)	Human Robot Interaction: Level 2 Direct physical interaction Robot robot interaction: Level 5 Team coordination

2.5.16.3 Dependability

All-weather missions	Dependability Levels 4-5
Long Term (Permanent) Deployment	Dependability Levels 4-5
Long Range Deployment	Dependability Levels 4-6

2.5.16.4 Motion Capability

High speed and agile autonomous driving on uneven and sloping terrains All terrain high speed and dexterous autonomous driving	Constrained Motion: Level 5 Dynamic motion

2.5.16.5 Manipulation Ability

Mobile manipulation on uneven sloping terrain and with floating robots	Constrained Motion: Level 5 Dynamic motion combined with Location perception: Level 5 Object coupled location combined with Decisional autonomy: Level 8 Dynamic autonomy.

2.5.16.6 Perception Ability

Coarse scene classification; update of the model based on observations	Scene perception: Level 4 Multiple object detection combined with Object recognition: Level 4 Object recognition - one of many.
Operation possible in most weather and environmental conditions;	Object Recognition Parameter: Environment Perception Ability Target: Immunity to natural variations.
Detailed scene classification & understanding; build high-level abstract information.	Scene perception: Level 5-6 combined with Object recognition: Level 6-9.
Cooperative Mapping (breakthrough in communications required)	Cognitive Action Ability: Level 5 Knowledge driven action combined with Robot robot interaction: Level 5 Team coordination.

2.5.16.7 Decisional Autonomy

Pre-planned missions; medium complexity tasks; limited human supervision; integrated planning among heterogeneous fleets of	Decisional Autonomy: Level 4 - Simple autonomy.

manned and unmanned vehicles	
Re-configurability of robot task depending on the changed environmental conditions	Decisional Autonomy : Level 7 - Constrained task autonomy.
Intelligent “Motivation Dynamics” with temporarily changing priorities (situation-specific priorities)	Decisional Autonomy: Level 10 - Mission oriented autonomy
High complexity tasks performed autonomously and in cooperation; collective behaviour; no human in the loop (human monitoring only); opportunistic mission planning capability, goal-based missions	Decisional Autonomy: Level 10 - Mission oriented autonomy combined with Cognitive Action Ability: Level 8-9
Re-configurability of more robots working cooperatively, reassignment of task domain/goals between robot	Robot Robot interaction Level 5-6, combined with Decisional Autonomy: Level 10 - Mission oriented autonomy combined with Cognitive Action Ability: Level 8-9

2.5.16.8 Cognitive Abilities

Interpretation of scenarios of limited complexity taking into account different inputs.	Reasoning Ability: Level 7 - Task Reasoning.
Interactive prediction of dynamic systems.	Adaptability: Level 2 Multiple parameter adaptation.
Wide comprehension of scenarios taking into account different/conflicting inputs;	Reasoning Ability: Level 4 Reasoning with conflicts.

2.5.17. Key Technology Targets

Key technology targets for the Civil domain can be categorised in to three different areas:

- *Safety by design:* The need to provide safety certification for systems operating in the Civil domain will be driven by advances in systems design methods that integrate safety into the design cycle such that safety performance can be guaranteed by design rather than proof of operation post design. Establishing acceptable levels of safety for each type of application and application area will also be a key part of design capture
- *Operation in unstructured and dynamic environments:* The unstructured nature of the main operating environments for the Civil domain require significant improvements in perception both in unstructured 3D terrains, under water and on the ground, and in terms of handling the effects of extreme weather conditions on perception and localisation. The unstructured and often dynamic nature of the operating terrain also provides significant challenges in the design of mechanical and motion control systems able to operate on unstable and rough terrain while maintaining sufficient localisation.

- *Cooperative missions:* In a number of potential application areas the Civil domain will require teams of robots to carry out tasks and will therefore rely in the underpinning technologies for the command and control of teams of both heterogeneous and homogeneous robots. Including the mixture of robot teams with human teams working in close collaboration. In more advanced applications scene interpretation and cognitive interpretation of both object and environment in play an increasingly important role.

The following lists specific technology targets that are relevant to the Civil domain:

2.5.17.1 Systems Development

System Design

- Development of standard architectures.
- Design tools for the integration of robots in wider pre-existing systems.
- Design of common platforms.

Long Term

- Standardised and certified platforms and development tool chains for mission critical and safety critical operations.
- Standard interfaces and systems for the deployment and retrieval of remote vehicles.

Systems Integration

- Development of interoperability standards for robotics components
- Development of system interoperability standards for robot and human teams
- Self-configurability of off-the shelf robotics components

Modelling and Knowledge Engineering

- Mechanisms for scene analysis and knowledge acquisition based on the perception of simple scenarios
- Mechanisms for scene analysis and knowledge acquisition based on distributed perception in teams
- Development of methods tools and techniques, for knowledge representation in domains of low and medium complexity
- Development of methods tools and techniques, for knowledge representation in in complex domains and scenarios

2.5.17.2 Mechatronics

Mechanical Systems

- Automatic buoyancy control systems
- Appropriate miniaturisation of current capable systems leading to reduced equipment and deployment costs,
- Commoditisation of common parts and systems,
- Simple and reliable systems for the deployment and retrieval of robots particularly in disaster scenarios and in marine and hazardous environments.
- Design of energy efficient autonomous robots for specific environments
- Multi-functional/multi-task and flexible end-effectors.
- Kinematic architectures that provide Unmanned Ground Vehicles with improved abilities in terrain/obstacle negotiation and constrained space operation.

Sensors

- Development of sensors for navigation
- Development of sensors for the reliable detection of people
- Acoustic sensors for marine remote sensing and map building applications.
- Specific new low maintenance and low cost chemical sensing mechanisms to enable the use of robot systems for environmental protection tasks.
- Development of sensors for underground localization.

Actuators

- Energy efficient propulsion systems in multiple environments.
- High efficiency miniaturised underwater propulsion systems
- Deep ocean propulsion systems
- Improved reliability and robustness of the actuation components for Unmanned Ground Vehicles.

Power Supply and Management

- High-density energy systems
- Energy management systems
- Fuel cells for underwater applications

Communications

- Ad hoc robust (broad-band and out of line of sight) communication through different media, technologies and capabilities (i.e. by means of fleets of robots)
- Robust communication & localisation systems for underwater applications.

Materials

- Advanced composites for vehicle hull and container fabrication
- New materials for deep water and water column exploration (such as variable forms for hydrodynamic task adaptation, reduced weight and lower deployment costs)

Control

- Integrated vehicle-arm control and vehicle stabilisation for mobile manipulation on uneven sloping terrains and floating robots
- High speed autonomous off-road path following and obstacle avoidance
- Cooperative control of multiple heterogeneous platforms, including air, surface, and marine robots.
- Low cost, medium performance, integrated sensors for accurate guidance & control.

2.5.17.3 Human Computer Interaction

Human Machine Interface

- Augmented reality tool for the remote operation and interaction with unmanned vehicles
- Systems for seamless mission specification and mission programming.
- Systems for mission follow-up and post-mission analysis
- Tools an ergonomics for reducing remote-operator workload and stress
- Natural human machine interface methods

2.5.17.4 Perception

Sensing

- Scene interpretation fusing different sensor modalities; multi robot perception in heterogeneous teams (both in terms of platform and sensors).
- Video and acoustic imaging data fusion for underwater applications.
- Distributed multi sensor fusion; Sensing/Control/Planning integration (i.e., plan to sense to control)

2.5.17.5 Navigation

Mapping

- Large scale mapping in dynamic environments, capable of handling vast areas of operation and supporting navigation for extended periods of time.
- Automatic underwater pollution mapping.
- Sea bottom/sub bottom mapping.
- All weather map management and update

Localisation

- Precise localisation in difficult environments such as indoor GNSS denied scenarios or underwater will allow the use of systems in a wider variety of applications.
- Cooperative localisation/geo localisation with robot teams.

Motion Planning

- Planning with kinematics and environmental constraints
- Real-time planning with kino-dynamics and environmental constraints
- Systems for cooperative, multiple vehicle motion planning in the presence of environmental disturbance and obstacles.

2.5.17.6 Cognition

Cognitive Architectures

- Development of architectures and models for representing and implementing cognitive tasks of low to medium complexity
- Development of Architectures and models for representing and implementing cognitive tasks of high complexity
- Development of methods, tools and techniques for modelling cognitive tasks of low to medium complexity
- Development of methods, tools and techniques for modelling cognitive tasks of high complexity

Learning Development and Adaptation

- Adaptation with respect to changing environmental conditions
- Adaptation to large vehicle parameter variations

Knowledge Representation and Reasoning

- Development of methods, tools and techniques for knowledge based reasoning in domains of low to medium complexity
- Development of methods, tools and techniques for knowledge based reasoning in complex domains and scenarios

Action Planning

- Advanced systems for multiple vehicle cooperative task and mission planning
- Highly abstracted mission definition and mission/task planning algorithms for interaction and operation with untrained users;
- Systems for operator-assisted manipulation
- Systems for autonomous intervention in underwater structures
- Systems for cooperative grasping and transportation of heavy objects.

Natural Interaction

- Cooperation and interaction among air, ground, surface, and underwater vehicles
- Systems for human-robot interaction and mixed team operations

2.6 Commercial Domain

2.6.1. Domain Overview

This domain covers the use of robots working as part of a commercial process. As with the other market domains these are well established markets where there is an opportunity to employ robotics technology.

The Commercial domain covers a wide range of different markets, two of these major sectors have already been highlighted elsewhere in the MAR (Manufacturing and Agriculture) so the purpose of this section is to detail other sub-domains where robots can have an impact on commercially led processes.

These robots are most likely to be operating within a work environment. They will be operated by skilled workers but may also come into contact with the general public through the work environment.

These robots have a single overriding goal, they must be cost effective. This can come about in many different ways for example by carrying out a process more quickly, or with less wastage than a human worker, or by working with a person to extend their skills, perhaps by reach or load capacity.

These robots work as part of a commercial process; manufacturing goods, providing service functions within a commercial organisation, or operated by a commercial organisation. Most often they will be operated by trained personnel, operating with or in cooperation with other people in a work environment.

The legal framework of operation is that of the work environment, be that a farm or a factory. This high level domain is characterised by Business to Business transactions (B2B).

2.6.2. Current and Future Opportunity

The sections on Manufacturing and Agriculture detail many of the key opportunities in this domain and these are currently seen as being the main growth areas in terms of goods production assisted by robots.

In a number of areas within the Commercial sector robotics technology provides and enhanced set of tools to allow existing and well established industries to operate more efficiently. The gaol of R&D&I funding must be to demonstrate the opportunity in order to enable to large take-up and adoption of robotics within these large scale industries.

Inspection and Maintenance

There are many different types of inspection and maintenance industry, ranging from the inspection of manufactured parts to the inspection of buildings, large scale infrastructure, industrial production and process plants and land usage. Commercial organisations interested in this sub-domain range from equipment suppliers to individual inspection companies in niche markets to government organisations enforcing legislation on pollution and safety. The energy and utility domains are key markets. Robotics technology has the potential to significantly impact all aspects of this market from the automated inspection of large manufactured parts such as aircraft, to remote camera systems used by domestic builders to assess roof repair more quickly and completely. The potential saving of time and cost in the inspection of large plant and equipment by reducing down time is significant. In the future it is expected that robotics technology will extend it's functional reach to include maintenance.

Mining and Minerals

There is a long standing use of robots and remote guided vehicles in the oil and gas sectors and more recently in mining. Many of the Mining and Mineral industries operate within hazardous environments and the extraction of earth resources is often limited by the level of risk associated with human working conditions. There is a significant opportunity to utilise robots for extraction in order to reach more inaccessible mineral resources. In particular there are considerable mineral resources on the deep ocean bed where robots could provide the solution to long term and viable extraction. Working in flooded mines may also be possible.

The significant cost of failures and the potential environmental impacts make this an area of application that demands high levels of reliability and dependability, but the high value of the infrastructure enables appropriate funding.

Utilities and Service

The utilities industries, power generation, water, gas and electrical supply all have high value assets that must remain operational 24/7 in order to minimise costs. Down time is costly in terms of lost capacity. In all of these industries the assets are widely spread geographically and although monitoring systems are in place regular inspection is a key part of maintaining operational integrity. Robotics technology has a key role to play in providing continuous inspection capabilities and in the future both inspection and repair (possibly in advance of failure) could be carried out by robots.

In particular the robot monitoring of power lines and robot assisted repair has been trialled over a number of decades, it is possible that new approaches may eventually make this a viable field.

The installation of new services using underground robots has the potential to reduce installation cost and time and decrease disruption to supply. Using multi-modal information sources and context aware sensing to detect other unknown services or errors in existing utility maps can help to reduce delays that can often cause the re-planning of new installations.

Construction and Demolition

The construction industry is highly cost competitive, faster time to completion is a key driver in the adoption of new working methods. Robotics co-working in construction has the potential to speed up construction and at the same time enable new ways of building that may be more cost effective. For certain competitive construction tasks such as road or rail construction a higher level of automation may be effective. In the demolition industry there are similar drivers, decreasing time to completion and correctly handling the deconstruction of complex buildings at speed may drive the adoption of robotics technology.

Marketing

In an entirely different commercial sector, marketing, robots have been used as visual icons and as the focus of attention for decades, in fact some of the earliest robots were constructed for advertising purposes. Modern robotics technology is also used extensively as a way of demonstrating technical sophistication for high tech companies. However the use of robotics in marketing has the potential to take on a much more direct role where roving vending machines service clusters of people, and robots are used to provide assistance and information within shopping environments. Such systems may range from animated advertising to interactive systems demonstrating product use.

2.6.3. Sub-Domain: Inspection and Maintenance

2.6.3.1 Sub-Domain Overview

Robotics provides significant advantages over current methods of inspection and maintenance, for example 24/7 working, and have the ability to operate in hazardous, harsh and dirty environments. The utility and energy domains have begun to explore the potential of robotic technology. There is an emerging trend for these industries to include robot based maintenance and inspection within their forward planning. However there is currently no wide scale adoption or validation of this technology.

The lack of wide scale adoption can be attributed to a number of different factors, such as insufficient availability of robust technical solutions and the concern of implementing innovations without track record. At the root lies a disconnect between the robot technology being developed for this industry and the requirements of the users. This is due to an insufficient understanding of what challenges are being faced by asset owners for inspection and maintenance tasks, and the basic requirements that drive their needs for robotic technology uptake.

From the asset owner perspective, several drivers for the use of robotics are apparent that will be key to the uptake of robots within the industry. The main drivers can be categorized under 3 topics:

- Safety impact
- Environmental impact
- Economic impact

The majority of these assets must be inspected at regular intervals, either driven by maintenance needs or safety requirements. Currently nearly all of these tasks are carried out by human intervention. In order to carry out the inspection or maintenance humans need to enter the asset, often a confined space, or be in an otherwise potentially hazardous location to perform the task. Furthermore, the assets can also be located in hazardous or remote locations. In some cases it might not be feasible to access the asset for inspection. Plant operation must often be interrupted to allow for safe execution of such tasks. These shutdowns not only lead to substantial production loss, but the shutdown and start-up operation itself causes risks to human and environment.

Taking the case of human access as an example; often the human access procedure may involve:

- Emptying the asset (a process easily taking several days *plus* another asset to compensate for the capacity loss)
- Erecting scaffolding in order to access the object to be inspected (and removal afterward)
- Isolation of the asset and re-installation of the asset afterward (completely detachment from the rest of the facility)
- Thoroughly cleaning, degassing and air quality monitoring of the asset
- Entering the asset to carry out the inspections.

Avoiding these activities represents huge savings as well as reduces risk associated with the activities themselves.

2.6.3.2 Current and Future Opportunity

Future Opportunity – The Vision

The top level vision for robotics in inspection and maintenance of process plant assets is characterized by stakeholders of the process industry as following:

Priority	Target	Time horizon
1	Move People away from hazardous spaces to safe areas by 50%	5 years
2	Reduce Plant Downtime by 50%	10 years
3	Reduce Environmental Impact of 50%	15 years
4	Coherent standards for robotic deployments	5 years
5	Step Change in data and information management	5 years
6	Plant design to support remote and autonomous robotic operation	10 years

The following robotic applications are those most highly ranked by asset owners as being of particular interest:

- Robotic inspection and maintenance in confined spaces such as pressure vessels, storage tanks, pipes
- Robotic inspection and maintenance of difficult to reach / remote locations such as flare systems, chimney stacks, structural parts, underwater structures, other remote facilities.
- On site / in situ robotic maintenance such as cleaning, surface treatment, repair, conservation, painting etc.
- Online visual or sensor supported monitoring and surveillance of plants and assets. Operations include, e.g. scheduled inspection rounds and first responder action in connection with alarm situations.

As with all adoption of new technologies into an industry, a number of challenging problems need to be addressed in order to deliver reliable robotic solutions which will be accepted by the market.

Commercial and Market Structure

In order for a viable market in inspection and maintenance to be created a number of key changes are required.

- Technology is needed that meets both the technical and safety requirements of the various industries requiring robot inspection.
- Systems need to be developed that are able to address multiple different types of inspection task.
- Robot developers and sources of innovation need to engage with End Users to address their specific needs.

The development of a new supply chain is dependent on connecting End Users, who are technology agnostic but prepared to pay for enhanced solutions that demonstrate economic advantage, with small scale innovation providers that understand the technology and its capabilities. This is an area of significant opportunity.

Critical to this relationship will be the setting of suitable standards and safety processes. Both are fundamental in enabling large scale deployment of robots and gaining traction in the market place.

Existing systems that utilise tele-operation are well known in a number of industries, typically in hazardous environments where inspection tasks present an unacceptably high level of risk to human operators.

In general the maintenance and inspection market is very conservative and risk-averse, so the economic and safety benefits must be overwhelming and the perceived additional risk must be acceptable low for the market to embrace such innovations. Understanding the market structure and developing economic and business cases for robotics within the market will be key to the success of this technology. Furthermore, involving asset owners input at the start of the research and development phase (both blue sky development and technology development) will speed up the uptake of the research and technology development thus providing quicker adoption and a consequential gearing effect on investment

2.6.3.3 Barriers to Market and Market Structure

Key barriers are both technical and non-technical. There is a need to develop both partnerships and appropriate technology. There are four principal focus areas that need to be addressed:

- Technical capability
- Technology safety conformance
- Economic viability
- Commercial and market structure

Technical capability gaps

There are several gaps in the technical capabilities for current robotic solutions that need to be addressed. A common denominator is that robot systems need to exhibit very high levels of safety and dependability in operation. The required technologies can be broken down into the following subcategories:

Mobility within the environment: The facilities that robots need to operate in or nearby are complex and not designed for robots. They contain many different types of assets, each having its own distinct method of inspection and maintenance, as well as complex supporting infrastructure. Robots will often be sharing space with human who may also be altering the environment. .

Sensing and localisation: Precise navigation of robot platforms and any associated manipulators plays a vital role in maintaining safe operation. This is not only critical for fully autonomous operations, but also with semi-autonomous and tele-operated robots. Mapping and sensing for interaction are also important for certain applications. Harsh environments pose particular challenges (e.g., dust, dew, dirt, etc.).

Control and automation; Reliable communication with robots is essential to maintain control. Knowledge on communication Quality of Service (i.e., availability, bandwidth, etc.) is important. In the absence of communication channels (or in presence of non-reliable communications), more higher levels of autonomy are needed to keep the robot operating dependably. Across the spectrum of applications different systems will be required to operate at different points on the autonomy spectrum based on the task to be performed. User interfaces also need careful design.

Sensor Delivery: Accurate delivery of a sensor may require precise and repeatable control of its location and orientation. The delivery of sensors to inaccessible locations is highly desirable.. In the future combining inspection with maintenance creates significant added value, this can be through tele-operation or through increased levels of autonomy. At one level the ability to operate control valves and at another the ability to carry out material repairs.

Power and communications: Safely providing robots with power, during long operating time is key. Advances in battery technology and alternative means of power generation are going to play a critical role. Communications is of similar importance. Robots often operate outside of available networks and may need to utilise Ad-Hoc communication systems. Aspects such as bandwidth, network protocols, network security, and operating environment are critical. Maintaining power and communications can also be critical to maintaining safety.

Inspection technology: Many inspection technologies exist but are not always fully suited for robot usage. Accordingly inspection technologies need to be adapted to suit the requirements of robotic operation. On the other side robotics need to consider the integration of proven inspection technologies.

Big Data: management & analysis: Managing the massive data that will be generated by robots will become a challenge. In some cases this data has intrinsic value both to the organisations that own the assets being inspected and to external customers.

Technology safety conformance

Safe deployment of robots is of paramount importance and is currently a barrier to market. To date there has been a limited number of robot solutions deployed in real-life inspection and maintenance scenarios (other than subsea), and those that have been deployed are mostly at a demonstration or trial phase this can be seen to be a direct result of a lack of safety performance certification. This is due to a number of factors:

- Lack of technology readiness when it comes to technology in explosive atmospheres (ATEX[6] and IECEx[7])
- The environmental robustness of current solutions (e.g. Ingress Protection class 67 or higher)
- Lack of demonstrated reliability of the robotic solutions: Broken down robots may become a safety hazard themselves as they may block equipment or prompt rescue activities.
- The need for demonstrated collision avoidance.
- Education gap between the developers of the technology and asset owners regarding safe operations and regulations for equipment in the industry (safety standards, regulations, operating procedures)

Economic viability

The primary driver for the deployment of robotics in inspection and maintenance tasks is economic advantage. Making the economic case is critical. Although the major driver of safety may outweigh the economic side of the equation systems will still have to be economically viable to be adopted.

The asset owners want to see robotics for inspection and maintenance as a commodity, with multiple vendors with multiple robotic solutions to inspection and maintenance. The inspection process is most often only a small part of the overall cost the major part being the cost of taking plan tout of service and providing safe access to human operators. Robot systems have the potential to reduce the overall economic impact of taking assets out of service. An example of this is when an above-ground fuel storage tank is shut down for inspection it can cost up to $1m before the inspection can occur. Similarly it was estimated that the majority of the time spent in the context of an internal pressure vessel inspection was related solely to human entry of the vessel. The goal is to drive the cost of robotic solutions to a point where alternative solutions for inspection and maintenance are no longer viable. Identifying and analysing key areas for the economically viable deployment of robots is a vital area of research

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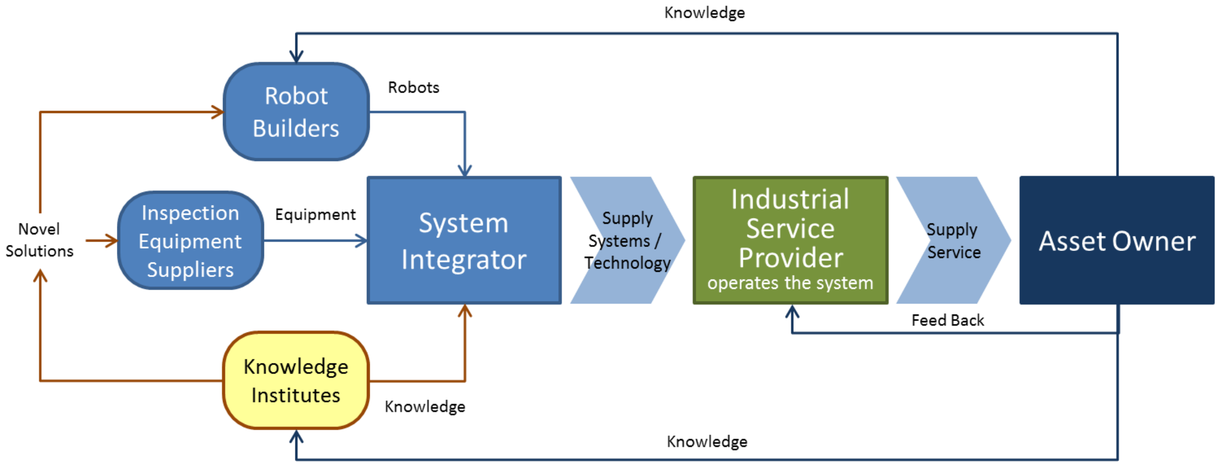
[6] The abbreviation derives from the French title: Appareils destinés à être utilises en ATmosphères EXplosibles.

[7] International certification directly referenced to IEC standards for equipment to be used in hazardous (classified) locations.

Commercial and market structure

There are 3 distinct market segments that make up the structure of the value chain: systems integrators/robot builders/component suppliers, service providers, and asset owners (purple). System integrators would consist of Inspection/maintenance technology providers, component suppliers and knowledge institutes. The service providers would provide the robotic service to the asset owners whilst taking care of items such as operations and maintenance of the hardware.



Market value chain for petrochemical robots

2.6.3.4 Relationship to other Domains and Markets

The Inspection and Maintenance Robotics sub-domain, has many relationships with the following domains listed in the SRA:

- Civil Robotics
- Manufacturing Robotics
- Space Robotics
- Underwater Robotics
- Aerial Robotics

These relationships operate on the basis of common technology and platform development and on the need to set common safety standards.

2.6.3.5 Europe's Place in the Market

Europe is well represented for the complete value chain necessary for an increased uptake of robotics for inspection and maintenance. As an example, Europe has a world leading role in Autonomous Underwater Vehicles (AUV), and relevant end-users. Many European energy companies have shown an interest in the increased use of robotics for inspection and maintenance.

2.6.3.6 Key Stakeholders

Key stakeholders are:

- Regulation authorities driving the rules and regulations for the inspection and maintenance in the process industry. Main goal is to assure the safe operation of assets and to minimize negative impact on humans and the environment
- NDT equipment suppliers supplying the industry with equipment for the inspection of assets
- Maintenance equipment suppliers supplying the industry with systems for the maintenance and repair of assets

- Industrial service provider executing the inspection and maintenance of the asset owner
- Robotic component / system supplier providing robotic technology / systems to industrial service providers or to the asset owner directly.
- Asset owners / plant operators running the industrial process facility.

2.6.3.7 Current Key Projects

Currently many EU funded projects are addressing the needed abilities and capabilities for maintenance and inspection robotics.

In parallel projects like the “PETROBOT” project are driving the industrial application of robotics.

In parallel a significant number of projects aiming for robotics in inspection and maintenance are driven by the industry within joint industry projects.

Finally asset owners have started to consider robotic competitions in order to drive robotics in the industrial domain such as the “ARGOS Challenge” organised by TOTAL.

2.6.3.8 European Products

The robotic market is highly fragmented. Most common are e.g. ROV or simple manipulators. At the moment US and Canada based companies are dominating the market of ROV. Regarding robotic manipulators Europe is dominating the market.

2.6.4. Sub-Domain: Mining & Minerals

2.6.4.1 Sub-Domain Overview

The mining domain covers robots used as part of explorative, extractive and related mining processes. Mining is one of mankind’s oldest undertakings and the first organized industry, it is a very well established market with many opportunities for the application of robotic technology. Raw materials are a fundamental resource for almost every industry. Developments in technology and new processes have over the decades enabled the broad availability of raw materials at acceptable prices. At the same time, due to novel processes and mechanization, the safety of personnel working in the mining sector has increased significantly and higher levels of sustainability and environmental compatibility have been achieved. Mining, unlike other industries, is dependent on a finite resource. Consequently, the basic conditions for mining are becoming more difficult over time. Untouched deposits are located in greater depths, which means they can only be mined economically when higher raw material prices prevail or when higher productivity levels are achieved to lower to cost of extraction. Moreover, an aging workforce and skill shortages require optimal usage of resources. The use of robots is still limited in this domain but it is recognised that it could enable great benefits. The three main areas where robotic technologies can realize significant impacts are:

- Safety
- Environment
- Economy

By reducing the presence of humans in mines, higher safety and health levels for the personnel will be achievable. One goal for robotics technology is to reduce the number of hours workers must be present in dangerous and hazardous working zones, significantly increasing the safety and health of personnel. Moreover, use of modern robotic technologies in mining will have a positive impact on the environment. Robot based mining systems have the potential to reduce the amount of waste cut, such that the cost for downstream processes like material transportation and processing is greatly reduced. As a result, higher overall resource efficiency and an overall reduced impact of mining activities can be achieved. The competiveness of European mining and Europe's industry can be increased with a reduced dependency on raw material imports for Europe resulting from more cost effective European extraction processes. In the long term, with new mining processes tailored for robotic technologies, even larger impacts are to be expected.

Robots for the mining and minerals sector must foremost be able to cope with harsh environmental conditions. They operate above or below ground in an environment where water, dust, dirt and high moisture levels are common and explosive atmospheres may exist. In deep mines the environmental temperatures can also be high. In mining, surfaces like walls, roof or ground are usually rough as they are typically not conditioned. Uneven ground with standing water and varying friction is common and the operating space changes as a consequence of the extraction process. The robot's propulsion and navigation systems must be able to work reliably in these conditions. In general mechanical robustness and reliability are paramount, especially for robots participating in extractive processes.

While the layout of a mine is constantly changing through these extractive processes, the environment can be assumed static or at least predictable for the most part. There are however some processes requiring highly dynamic perception capabilities. While in many areas of mining fully autonomous robotic systems without human interaction would be most desirable, stepwise integration of robotic technologies into this domain will need interaction ability with human workers.

2.6.4.2 Current and Future Opportunities

The integration of robotic technologies into mining offers numerous opportunities. The Smart Mine of the Future (SMIFU)[8] project has identified a number of key future developments in mining and sets goals for the long term. It identifies that although there is a high level of mechanization very few processes are autonomous. It sets the goal of improved productivity, safety, resource and capital efficiency and sets out the market for robotic technologies.

Longwall complex

The longwall system is the basic method of mechanical coal mining in coal mines. The longwall complex consists of coal shearer, face conveyor, stage loader and other auxiliary equipment. All these machines are linked via a computer system to control their operation. While the level of automation is high after appropriate preparation of the technological process, the system can then operate in automatic mode, however it must be still monitored by person located at a short distance.

The goal is to further develop systems aimed at achieving autonomous operation that will remove people to an even greater distance or even to the surface. To achieve this goal will require new sensors, control and decision-making systems as well as development of more powerful tools subject to remote control.

Mechanized complexes for tunnel boring

The construction of tunnels, for transport and in mining is associated with the use of two types of machine – roadheaders and mobile drilling platforms. These machines are commonly used in any underground tunnel construction.

Due to the high repeatability of drilling and mining operations advanced control systems are used to automate the alignment of the drill head with the platform. Parameters of the path to be followed can be uploaded to the machine and can then be used to implement the process automatically. The steering of the whole system against absolute position still requires a

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[8] http://rocktechcentre.se/wp-content/uploads/2013/04/MIFU_final_report_WP7_101112_red.pdf

skilled “pilot”. Currently under investigations are geodetic systems to be integrated with this type of machines.

Mining transport systems

Transport systems are the basis for every industry sector. In mining different means of transport are used and the most common are haulers, suspended monorail and conveyors.

The development of these systems is aimed at the reduction of energy consumption and extending the lifetime of moving parts, remote control of machine condition and development of automation leading to the autonomous operation of these machines.

Hauler development has advanced to the point of the tests being carried out of autonomous systems moving in real mines. It is expected that further development of navigation, detection and collision avoidance systems will be required.

In mining rail cars special emphasis is put on autonomous drive use. Thus simplifying mines infrastructure and increases the range of applications. Currently combustion based propulsion needs to be certified for EX zones, battery powered electric drives are also used.

As regards all types of conveyors (belt, scraper) studies are being conducted towards energy consumption reduction by regulating belt speed.

There are also opportunities to provide integrated transport management and control to maximise the efficient use of roadways and reduce energy consumption.

Inspection robots for assessment of technical condition mining infrastructures and for active support of mining rescue teams

The use of robotic systems to inspect mine infrastructure has high application potential. Existing systems successfully use laser heads in mining shafts to assess the state of lining as well as its construction. Multi-modal systems have a broad potential for providing inspection capability but localisation systems suitable for use in mines need to be developed in order for mobile platforms to be used in inspection tasks requiring accurate measurements. Once such systems can be deployed on a regular basis in mines they have the potential to spot problems occurring over longer time frames and provide alerts to the mine controller. The accumulated data from such inspections will also act as a valuable data resource.

The use of the robot systems goes beyond regular mining work. There is a real need for solutions that can be used in rescue team actions. Autonomous or semi-autonomous mobile robots during underground rescue operations can be used to explore areas/zones dangerous to human life by observing, assessing and communicating information about the environment in these regions. Such systems should be able to test hazardous areas and deliver measuring data and images from cameras to rescue teams and to control centres. The gaol being to increase safety for rescuers and improve the chances of rescue. Also shortening the time taken to restore a mine to operational status after an incident will have a positive impact on the commercial viability of a mine.

Ideas for targets

Priority	Target	Time horizon
1	Increase Machine Safety	5 years
2	Increase Productivity	5 years
3	Reduce Waste generated by 10 %	10 years
4	Increase production consistency	5 years
5	Reduce necessary human presence hours in dangerous and hazardous working zones by 70 %	10 years
6	Reduce unscheduled downtimes by 30 %	10 years

7	Realization of autonomous haulage systems in areas with human presence	10 years
8	Fully autonomous extractive machinery	15 years

2.6.4.3 Barriers to the market

- Lack of technology suitable for mining operations
- Low awareness of capabilities of robotic technologies in the application area
- Concerns about reliability and performance issues
- Frequent changes in the law on mining
- All sub-assemblies for mining robots should be very robust against mechanical exposures (reinforced enclosures, higher ingress protection IP>54, immunity for shocks and vibrations)
- If robots are used in explosive zones all sub-assemblies have to be made in explosion-proof techniques (flame-proof enclosures, intrinsic safety, increased safety etc.). The explosion-proof protections have big influence for weight and dimensions so the limit the functional achievements of robots.
- All machines utilized in European Union have to fulfil the requirements of EU directives like 2006/42/EC (machinery directive) 2004/108/EC (electromagnetic compatibility directive) and for explosive zones 94/9/EC (ATEX). To fulfil all the requirements is difficult, time consuming and expensive.

2.6.4.4 Key Market data

Mining and raw materials

- Example Poland: Cooper Industry KGHM in year 2014 made €600M net profit
- Huge potential for value creation within EU and reduced import dependencies

Equipment and Investments

- Market research: Around $100bn a year for mining equipment market size at annual growth rates of 4-6%
- Example Chile: Big investments, from 2012 to 2020 about $60bn investments (Engineering and Mining Journal March 2012)

2.6.4.5 Relationship to other Domains and Markets

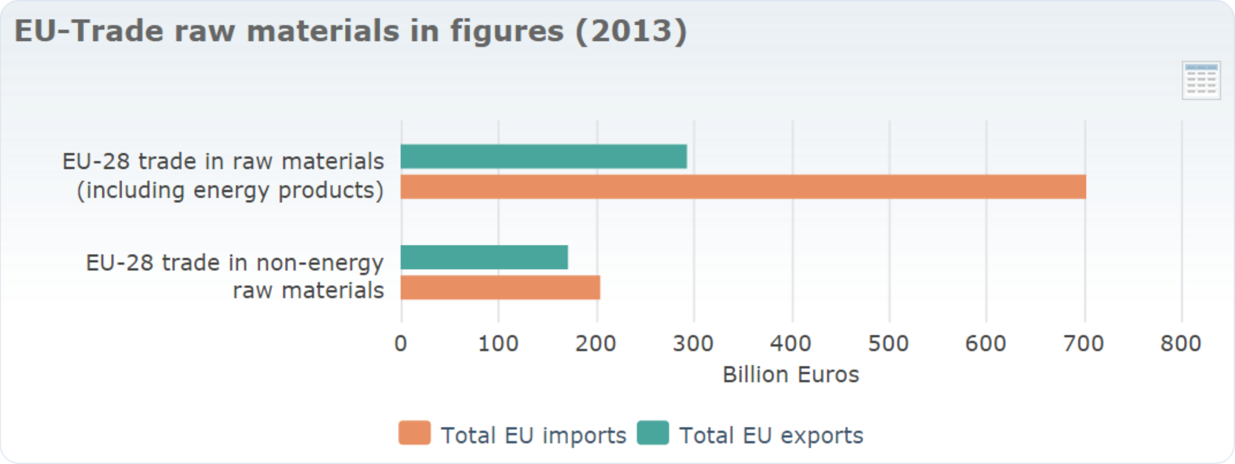
- Maritime robotics - Deep sea mining
- Commercial domain - Inspection and Maintenance. The envisioned hazardous harsh and dirty environments here of great help (safety, environmental, economic impacts)
- Transport domain: transportation of spare parts (e.g. picks) needed: autonomous vehicles. Also storage and handling systems
- Agricultural domain: also ruggedized components needed
- Emergency/Rescue robotics (firefighting etc.): Also sensors/perception in harsh conditions needed
- Suppliers of highly advanced products and technologies like cameras, microcontrollers, integrated circuits, sensors, optical fibres, caterpillars, bearings, actuators, electrical motors, gears, breaks and etc. can co-operate during designing mining robots
- Research centres and notified bodies offer tests and certification for complying of essential requirements of European directives (EMC, IP, vibration, environmental tests etc.)

2.6.4.6 Europe's Place in the Market

Raw materials are the basis of a large number of industrial value chains in the EU. Specific raw materials are needed to make a wide range of industrial goods such as car engines, mobile phones or wind turbines.

The following snapshot is taken from http://ec.europa.eu/trade/policy/accessing-markets/goods-and-services/raw-materials/ and illustrates the importance of the raw materials market within the EU.

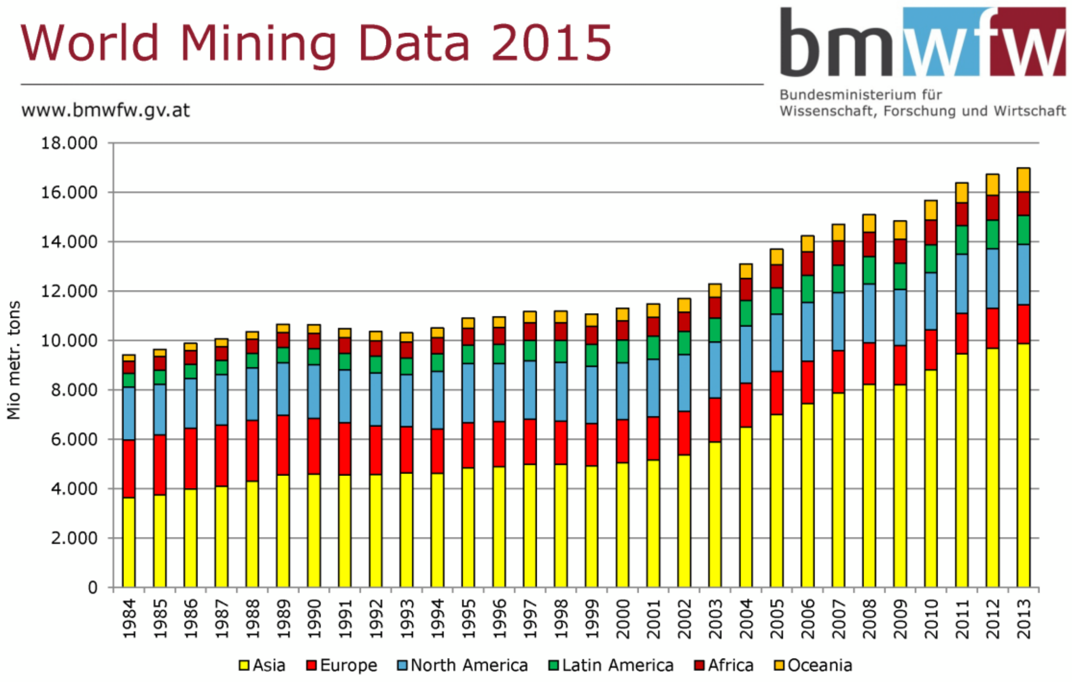
> ***"EU raw materials' industry in a nutshell***
>
> - *A large number of industries use raw materials as inputs, providing a total added value of €1300 billion.*
> - *There are some 30 million people employed in the raw materials' industrial sector.*
> - *A sustainable supply of particular raw materials is of crucial importance for the development of green technologies.*



> *Raw materials play a significant role for the EU trade policy. In concrete terms, the European Commission developed a fully-fledged strategy for raw materials, which was outlined in the 2008 Communication entitled the Raw Materials Initiative. This was revised in February 2011 in a Communication, which further boosted the integration of raw material priorities in EU policies."*

World Mining data

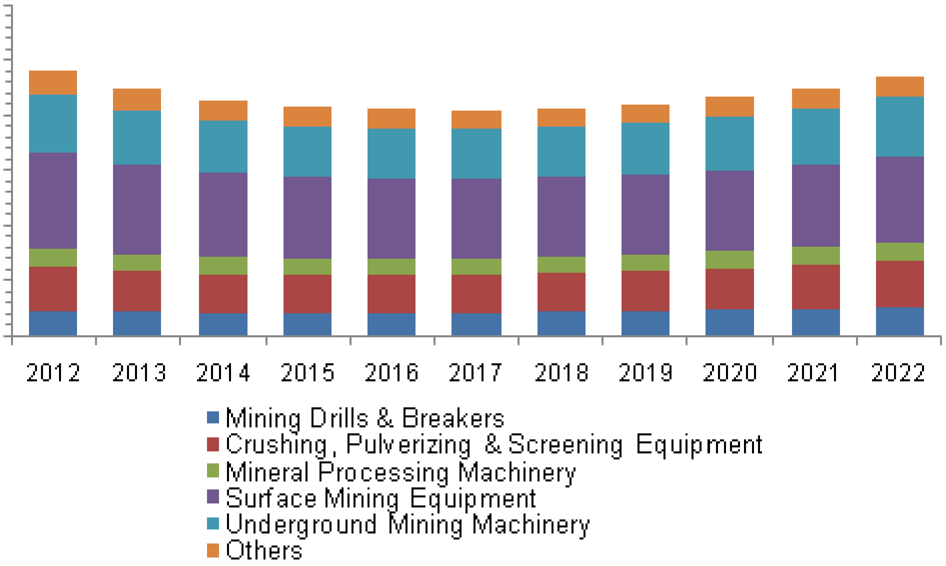
The following provides an overview of the global mining industry.



World mining production 1984 - 2013 by continents
(without construction minerals, in Million metr. t)
Weltbergbauproduktion 1984 - 2013 nach Kontinenten
(ohne Baurohstoffe, in Mio metr. t)

SOURCE: REICHL, C., SCHATZ, M. & G. ZSAK: WORLD MINING DATA 2015

The global mining equipment market size is expected to reach $95.14bn by 2022, growing at a CAGR of 4% from 2015 to 2022. Growing mining activities on a global level are expected to be the key driving force for the market over the next six years.



Europe mining equipment market by product, 2012 – 2022 ($bn)[9]

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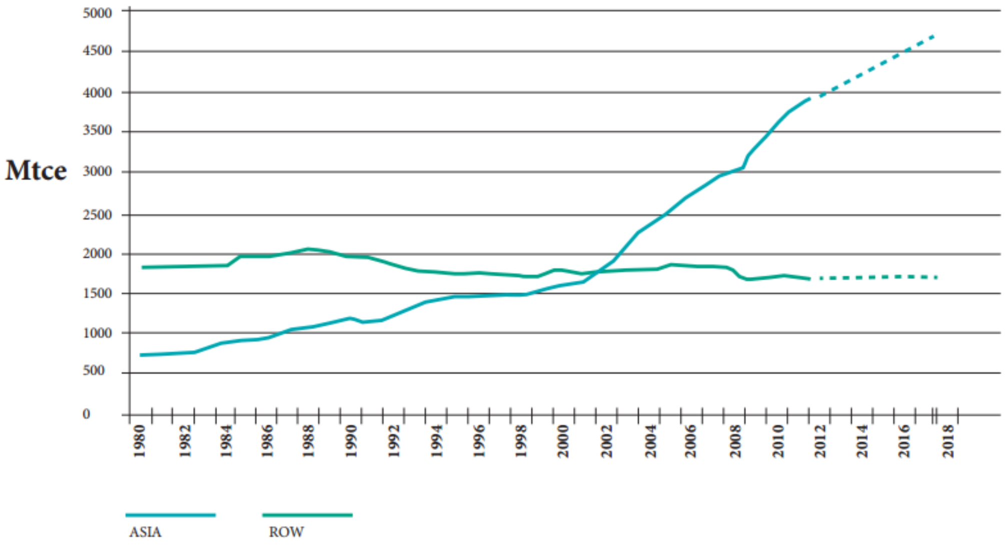
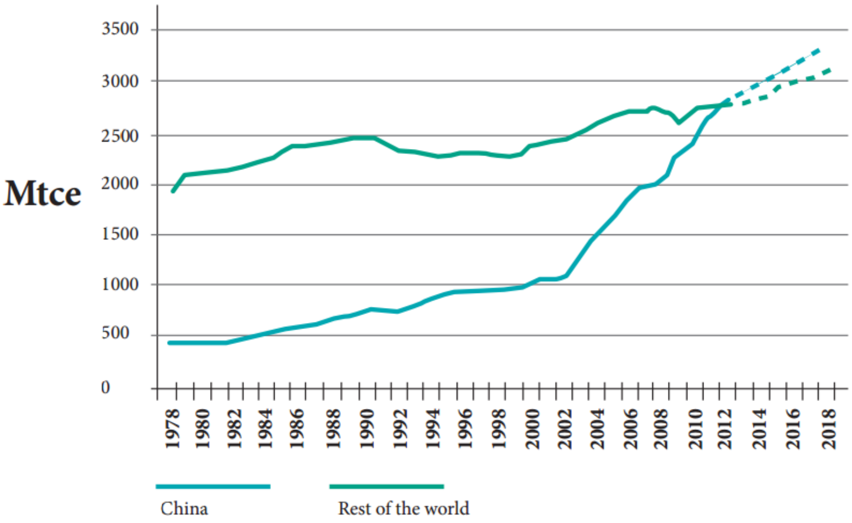
[9] Source: Mining Equipment Market Analysis by Product (Mining Drills & Breakers, Crushing, Pulverizing & Screening Equipment, Mineral Processing Machinery, Surface Mining Equipment, Underground Mining Machinery) By Application And Segment Forecasts To 2022 http://www.grandviewresearch.com/industry-analysis/mining-equipment-industry



The prediction of demand for coal in Asia and Rest Of World (ROW) according to International Energy Agency.



Źródło: Międzynarodowa Agencja Energetyczna

***The prediction of demand for coal in China and Rest Of World (ROW)*[10]**

2.6.4.7 Key Stakeholders

- European Commission and European Society is impacted by market prices, higher health standards, lower environmental impact, higher resource efficiency, job upcycling, aging workforce, lower dependence on imports.
- Manufacturing Industry is impacted by new markets, lower raw material prices.
- Robot solution provides (sensing, control, actuators etc.): New markets, New products, increased competitiveness, ...
- Machine manufacturers: increased market share, increased competitiveness, new products
- KIC Raw Materials
- Euromines - European Association of Mining Industries, Metal Ores & Industrial Minerals

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[10] Source: http://wei.org.pl/files/manager/file-a78b71f6478f8bebaf414ff4582f6dc2.pdf

- in Sweden the Strategic innovation programme for the Swedish Mining and Metal producing Industry, STRIM (2013-2016), whose aim is to contribute to sustainable growth and strengthen the Swedish mining and metal extraction industry.
- in Finland the Green Mining programme (2011-2016), with its main objective to make Finland a global leader of sustainable mineral industry by 2020, with two main thematic areas: intelligent and minimum-impact mines and new mineral resources.
- Assumptions for the Action Plan in the field of security of Polish non-energy raw materials has been approved by the Ministry of Economy in September 2015 http://www.mg.gov.pl/node/23408

2.6.4.8 Current Key Projects

Project Acronym	Full Name and Target
Real-Time Mining	Full Name: “Real-time optimization of extraction and the logistic process in highly complex geological and selective mining settings” Target: Enabling real-time information exchange and availability across the mining value chain. This involves usage of novel sensor technology, data processing and data exchange for material characterization and positioning applications. (EU funding)
UPNS4D+	Full Name: “Underground 4D+Positioning, Navigation and Mapping System for Highly Selective, Efficient and Highly-secure Exploitation of Important Resources” (National funding (BMBF)) Target: Development of a system that is able to generate high quality data to enable efficient and selective mining and autonomous vehicles for the extraction of critical resources.
CuBR	Full Name: support for research and development work for industry, non-ferrous metals. Target: The main aim is to take joint efforts to develop and implement innovative technologies, equipment, materials and products in order to increase the competitiveness of the Polish industry non-ferrous metals as a participant in the global market and the global economy, which in turn will contribute to achieving global leadership by Polish industry non-ferrous metals, especially in the production of copper.
MPI	Full Name: Mobile Inspection Platform. MPI is a mining robot for inspection of potentially explosive atmospheres of hard coal mines. It may be a scout and a support for mining rescue teams. It has double explosion-proof protective techniques in compliance with the IEC 60079 series and in order to achieve M1 category according to EN 50303. The MPI model was designed by the Institute of Innovative Technologies EMAG and the Industrial Research Institute for Automation and Measurements PIAP from Poland and financed by national budget.

Also related projects:

ARGOS Challenge by Total

2.6.4.9 European Products

Europe: Good market share, but under pressure from China and USA. For instance, Chinese company Tangshan Kaicheng Electronic estimates its production of hard coal mining robots for 1800 pieces per year. Also Sandia National Laboratories (USA) sold the licence for production of the Gemini-Scout mining rescue robot to Black-I Robotics from Boston.

European products: offer a more integrated approach, other markets often use more fragmented designs.

Some products employ robotic technologies. Mostly these work in highly static or predictive environments (LHDs, drill rigs, locomotives). A higher degree of robotic technology usage is generally beneficial

Drill rigs: Sandvik, Atlas Copco, Minemaster,

Extractive machinery (continuous miners, shearer loaders): Famur, Sandvik, Eickhoff

Transportation vehicles (large scale dump trucks, LHDs, locomotives, haul trucks): Liebherr, Famur, GHH, KGHM Zanam,

Shaft sinking machinery: Herrenknecht, Kopex PBSz.

Belt Conveyor systems: KGHM Zanam, Kopex.

Crushers: KGHM Zanam, Minemaster, Fugor.

2.6.4.10 Key Technology Targets

Mechanical Mining of Hard Rock

The majority of technological operations in the mining industry is related to mining and crushing hard rock during deposits development, extraction and processing. The tools used and their development directly affects the speed of these operations. One of the primary goals of R&D&I should be to increase machinery life time though smart sensing and control that can optimize tool use over time in extreme conditions. It is expected that this will also impact on the development of mine recue systems able to effectively clear cluttered roadways and operate in difficult conditions occurring after a mining disaster i.e. high dust and temperature.

Safety and Self-service

Development of standard safety systems compliant with the requirements for machines operating in explosive zones. Unification of safety systems and the development of modular standards will improve opportunities for devices to be integrated into machines designed for radically different operations.

Implementation of autonomous machines also requires a level of self diagnosis in order to maintain efficient and safe operation. Possible fault or damage must be detected efficiently and quickly in order to protect the machine and the environment against an unspecified condition caused by a failure.

Navigation

A primary R&D&I objective is to develop navigation systems without the need for a localization infrastructure and that can adapt to the changing space within a mine as the process of extraction continues and machinery is brought into use during different parts of the mining process. Such systems will also need to integrate into the existing machinery used within mining and be tolerant to a harsh environment.

2.6.5. Sub-Domain: Construction Robotics

2.6.5.1 Sub-Domain Overview

Construction and demolition, sub-domain of the commercial domain, has so far seen minimal use of robotic technology. Yet construction and related markets constitute a significant share of the European and world-wide economy. Widespread robotics in this domain would significantly reduce time to completion, waste and need for rework. It would lift health and safety standards as well as upskill and futureproof the workforce, creating added value and attractive jobs. Robotics are also key to meeting the demand for affordable, sustainable and individualised housing and infrastructure.

Currently the greatest levels of automation are highest in the production of construction material and construction of civil infrastructure. The lowest levels can be found in on-site construction of buildings. Introduction of robots into construction is hindered by the size and weight of parts involved, the flexibility requirements for efficient use in individualised buildings, the challenging environment of construction sites and weight limits inside of buildings. Low value parts/materials, limited standardisation in scale and region combined with high price/risk projects limit the ability of construction companies to invest in robotics.

Novel business models and end user driven applications also need to be developed. Step changes towards dependable, configurable systems with manipulation abilities suited for construction tasks are needed to bring robotics from prefabrication into the construction site. Existing robotic technology levels are not fully sufficient for application in this domain. Integrated robotic systems with novel kinematics are required. They need to handle the complex environment and weather conditions of the sites and provide flexibility with high payloads in reduced in-door spaces.

2.6.5.2 Current and Future Opportunity

Current

Existing robot technology is well suited for further automation in pre-fabrication and inspection in principle. Applications relevant to industry/end-users will lead to the industry engagement needed for widespread disruption.

Commercial availability of mobile robotic platforms with powerful sensor systems makes robotic production and inspection possible at the scales relevant to construction. Developments in Building Information Management (BIM) may be partially suited for programming of robotic systems. Full exploitation will require BIM models that include process information models such as they already exist for the production of cars, ships and aircraft. Task primitives can be developed on existing hardware for common construction and demolition processes.

Future

Novel robot platforms for construction sites as well as the automation of existing construction machinery will bring the advantages of automation (reliability, efficiency, safety) to the construction site. Robotic support of human workers and human-robot-collaboration/interaction will increase efficiency and make construction a safer, healthier more attractive job.

Robots will allow for a more complete digitisation of the construction process, feeding up to date information from the construction site back into the digital models. Extending digital models of the final product to include modelling of the construction processes will ease robotic introduction. Construction robotics will transform the design of buildings and could potentially lead to increased reuse instead of recycling of construction materials.

Faster, adaptive and parametric programming methods with increased decisional autonomy in the robot systems will lead to robots becoming attractive at lot size one. Reduction of waste and rework as well as shorter times to completion will alter the risk model of the construction industry. This will motivate introduction of robot technology and severely disrupt existing business models.

Moreover, construction industry has one of the highest accident rates compared with other traditional sectors. Massive robotisation of construction will not only will substitute low-skill and dangerous jobs but also create a high-quality jobs with novel opportunities (Economic Report of President of the USA, 2016) while drastically reducing accidents.

New robot kinematics, platforms and systems will impact the market along the entire value chain. From providers of robust sensors and actuators through machine manufacturers to a new field of robotic integrators and operators market opportunity will be created. Robotic construction and demolition will also lead to new, robot-orientated design of our built environment.

2.6.5.3 Key Market Data

Construction constitutes 3 million businesses, 8.8% GDP and 28.7% of industrial employment (6.5% of total) in the EU28. Of the 3 million businesses 95% have less than 20 workers. Construction accounts for 45.1% of gross fixed capital formation in the EU28, meaning that roughly every second Euro is spent in construction. (FIEC Key figures)

In 2014 the building industry was the largest employer in Germany, surpassing both automotive and chemical industry.

Demographic changes, increased urbanisation and a move towards more a sustainable and energy efficient build environment result in a large demand for construction, demolition and refurbishment. Europe won’t be able to fulfil this demand without major increases in automation within this domain.

The construction equipment industry in Europe has an annual turnover of 26 billion Euros and accounts for 5% of the EUs engineering output. The EU construction equipment industry accounts for roughly 20% of the global market. (CECE Economic Report)

In 2013 European construction companies had an international turnover of 163 billion Euros, which constitutes over 50% of the global construction market.

In 2014 the European construction equipment industry covered 20% of the global market.

2.6.5.4 Relationship to other Domains and Markets

Demands regarding safety and reliability of robot systems in harsh, dynamic environments is an issue also facing mining, forestry, agriculture, SAR, inspection and space robotics.

Construction robotics is also closely linked to the topic of smart cities and healthcare since both involve the built environment to a large degree. Smart cities will be built for but also with robots. Robotic transportation as well as in home assistance will profit from holistic thinking that encompasses the life cycle of our buildings and how they interact with robots.

Efficient programming at lot size one is also an issue in manufacturing, but manufacturing has much larger degrees of standardisation and digital product representation.

What sets construction robotics apart is the combination of large dynamic workspaces, with heavy parts in highly individualised products. The much larger tolerances in construction projects necessitate more frequent adjustments with shorter lead times compared to manufacturing. While agriculture and mining operate in similar environments, they are dominated by a few long and continuous tasks (e.g. harvesting a field, transporting soil to a fill) whereas construction has shorter, more varied tasks.

2.6.5.5 Key System Ability Targets

Robotic systems capable of operating semi-autonomously on construction sites require increased dependability and decisional autonomy in harsh, dynamic environments. Existing systems regarding motion and manipulation ability need to be brought to higher TRL for applications relevant to construction. Higher power/reach to weight ratios of robot platforms are needed to overcome low floor loads and narrow entrances. Agility of robotic systems must be improved by means of novel tailored kinematics but also by exploiting the structural dynamics of large mechanical systems. Greater decisional autonomy in task planning and process adaptation is needed for robots to be effective on-site and at lot size one.

Currently TRL-9 implementations are very sparse. Most of the required ability levels are needed to allow robust, safe and easy-to-use operation. While certain target levels have been reached elsewhere they must still be implemented for the domain at hand.

Ability	Domain Need	MAR Level
Configurability	easy enough to be efficient in individualised production	Level 2 - User Run-time Configuration
Adaptability		
Interaction Ability		
Dependability	reliable and safe operation in semi-controlled environments	Level 2 - Fail safe
Motion Ability	variable and controllable stiffness in constrained motions; smooth transition from free to constrained motions	Level 2 – Reactive motions
Manipulation Ability – Handling Ability		Level 8 - Unknown Object Handling
Perception Ability	detecting, recognizing and localizing individual parts and objects; fast robot-sensor calibration and self-calibration during setup	Level 3 – Multiple parameter perception to Level 6 - Object identification
Perception Ability – Object Recognition	object detection and recognition based on programming-by-showing and model based recognition	Level 4 - Object recognition - one of many to Level 5 - Parameterised object recognition
Perception Ability – Scene Perception	detect objects from a group of partially organised objects	Level 4 - Multiple object detection
Perception Ability – Self Localisation		Level 4 - Feature based Location to Level 5 - Mapped location
Decisional Autonomy	robot makes decisions based on basic perceptions and user input; chooses its behaviour from predefined alternatives e.g. for robust behaviour against environment disturbances.	Level 2 - Basic decisional autonomy

Ability	Domain Need	MAR Level
Cognitive Ability – Action Ability	react on sensor based events in a predefined way	Level 2 - Decision based action to Level 3 - Sense driven action
Cognitive Ability – Interpretive Ability	observe robot's own work progress	Level 3 - Function projection
Cognitive Ability – Acquired Knowledge	acquire (sensor based) knowledge about targets objects and other objects in the environment	Level 3 - Property knowledge
Cognitive Ability – Reasoning	detect objects and reason about its quality or completeness	Level 4 - Reasoning with conflicts
Cognitive Ability – Object Interaction	manipulate and place object appropriately depending on its state	Level 3 - Object placement
Cognitive Ability – Human Interaction	utilize user commands appropriate to the task context	Level 2 - Task context interaction

2.6.5.6 Key Technology Targets

Novel programming approaches are needed allowing for fast, on-site configuration. Sensor information needs to be handled robustly in dynamic environments to allow dependable semi-autonomous operation of construction equipment. Semi-automatic generation of process models from product models will enable efficient robotic use at lot size one and autonomous process monitoring on-site. Advanced control concepts are required for robust adaptive control of construction robots. Robot autonomy for inspection of buildings and civil infrastructure must be improved.

Human Robot Interaction

Existing construction workers will need to operate new autonomous systems placing emphasis on ease of use, efficient and intuitive user interface development. Operators with different skill levels must be accommodated whilst maintaining safe operation within specified guidelines and construction standards and guidelines.

Autonomous operation in dynamic and unstructured environments requires new strategies and standards for safe human- machine collaborative working.

Perception

Perception tasks in construction require local mapping of environment and position as well as advanced abilities in object recognition and handling. Multi sensor technologies are needed for surface and volumetric measurements, precise localisation and motion control. The perception systems have to support he adaptive path planning and provide environmental awareness and object recognition needed for safe operation in minimally structured, collaborative environments. The systems must operate in harsh operating conditions e.g. high and low temperatures, high humidity, rain, snow, ice, mud and steep gradients.

2.6.6. Sub-Domain: Laboratory Robots

2.6.6.1 Sub-Domain Overview

A great many industries rely on laboratory procedures to obtain information from physical samples. For example, the pharmaceutical industry carries out large numbers of biochemical reactions in the search for new drugs. The information obtained is used to guide decisions, secure intellectual property improving competitiveness, and ultimately save lives. Similar tasks are carried out during diagnostic testing in hospitals and clinics, and in medical research, as well as in industrial research more broadly, for example in quality control and the development of new materials. The testing of food and environmental samples is important to ensure public safety. Robotic technology plays a valuable role in all these industries, saving time, improving the quality and consistency of results, and permitting more thorough examinations and ensuring timely results. In many cases the rate and complexity can resemble those found in manufacturing production lines.

At the heart of the laboratory are the tools that obtain information from physical samples. These include a wide variety of instruments, for example microscopes and other optical readers. These are supported by tools for preparing samples prior to analysis such as centrifuges and chromatography systems. In some cases, the processed sample is also one of the outputs of the laboratory, where such samples are subject to further work such as usage in the field, aging or archiving for later study.

In the context of defining Laboratory Robotics it is important to distinguish between **laboratory automation;** the software and hardware technologies and engineering adaptations that control instruments and improve work flows without human intervention; from **laboratory robotics**, which relates more specifically to the physical manipulation of samples and their containers. The use of advanced robotics in this context is invaluable since entire processes may be required to operate for days at a time with minimal supervision.

2.6.6.2 Current and Future Opportunity

There are a number of areas of future opportunity both in terms of markets and technical advance. Primary markets in Healthcare and Agri-food are likely to further develop as technical advances reduce cost, increase capability and add functionality. In particular future opportunities exist as technology develops to enhance the following areas of functional development:

Reduction in size: Since many laboratory processes arose originally from manual tasks, it is natural that they follow what humans can comfortably handle. As a consequence traditional laboratory robotics has re-used tools from other industry sectors such as automotive manufacturing designed for handling e.g. metal parts.

However the number of samples to be studied has tended to increase, the size of the individual samples has tended to shrink (e.g. from millilitre to microliter, from 96 to 384 to 1536 wells per plate). In part this is because measuring instruments have become more sensitive. In turn this has reduced the usable samples size thereby including those that are more precious where less material is available. As a consequence there is reduced reagent use and the possibility of running more experiments in the same physical laboratory floor area.

There is therefore an opportunity to develop a next generation of laboratory robotics systems which makes use of recent advances in miniaturised electro-mechanical technologies which will be attractive to some user groups. Miniaturised robotics systems able to handle grams of material may also open up new fields of applications.

Advanced **microfluidics** approaches address miniaturisation at the level of single cells but would need to offer new levels of flexibility not currently available. Here there are significant synergies with advances in micro and nano robotics.

Handling of complex solid samples: While laboratory robotics has developed impressive liquid handling capabilities, the management of solid samples is not yet as advanced.

Such samples are challenging because they are heterogeneous (a bone with DNA in the marrow), irregularly shaped (artificial knee joint with potential contamination) or even uncooperative (a live rodent). Indeed the management of experimental animals is a valuable but unpopular task. Advances in compliant robots and 3D vision systems may support the development of such systems.

Laboratory assistant: Traditional gantry robots have proven their usefulness in a wide range of routine tasks. However emerging needs and new technologies demand increased flexibility.

In order to implement newer protocols, easier configuration is required. Detecting a change in a situation requires improved perception capabilities. Dealing with unexpected situations requires greater adaptability; while utilising a human in the loop requires better interaction capabilities, and improving the off-loading of repetitive and stressful tasks to the robot with a minimum of interaction and configuration.

A laboratory assistant able to use other laboratory tools (pipettes, centrifuges, balances, incubator, hot plates, etc.) and communicate with them and the user would be a powerful asset. Developing an ontology and standards for interoperability could help to facilitate plug-and-play architecture or self-configuration during run-time. Safe co-operation with humans is a pre-requisite for such a “co-bot” system.

Smart laboratory: While islands of automation involving robots and laboratory equipment operate effectively, integration with the rest of the workflow is less well developed. This topic is already being actively pursued by several players, moving beyond barcodes and ELN (Electronic Lab Notebooks), cloud-based approaches are appearing. However there are still opportunities to better utilise ideas from the Internet of Things, including the development of suitable business models and smart tools and equipment.

2.6.6.3 Key Market Data

Laboratory automation and robotics play an important role as an enabling technology for a number of industries as noted below based on estimated obtained from publicly available reports.

End user market segment	Drivers and role of robotics	size
Pharmaceutical of which Pharmaceutical R&D	New pharmaceutical products, increased productivity and reduce time to market	$500bn $50bn
Clinical testing	Reduce cost, improve throughput	$60bn
In vitro Diagnostics	Quality of results, throughput for diverse samples	$35bn
Forensic testing	Improves traceability & reduced error rate	$20bn
Food testing	Reduce cost, increase coverage of tests	$11bn
Supplier market segment		
Laboratory instruments of which laboratory robotics incl. consumables	More complex procedures, increased quality of results, reproducibility	$40bn $2-3bn

In this breakdown scientific research is not presented as a specific sector, although some reports list academic, government, clinical and private research as separate end-user categories. To give an idea of the number of installations, the number of biological laboratories at the highest safety level (BL4) is about 50 worldwide; the next BL3 level counts some 1350 in the USA alone. Likewise, the number of large hospital worldwide is around 1000, with some 10 000 smaller ones.

Socio-economic trends in the end-user markets, such as aging populations as well as enhanced focus on food safety and security; high value manufacturing and globalisation of research and improvement of tools such as genomics, all suggest strong demand in the coming years, estimated at 4-6% pa.

Increased use of analysis at the point of care can be achieved with greater levels of autonomy in laboratory processes, in addition the delivery of personalised medicine can be speeded up with laboratory robotics and the maintenance of food security achieved through better monitoring of plant disease and food contamination. These are likely to become significant markets for laboratory robotics.

2.6.6.4 Relationship to other Domains and Markets

Laboratory robotics has extensive application in Healthcare particularly in analysis, sample assessment, in the pharmaceutical industry and in the control of contamination. In the Agri-Food sector the use of laboratory robotics can help to provide both expertise on the handling of liquids and small precise quantities as well as in assessing food quality and providing quality assurance. In industrial applications laboratory robotics can provide assay services and contamination assessment both of parts and factory environments.

2.6.6.5 Europe’s Place in the Market

Laboratory robotics is already a substantial economic activity within Europe. European companies engage in system integration, OEM supply of components and complete subsystems such as arm subsystems, camera and detectors, software, etc. though some of these are also supplied to related industries (automotive, packaging, electronics, semiconductor). In addition there are the many suppliers of consumables and reagent kits these are a critically important part of the business ecosystem.

2.6.6.6 Key Stakeholders

European companies are in a majority in this sector, both in number and also in market share. Europe is therefore competitive and world leading in this sector. Europe also hosts several leading clusters, notably in Switzerland as well as UK and Finland for liquid handling; optics in the Netherlands and others. However the link to the research base is not so strong. Among end users, the EU has recognised strengths in the pharmaceuticals, diagnostics, food and forensics sectors.

2.6.6.7 Current Key Projects

HYLAM ECHORD experiment for handling of eggs for vaccine production

LISA autonomous mobile robot to transfer samples with the laboratory

AccMet: accelerated metallurgy project using high throughput techniques in materials science

UNICELLSYS (systems biology of the control of cell growth) developed the robotic scientist

'Big Mechanism' DARPA project on robot scientist to explore cancer pathways

Evobliss FET project developing novel robotics to support experiments in artifical evolution

AdaLab (Adaptive Automated Scientific Laboratory) to develop and evaluate a framework for automated knowledge discovery and experiment execution by robot scientists - funded under CHIST-ERA

2.6.7. Key System Ability Targets for the Commercial Domain

2.6.7.1 Configurability

Possibility to configure a robotic system to suit varying geometries of typical environments	Level 2 – User run time configuration
Possibility to integrate various applications within a system	Level 4 – Autonomous configuration

There are different task in the development and lifetime of a mine and different regulations for different mining companies and legislations.

Configurability to different mines types, company policies and/or legislations	Level 0 – static configuration
Configurability for different tasks (roadway development, extraction etc.)	Level 2 – User run-time configuration

2.6.7.2 Adaptability

Real time real-world learning	Adaptability: Level 4 - Task adaptation
Capabilities to allow the system to adapt paths or actions to the current situation (geometrical, environmental, etc.)	
Adaption to changing environmental operating conditions (e.g. in terms of sensor fusion, adaption to achievable communication bandwidth etc.)	Level 3 – Multiple task adaption
Adaption to targets given by the user, e.g. cut off grades for extractive machinery	Level 3 – Multiple task adaption
Adaption to breakdowns, wear and problems	Level 4 - Communicated task adaption
Human remote controlled mining in dangerous zones	Human-Robot Interaction: Level 7 – Tele-Presence
Cooperation between robots to achieve a goal e.g. extractive and transportation robot cooperation	Robot-Robot Interaction Level 4 – Team coordination
Safe human interaction with large machines	Human-Robot Interaction Safety Level 4/5- Work space detection/Dynamic User detection

2.6.7.3 Interaction Ability

Cooperative behaviour limited to specific	Cognitive Human Interaction: Level 2 Task

tasks;	context interaction.
Robot and human-robot teams, full cooperative behaviour	Cognitive Human Interaction: Level 3 Object and location interaction combined with Human robot Interaction Level 4-6 and Robot robot interaction Level 4-5.
Human-robot interaction: Laboratory robotic systems may be operated tele-operated, pre-programmed and supervised	Interaction Level 3 - position selection by user with a controlled environment over moderate timescales (hours-days) with trained users
Robot-robot interaction:	Interaction Level 2 - communication of task status
Human-robot safety levels:	Interaction Level 2 – safety using enclosure and safety interlocks Interaction Level 3 – user detection in mobile platforms

2.6.7.4 Dependability

All-weather missions	Dependability Levels 4-5; Perception Ability target “Immunity to Natural Variations”
Long Term (Permanent) Deployment	Dependability Levels 4-5
Long Range Deployment	Dependability Levels 4-6
Missions in explosive environments	
Safety guarantee under all operating conditions	Level 2 – Fails Safe, Certification and Classification for critical systems highly desirable
Highly automated systems working in dangerous areas should be able to move out of these zone prior to failures	Level 4 – Graceful Degradation

2.6.7.5 Motion Ability

High speed and agile autonomous driving on uneven and sloping terrains All terrain high speed and dexterous autonomous driving Driving in narrow and confined spaces with the possibility to circumnavigate obstacles or to climb over obstacles	Constrained Motion: Level 5 - Dynamic motion
Track and path planning through open pit and	Unconstrained Motion Level 4 – Position

underground mines	constrained path motion
Following a track while interacting with the environment (e.g. during drilling/cutting/bolting)	Unconstrained Motion Level 5 – Force constrained path motion
Manoeuvrability over difficult terrain	Constrained Motion Level 4 – Multiple soft medium motion
Mobility of arm or carriage:	Mobility Level 4 – position constrained motion taking in account known obstacles and no-go regions Mobility level 5 – some controlled force motion Mobility level 6 – parameterised motion to maintain eg orientation or force

2.6.7.6 Manipulation Ability

Collaborative robot-robot and human-robot manipulation (e.g., load sharing)	Human Robot Interaction: Level 2 Direct physical interaction Robot robot interaction: Level 5 Team coordination
Mobile manipulation on uneven sloping terrain and with floating robots	Constrained Motion: Level 5 Dynamic motion combined with Location perception: Level 5 Object coupled location combined with Decisional autonomy: Level 8 Dynamic autonomy.
Manipulation of objects:	Manipulation Level 5 – location unknown pick and place Mobility level 6 – generic pick and place, for a give class of object such as a sample tube.

2.6.7.7 Perception Ability

Coarse scene classification; update of the model based on observations	Scene perception: Level 4 Multiple object detection combined with Object recognition: Level 4 Object recognition - one of many.
Operation possible in most weather and environmental conditions;	Object Recognition Parameter: Environment Perception Ability Target: Immunity to natural variations.
Detailed scene classification & understanding; build high-level abstract information.	Scene perception: Level 5-6 combined with Object recognition: Level 6-9.

Cooperative Mapping (breakthrough in communications required)	Cognitive Action Ability: Level 5 Knowledge driven action combined with Robot robot interaction: Level 5 Team coordination.
Reliable perception in harsh environmental conditions	Immunity to natural variations
Accurate self-localization in the mine	Self Location Perception Level 5/6 – Mapped Location/Spatial Occupancy
Localization of humans and other machinery or infrastructure	Scene perception Level 4 – Multiple Object Detection Tracking Ability Level 3 – Dynamic Object Tracking
Analysis of extracted material	Recognition Level 5 – Parameterised Object Recognition
Ability to identify objects and patterns, e.g. vessels, caps, liquid levels, distinguish different types of objects.	Perception Ability: Level 5-7
Ability to measure distances between different objects and locates and guides them in 3D space.	Perception Ability: Level 5-8.

2.6.7.8 Decisional Autonomy

Pre-planned missions; medium complexity tasks; limited human supervision; integrated planning among heterogeneous fleets of manned and unmanned vehicles	Decisional Autonomy: Level 4 - Simple autonomy.
Re-configurability of robot task depending on the changed environmental conditions	Decisional Autonomy : Level 6 - Constrained task autonomy.
Intelligent “Motivation Dynamics” with temporarily changing priorities (situation-specific priorities)	Decisional Autonomy: Level 9 - Mission oriented autonomy
High complexity tasks performed autonomously and in cooperation; collective behaviour; no human in the loop (human monitoring only); opportunistic mission planning capability, goal-based missions	Decisional Autonomy: Level 9 - Mission oriented autonomy combined with Cognitive Action Ability: Level 8-9
Re-configurability of more robots working cooperatively, reassignment of task domain/goals between robot	Robot Robot interaction Level 5-6, combined with Decisional Autonomy: Level 9 - Mission oriented autonomy combined with Cognitive Action Ability: Level 8-9

Automated wear-part exchange and self-repair or cooperative repair	Level 8 – Multiple Task Autonomy
Robust and safe navigation and path planning in difficult environments	Level 9 – Dynamic Autonomy

2.6.7.9 Cognitive Ability

Interpretation of scenarios of limited complexity taking into account different inputs.	
Interactive prediction of dynamics systems.	Parameter Adaptability: Level 3 Multiple parameter adaptation.
Wide comprehension of scenarios taking into account different/conflicting inputs;	Reasoning Ability: Level 4 Reasoning with conflicts.
Self-diagnosis and understanding of effects of component failures (enabling to drive outside of dangerous zone for repair)	Interpretive Ability Level 7 – Property interpretation
Ability to learn about the environment to optimise operation parameters and provide information for downstream processes	Acquired Knowledge Levels 4/8/11

2.6.8. Key Technology Targets for the Commercial Domain.

2.6.8.1 Systems Development

System Design

- Development of standard architectures.
- Design tools for the integration of robots in wider pre-existing systems.
- Design of common platforms.
- Design for harsh environments and/or explosive atmospheres.

Long Term

- Standardised and certified platforms and development tool chains for mission critical and safety critical operations.
- Standard interfaces and systems for the deployment and retrieval of remote vehicles.

Systems Integration

- Development of interoperability standards for robotics components.
- Development of data storage and exchange formats.
- Development of system interoperability standards for robot and human teams.
- Self-configurability of off-the shelf robotics components.
- Plug and Play platforms to facilitate upgrading of components and capability.
- Integration with process management and optimisation systems.

Modelling and Knowledge Engineering

- Mechanisms for scene analysis and knowledge acquisition based on the perception of simple scenarios
- Mechanisms for scene analysis and knowledge acquisition based on distributed perception in teams
- Development of methods tools and techniques, for knowledge representation in domains of low and medium complexity
- Development of methods tools and techniques, for knowledge representation in in complex domains and scenarios

2.6.8.2 Mechatronics

Mechanical Systems

- Appropriate miniaturisation of current capable systems leading to reduced equipment and deployment costs,
- Commoditisation of common parts and systems,
- Simple and reliable systems for the deployment and retrieval of marine robots.
- Design of energy efficient autonomous robots for specific environments
- Multi-functional/multi-task and flexible end-effectors.
- Design for harsh environments and/or explosive atmospheres.

Sensors

- Development of more robust sensors for navigation, particularly in hazardous and dirty environments.
- Development of sensors for the reliable detection of people
- Acoustic sensors for marine remote sensing and map building applications.
- Specific new low maintenance and low cost chemical sensing mechanisms to enable the use of robot systems for environmental protection tasks.
- Integration of sensors and methods used for non-destructive testing and evaluation into the overall system and into the robotic control in particular.
- Design for harsh environments and/or explosive atmospheres.
- Sensors for task specific materials or hazards.
- Sensors for mechanical system monitoring able to detect wear and degrading performance.

Actuators

- Energy efficient propulsion systems in multiple environments.
- Sun sea propulsion systems.

Power Supply and Management

- High-density energy systems.
- Energy management systems.
- Fuel cells for sub sea applications.
- Power systems for hazardous environments.

Communications

- Ad hoc robust (broad-band and out of line of sight) communication through different media, technologies and capabilities (i.e. by means of fleets of robots).
- Robust communication & localisation systems for underwater applications.

- Robust and safety critical communications for hazardous and electrically noisy environments.
- Quality of Service (QoS). Performance and knowledge about performance of communication networks.

Materials

- Advanced composites for vehicle hull and container fabrication.
- New materials for deep water and water column exploration (such as variable forms for hydrodynamic task adaptation, reduced weight and lower deployment costs).

Control

- Integrated vehicle-arm control and vehicle stabilisation for mobile manipulation on uneven sloping terrains and floating robots.
- High speed autonomous off-road path planning/following and obstacle avoidance.
- Cooperative control of multiple heterogeneous platforms, including air, surface, and marine robots.
- Low cost, medium performance, integrated sensors for accurate guidance & control.
- Control processes that adapt to wear and reduced capability.

2.6.8.3 Human Computer Interaction

Human Machine Interface

- Augmented reality tool for the remote operation and interaction with unmanned vehicles. Particularly large scale machines operating in hazardous environments including extending the field of view.
- Inclusion of external communication with other human and autonomous operators into an augmented reality.
- Systems for seamless mission specification and mission programming.
- Systems for mission follow-up and post-mission analysis.
- Tools an ergonomics for reducing remote-operator workload and stress.
- Natural human machine interface methods.

2.6.8.4 Perception

Sensing

- Scene interpretation fusing different sensor modalities; multi robot perception in heterogeneous teams (both in terms of platform and sensors).
- Video and acoustic imaging data fusion for underwater applications.
- Distributed multi sensor fusion; Sensing/Control/Planning integration (i.e., plan to sense to control).
- Scene interpretation with reduced quality data due to, e.g., harsh environments (rain, dust, ice, etc.).
- Interpretation of sensor data for mechanical system reliability, prediction of failure and monitoring of wear.

2.6.8.5 Navigation

Mapping

- Large scale mapping in dynamic environments, capable of handling vast areas of operation and supporting navigation for extended periods of time.
- Sea bottom/sub bottom mapping.

- All weather map management and update

Localisation

- Precise localisation in difficult environments such as indoor GNSS denied scenarios or underwater will allow the use of systems in a wider variety of applications.
- Cooperative localisation/geo localisation with robot teams.
- Subsea localization

Motion Planning

- Planning with kinematics and environmental constraints
- Real-time planning with kino-dynamics and possibly partial unknown environmental constraints
- Systems for cooperative, multiple vehicle motion planning in the presence of environmental disturbance and obstacles.

2.6.8.6 Cognition

Cognitive Architectures

- Development of architectures and models for representing and implementing cognitive tasks of low to medium complexity
- Development of Architectures and models for representing and implementing cognitive tasks of high complexity
- Development of methods, tools and techniques for modelling cognitive tasks of low to medium complexity
- Development of methods, tools and techniques for modelling cognitive tasks of high complexity
- Design guidelines for developing autonomous systems.

Learning Development and Adaptation

- Adaptation with respect to changing environmental conditions
- Adaptation to large vehicle parameter variations

Knowledge Representation and Reasoning

- Development of methods, tools and techniques for knowledge based reasoning in domains of low to medium complexity
- Development of methods, tools and techniques for knowledge based reasoning in complex domains and scenarios
- Intelligent algorithms for reasoning based on distributed sensing.

Action Planning

- Advanced systems for multiple vehicle cooperative task and mission planning
- Highly abstracted mission definition and mission/task planning algorithms for interaction and operation with untrained users;
- Systems for operator-assisted manipulation
- Systems for autonomous intervention in underwater structures
- Systems for cooperative grasping and transportation of heavy objects.

Natural Interaction

- Cooperation and interaction among air, ground, surface, and underwater vehicles
- Systems for human-robot interaction and mixed team operations

2.6.9. Key Market Data

The commercial domain is very broad based and this makes it difficult to assess total market value. Limited information is available for certain parts of this domain and this is detailed below.

For the inspection of industrial plant significant costs are involved. The most expensive aspect of an inspection is taking the asset off-line and the related lost production. The required off-line time may range between one day and several weeks. For a refinery typical costs associated with this down-time may reach over $10m per day in lost production. In a practical real-world exercise it was estimated that 80% of the time spent in the context of an internal pressure vessel inspection was related solely to human entry of the vessel. Also in terms of human safety, from time to time accidents occur that are related to human entry of confined spaces and the erection of scaffolding.

As similar opportunity arises in the inspection of power generation plants where for example, the inspection of many plants can only be performed when the plant or critical subsets are stopped. In a 300 MW power plant the deduction of the outage gains is about €750k per day.

It is clear that robotics technology could have a major impact on these figures warranting significant investment in R&D&I.

2.6.10. Relationship to other markets

There are strong links to the system deployed in the Civil domain and the Agricultural domain and it is reasonable to expect common platforms and modules to be developed for both markets.

2.6.11. Europe’s Place in the Market

Europe has significant investment in the oil and gas sectors and a history of using robotics technology in inspection tasks.

Europe has invested in R&D&I, particularly in marine robotics and is well placed to exploit the global market.

There are significant opportunities in the mining and mineral sub-domain and in the construction sub-domain where robotics is at a very early adoption stage.

2.6.12. Key Stakeholders

All of the Commercial sub-domains are related to strong existing industries with significant presence across Europe. Critical to the development of this sector is the engagement of these industries in addressing R&D&I to enable the benefits of Robotics Technology within their respective industries.

Within each of these industries are multiple tiers of producers and service providers and each layer in this structure will need to engage with the opportunity.

In many cases regulatory bodies are also significant stakeholders in that safety legislation and quality standards are often limited by technical capability.

In some sectors there are embedded methods with a low incentive for change, the step change impact of robotics technology will be highly disruptive and is likely to create significant change and opportunity.

2.7 Logistics and Transport

2.7.1. Domain overview

The domain of logistics and transport encompasses all the procedures, methods and processes involved in the movement of people, raw materials and goods along the supply chain and through the transport system.

Transport: autonomy in transport systems cuts across work in robotics, autonomous and embedded systems. Robotics aspects touch on or include autonomous and semi-autonomous cars, trains, UAVs and shipping. Each transport industry is already highly structured and regulated. Systems are also safety critical where humans are involved. The car industry is a significant part of manufacturing in the EU, and autonomy and robotics technologies in the products will bring key competitive advantage.

Logistics: Sub-processes involved in the logistics domain include: receiving goods, material handling, workflows of items within manufacturing sites (intra-logistics), sorting and storage (warehousing), order picking and packing (distribution centres), aggregation and consolidation of loads, shipping and transportation (uni-modal, multimodal and last mile delivery).

From a systems perspective the logistics domain can be divided into three different types of system. These cut across the sub-processes above, so all three are typically present at any site

- Transportation systems,
- Storage systems
- Handing systems.

Each has distinct technical characteristics:

- ***Transportation systems*** *require navigation technology and depending on their operating environment varying degrees of perception and cognitive ability. Transportation systems are also likely to need significant infrastructure including communications and coordination systems and an environment that is configured for their use. They must also be integrated with existing infrastructure, e.g. warehouse management systems. While AGV technology is well established it requires infrastructure, and transport systems must also integrate safely with human users.*

- ***Storage Systems*** *automate the process of storage and retrieval from a store. These systems are typically closed to users and operate through portals where fixed site storage units are collected and delivered. The system tracks the location and content of storage units. Packing and unpacking into these units is currently a manual task. Future systems are expected to become more collaborative with mixed working between human and robot that is designed to increase efficiency. Storage systems will also begin to include handling capability and the ability to manage variable sizes items for storage. Efficient resource optimisation is a significant challenge in large systems.*

- ***Handling systems*** *are present at every interface between different transport and storage processes. Robotic handling systems are at an early stage of development. The most basic picking, packing and unpacking functions can be demonstrated in research environments but market viable systems have not yet been produced. It is possible that initial commercial deployment will be in hazardous environments or where hygiene or health concerns will make automatic handling highly desirable. The development of human speed manipulators able to grasp and handle complex objects is still a research challenge. Pick, pack, de-palletising, palletising and sorting all require advances in manipulation and perception. However, it is also the case that logistics is an area where autonomous manipulation is relatively close to first* *application, as indicated by first attempts to build autonomous robot material handling systems.*

Benefits: It is widely recognised that the autonomous transportation of goods and people has the potential to transform a wide variety of services. Logistics represents >10% of the EU economy. There is already considerable interest from both logistics and transport stakeholders seeking new market opportunities. Advancements in the domain of logistics and transport is also likely to benefit European SMEs, as the existing supply chain is highly compartmentalised and relies on a high level of sub-contracting. Autonomous or decision support functions in transport systems, e.g. cars: including cognitive vision, navigation, semi and full autonomous driving will gradually be adopted, adding value to the product, enabling driving in an ageing population, and reducing social harm such as the level of road traffic accidents.

Market Drivers: The need to increase traffic capacity using the existing infrastructure and to increase safety levels are significant drivers for the development of autonomous transportation systems. While these are long term goals for road transport there is already considerable interest and investment in the technology that will be required to achieve these goals. In Logistics the key drivers are the need reduction in cost in the supply chain and consequent increases in competitiveness for manufacturers and reduction in cost for consumers.

Technical Barriers: Within materials handling and logistics there are many barriers that must be overcome before commercially viable solutions can be developed. Early systems are able to handle and palletise items whose characteristics are standardised and known (dimensions, weight and geometry). However there is the need for more flexible solutions which can handle unknown objects of variable size and shape without the need for a human operator.

For viable autonomous transport (e.g. autonomous cars) on existing transport networks to become a reality step changes in technical capability are required. In particular safety certifiable systems and step changes in the dependability of autonomous decision making and in perception and cognition ability are required.

2.7.2. Current and future opportunity

Transport: While autonomous transport is a high profile technology it is likely that the market impact from this will be incremental as vehicle manufacturers steadily increase the level of automation in products and the regulatory environment alters to adapt to new increments in technology. This is seen as a synergistic process. While technology advances are still needed for fully autonomous transport this is in the long term future. In the short to medium term robotics technologies will, however, provide opportunity for product improvement and safety, and reduced fuel consumption, increasing the value of products in the market. This is critical for EU vehicle manufacturers. Opportunities arise around navigation for tasks such as navigation support at night, in GNSS denied zones, and for disabled and ageing drivers. Partial or fully autonomous driving will be used in low speed urban transport, and in reducing insurance premiums.

Logistics: Within the logistics domain the highest impact in the short to mid-term is in warehouse based systems (especially order picking and distribution centres) and intra-logistics operations in factories and retail.

The Gartner report [1] identifies warehouse robots as a rapidly evolving technology within the supply chain. Robotics in logistics grew at an average 14% p.a. in the past two years according to the IFR World Robotics report, and logistics is the 4th largest sector in professional service robotics. Although large-scale automation is increasingly used, current Automated Guided Vehicle (AGV) systems provide quite rigid solutions with high deployment costs and high impact on warehouse layout. There is a need for much cheaper and more flexible systems that will provide greater levels of scalability, and adaptability while being easier to integrate with.

This human-robot integration will be critical to achieving migration from fully human operation, since robots will need to be part of a larger set up, and work alongside humans for full flexibility. More sophisticated and versatile systems have the potential to improve the end-to-end supply chain visibility, by combining the tasks of handling goods, controlling stock levels and continuously checking and updating information about the products (e.g., expiration dates).

Technical Opportunities

Future technically focussed opportunities for the development of automated systems in the logistics and transportation sector can be highlighted as follows:

Autonomous vehicles: Autonomous transportation systems are currently available for indoor, structured spaces. The next generation of autonomous transportation and logistic systems needs to tackle a number of challenges: autonomous navigation, map building and localisation, operation in dynamic environments; operation in close proximity with humans; and adaptability to environments with changing layouts.

Autonomous Picking: The increase in B2C (Business-to-Customer) trade has shifted the focus in commissioning tasks from large-scale pallet or crate picking to unit picking operations. Therefore, there is a new need for systems capable of picking single items in a store, or assisting human workers in the process. Autonomous systems can also perform picking operations in harsh environments with extreme temperatures and can transport items over long distances.

Autonomous Packing and Loading for Distribution: The growth of online sales has increased the volume of goods that are delivered directly to customers. As a consequence, the distribution centres of any rapid delivery operation need to handle a continuously growing number of parcels and goods. In this sector, the next challenge to be addressed could be to create autonomous systems able to recognize, pack, handle and load the items for distribution in an efficient and reliable way. Furthermore, by implementing smart techniques for load planning, such systems have the potential to improve the load and travel costs of vehicles and reduce energy usage and costs.

Warehouse optimisation and operations planning: robotics in the operation of storage areas and of larger warehouse operations is a significant challenge. This includes autonomy in warehouse management systems, but also integration with increasing roboticisation. This also includes the need for improved autonomous planning and scheduling methods for all stages of the partially roboticised logistics process, including unloading, storage, intra-logistics, order picking, packing and delivery. These planning and scheduling algorithms will need to take into account risk of failure or delay, and variability in human and robot behaviour. Mixed multi-robot and multi-human planning and scheduling will bring particular benefits.

Safe Human Robot Interaction: As mobile systems will share space and collaborate with human operators, it is of paramount importance that future autonomous robotic systems should take into account human safety and comfort. These needs should be addressed both at a low level (e.g. guaranteed reliable sensors for people detection), and at a systems level (e.g., new algorithms for people tracking, new human-robot interfaces) and through systems for validation and certification.

Unloading, de-palletising, unpacking, re-packing and re-palletising: A currently open problem in warehouse automation is providing flexible solutions for loading and unloading goods from/to transports and containers, and re-packaging their content. Systems providing these functionalities could reduce bottlenecks in the throughput of goods from/to the warehouse and improve the identification of incorrect shipments.

Retail logistics: At the level of the logistic chain closest to the consumer, cost-efficient robotic solutions could also be used in a consumer environment, to continuously monitor stock levels and identify salient features of the goods (e.g., expiration dates, mislabelled merchandise).

2.7.3. Barriers to market

Barriers to market of robotics systems in logistics are:

- Lack of flexibility and adaptation of systems to changing needs.
- High cost of ownership and long term return on investment.
- Low user awareness of robotics technology capabilities.
- User concerns about system complexity.
- Lack of standard interfaces between systems.

2.7.4. Key market data

Statistical data regarding the market for logistics robots illustrates the potential for growth. According to the last study published by the International Federation of Robotics (*"World robotics, service robots 2013"*), the trend related to logistics service robots shows that 1,376 logistic systems were installed in 2012, 11% more than in 2011. Growth in value has been faster, rising at an average of 14% p.a. since 2011. This market accounts for 9% of the total sales of professional service robot systems. It is also likely that this analysis is based on data that does not cover the whole market. It can therefore be assumed that the actual number of newly deployed systems is higher. Logistic systems are seen as a significant growth sector.

Intra-logistics is increasingly robotised. From warehouse handling with robot arms, to moving around pallets with automated guided vehicles, from sorting products for mixed orders to delivery of meals in hospitals, robotics and automation are indeed the most important technology for logistics. The growth potential is however still huge. For example every year 200-300 thousand manual forklifts are sold in Europe. Automated guided vehicles are in comparison are at only 1-3 thousand sales per year. This means that automated forklifts represent approximately 1% of the European market. With the increasing cost of labour, the automation of intra-logistics solution is expected to dramatically grow in the near future.

There are also strong signs that there is an increasing market demand for autonomous logistics systems, especially for unloading and loading operations. Technologies in this field have attracted a lot of attention at recent logistics fairs (e.g. CeMat 2014). Autonomous systems able to unload containers, swapbodies, trailers or trucks full of different kinds of items are highly desirable.

More stringent regulation is also driving the market. The regulation surrounding logistics is becoming increasingly restrictive. Regulations that guarantee continuous improvement of working conditions has always been the aim of the trade unions. Action has been taken in this direction, especially in the northern region of Europe (Denmark, Belgium, Netherlands, etc.). For example working time reduction, total weight limit to be handled within a working shift, height limitations in the loading of container (impact on the capacity utilization rate). These regulatory restrictions provide an incentive to develop robotic co-worker technology to help ensure that workers are safe and working within regulations.

2.7.5. Relationship to other domains and markets

Given that logistics accounts for a relatively high proportion of European GDP it is inevitable that there are extensive relationships between the Logistics and Transport Domain and other domains.

Although many logistics operations are self contained a large number are closely coupled to manufacturing operations, either providing goods-inward sorting and storage, or finished goods distribution or in intra-logistics within manufacturing. The technical requirements for handling and manipulation are closely paralleled with those in industrial robotics for advanced manufacturing resulting in a strong synergy between logistics robotics and industrial robotics.

In consumer retail outlets, particularly operations that are closely coupled to warehouses for replenishment or where the warehouse is the retail outlet there are opportunities for common systems development with the commercial and consumer domains. Particularly in building systems able to work in shared spaces.

Within the healthcare domain logistics within hospitals is a major element of hospital support services, transporting linen, people, samples, supplies and equipment. Logistics robotics has the potential to impact on raising service efficiency in hospitals.

A significant part of the robotics technology opportunity in agriculture is based on handling, sorting and storage together with packing and unpacking. Therefore common development in these areas is inevitable. Safety certification and in-farm transportation will also draw on common technology in Logistics and Transport.

In nearly all of these areas there is an additional common functional goal in the desirability of a tight collaboration between robots and workers needed in order to reach desired levels of performance on tasks. This too has the potential to lead to collaborative development.

2.7.6. Europe’s place in the market

Many important European actors are already involved in producing autonomous systems for logistics and transportation, manufacturing AGV solutions, innovative manipulators and new sensors. In order to increase the market share for European companies against US and Asian competitors novel and deployable technology needs to be brought to market to create a leading edge.

2.7.7. Key stakeholders

Europe has some of the largest logistics companies in the world. It is also home for a number of leading automotive manufactures and their extensive supply chains. Europe is therefore well placed to exploit the opportunities presented by Robotics in Logistics and Transport. A number of these organisations have set up specialised research and development centres in the expectation that this will become a significant area of growth.

Some National initiatives also exist to enhance supply chains and logistics operations as it is recognised that this is key to better utilisation of the transport infrastructure and reducing energy consumption to meet environmental targets.

Europe has a strong academic community capable of developing and delivering technology to the market and there is good academic and industrial collaboration in this area.

2.7.8. Current key projects

RobLog	Cognitive Robot for Automation of Logistic Processes	http://www.roblog.eu/
CableBOT	Parallel Cable Robotics for Improving Maintenance and Logistics of Large-Scale Products	http://www.cablebot.eu/en/
PAN-Robots	Plug and navigate robots for smart factories	http://www.pan-robots.eu/
TAPAS	Robotics-enabled Logistics and Assistive Services for the Transformable Factory of the Future	http://www.tapas-project.eu/

STAMINA	Sustainable and Reliable Robotics for Part Handling in Manufacturing Automation	http://stamina-robot.eu/
CHAT	Control of Heterogeneus Automation Systems: Technologies for scalability, reconfigurability and security	http://www.ict-chat.eu/
FURBOT	Freight Urban RoBOTic vehicle	http://www.furbot.eu/
FIRST-MM	Flexible Skill Acquisition and Intuitive Robot Tasking for Mobile Manipulation in the Real World	http://www.first-mm.eu/
Cargo-ANTS	Cargo handling by Automated Next generation Transportation Systems for ports and terminals	http://www.iri.upc.edu/project/show/133

2.7.9. European products

Numerous European transport and logistics products exist. However these are either whole systems designed for specific storage and distribution tasks or are specialised systems used in particular industries. There are many early stage products, including

- Automatic unloading of containers
- Robotic palletizing (including planning software, (special) grippers, system solutions e.g. Grenzebach)
- AGVs
- Stock control robots
- Soft-robotic systems for safe interaction with humans

2.7.10. Logistics and transport sub-domains

In analysing this domain it can be considered as a set of three separate but interrelated sub-domains:

- Autonomous transport vehicles and systems
- Warehouse handling systems
- Logistics

Autonomous transport systems

Autonomous transport can be divided into set of different markets where there are common technology requirements. In this sub-domain the main issues concern the development of complete systems, the development of reliable sensing technology, and the development of viable deployment strategies.

Investment in this sub-domain with respect to autonomous road transport is already at a very high level with nearly every major car and systems manufacturer investing to reach the market first with incremental products that will progressively automate the process of driving. This area is not seen as a direct priority because of the levels of existing investment however it is recognised that technology development may well impact on this sector as there are still significant technology challenges.

Handling systems

At every transition point in a logistics system goods must be handled; unpacked, sorted, stored and repacked. These functions vary in complexity based on the goods and the level of human interaction that is needed to carry out the task. Current systems segregate functions that are automated from those that involve people. Future systems will be designed to allow robots and humans to work in close collaboration.

Current systems can handle regular package, or goods sizes but are unable to currently handle variable sizes of goods within the same operation, and are less able to handle irregular items such as natural products or soft or flexible goods that require manipulation prior to packing.

Autonomous warehouse handling systems are already available for a number of specific types of warehouse operation. These are typically closed systems that only collaborate with people at the input and output of the process. A greater technical challenge is presented by systems that work in continuous collaboration with people. Existing systems are also based on fixed load sizes where automation is scaled to a specific storage container size. Handling variable sized goods is still a manual operation. This manifests itself in the final box packing or unpacking in most logistics and distribution operations where variable sized items must be packed and shipped. The second major challenge is thus in the autonomous handling and packing of varied sized loads. This might be into shipping cartons or into delivery vehicles.

Logistics Systems

Managing the flow of goods from source to destination requires an integrated system where each component interacts efficiently.

Logistics is a vital sector for the European economy it contributes nearly 14% to the European GDP (€900bn) and has a significant impact on the service sectors it serves. Logistics is a global business and Europe has a high proportion of the top performing global Logistics companies.

Key drivers are; the opening of new markets both within existing territories and, the opening of new global markets; delivery service parameters such as time guarantee and delivery duration; conformance with environmental legislation; adaptation to demographic shift and resource scarcity. Logistics is a good example of an End User for robotic technology, it owns a series of problems where robotics technology might be able to deliver systems but as an industry it is not specifically looking to robotics as the answer to these problems.

The primary challenge in logistics is to address the fundamental operating parameters of cost and time, while also enhancing value added services, such as higher levels of customisation, for example on-demand delivery. If robotics technology can address these issues then investment will follow. The secondary challenge in logistics is synchronisation. Timing the manufacturing and fulfilment cycle with the transport and delivery systems in order to minimise waiting, storage and costs is an important goal.

One of the key challenges within the development of logistics systems is configuration management. The deployment of any system must be configurable such that it can be made to fit the particular circumstances of any customer. System configuration has the potential to become a dominant cost in the deployment of logistics systems

2.7.11. Current and future opportunity

The current opportunity within each of the three sub-domains is considerable and there is already End User investment in each area. However opportunity for autonomous transport is currently constrained by existing transport legislation and although there is a strong will on behalf of policy makers to remove these barriers it will take time for the existing regulatory system to adapt to the introduction of autonomous transport. It is expected that this will be an incremental process that synchronises to incremental technical advances.

While regulation is also an issue with respect to warehouse systems these operate within well defined spaces inside factories and warehouses where regulations can be implemented more easily. Here the opportunities are considerable provided that the technology can be proved. While there are individual systems that are being trialled there is still a high level of opportunity particularly in the development of handling and packing/unpacking systems which are at an early stage of development.

Opportunities exist within the Logistics sub-domain related to novel means of deployment, for example using UAVs to deliver over the final kilometre or within the optimisation and coordination of multi actor systems. It is expected that novel technology will be highly disruptive.

Opportunities exist within intra-logistics particularly in the area of human robot collaboration both at the point of delivery to a production line, and in intra-warehouse operations. As the ability to handle a more varied range of goods increases so to will the opportunity to develop greater sophistication within intra-logistics applications.

At the core of many future opportunities are technical capability enhancements that will enable faster more accurate handling, inherently safe operation when sharing work spaces, and solutions to the real time optimisation of multi actor systems.

Logistics systems to not operate in isolation they form part of a larger business model of operation. New technology will alter and disrupt these business models and enable new types of service to exist. So for example the automatic handling of goods will allow greater levels of tracking within a warehouse, the automated assessment of item condition or inventory will reduce costs and errors. In the future it is envisaged that these systems may also be able to handle item return, an increasingly important part of on-line trading, assessing the returned item, repacking it and returning it to storage.

Within intra-logistics improving the flexibility of delivery systems and increasing coordination with other systems will in turn improve efficiency. Improved optimisation in system management is also critical to achieving overall efficiency.

2.7.12. Key system ability targets

2.7.12.1 Configurability

Due to the wide variety of goods transported, robotic systems must be able to manipulate objects with different physical properties. Due to the variety of goods to be handled in intra-logistic tasks, systems may require reconfigurable grippers. The last-mile delivery problem requires the ability to travel in different environments (pavements, roads, pedestrian zones). Robots may require dynamic reconfiguration in order to achieve efficient locomotion across different environments.

Configurability of Logistics systems is critical to increasing the deployment range when installing systems.

Target	Ability level required and related abilities
Autonomous gripper configuration to manipulate different objects	Configurability Levels 2-4
Autonomous configuration of sensing systems	Configurability Levels 2-4
Adopt different locomotion systems	Configurability Levels 0-1

Autonomous re-configuration of multi-robot and human-robot systems	Configurability levels 2-4

2.7.12.2 Adaptability

In order to improve overall efficiency, logistics and transportation systems must be able to adapt to changes in the environment, as well as to learn from experience and use that knowledge to improve over time. Adaptability is necessary in several key aspects:

Target	Ability level required and related abilities
Process optimization (e.g, routes taken, warehouse layout optimization, task allocation optimization)	Task Adaptability levels 3-4 Component Adaptability 1-3
Local parameter adaptation for vehicle subsystems (e.g. Localization parameters, sensor calibration parameters, etc.)	Component adaptability levels 1-3
Re-planning of operations under changing conditions, e.g. rescheduling of operations over robots and humans	Task adaptation levels 2-4

2.7.12.3 Interaction

Logistics and transportation systems are often deployed in close proximity to human workers and/or the general public. Thus, systems should be designed with inbuilt safety capabilities, as well as adequate interaction abilities. Safe interaction is of critical importance in intra-logistics. Levels of social interaction will also be required during delivery to end customers and to a lesser extent in collaborative operation within warehouse operations.

Target	Ability level required and related abilities
Human-robot or robot-robot exchange of goods	Human-Robot Interaction Ability Levels 6-8 Robot-Robot Interaction Ability Levels 4-6 Human robot interaction feedback 1-2
Shared workspaces and human safety	Human-Robot Interaction Safety Levels 6-8 Human-robot interaction feedback 1-2
Recognition of and adaptation to human behaviour	Human-Robot Interaction Safety Levels 6-8
Modelling and planning of safe interactions between humans and robots.	Human robot interaction 3-8 Human robot interaction feedback 1-2 Robot to Robot interaction levels 2-5 Human-Robot Interaction Safety levels 3-5

2.7.12.4 Dependability

Logistic and transportation systems are key components in the manufacturing and delivery processes and thus should be highly dependable. System failures can cause considerable delays in production and high economic losses. Systems need to be designed to be dependable in order to facilitate large-scale adoption.

Target	Ability level required and related abilities
Long-term, failure-free navigation	Dependability Levels 2-7
Long-term, failure-free handling of goods	Dependability Levels 2-7
Long-term, deadlock-free coordination	Dependability Levels 2-7
Risk aware planning, scheduling and optimisation of operations to reduce risk as demands vary	Dependability Levels 5-7

2.7.12.5 Motion Ability

The ability to plan and execute accurate and precise motions is paramount in both intra-logistic and transportation systems. Motion capabilities are required both for the handling of goods and for their transportation, in warehouses as well as on open roads.

Target	Ability level required and related abilities
Accurate and precise kyno-dynamic motion planning and execution	Unconstrained Motion Level 3-6 Constrained Motion 1-2
Accurate aerial navigation	Unconstrained Motion Level 3-7 Constrained Motion 0-1

2.7.12.6 Manipulation ability

Intra-logistic tasks require robots to interact with goods for loading and unloading operations. Future advances in the manipulation capabilities of the vehicles will result in broadening of the target application domains of the systems.

Target	Ability level required and related abilities
Loading and unloading of goods with various physical properties	Grasping Ability levels 3-6 Holding Ability levels 0-1 Handling Ability levels 2-4
Dexterous and in-hand manipulation of goods	Grasping Ability levels 6-8 Holding Ability levels 1-5 Handling Ability levels 3-4
Manipulation of deformable goods	Grasping Ability levels 4-8 Holding Ability levels 4-5

	Handling Ability levels 2-3
Packing, loading and unpacking in the face of clutter and packaging materials.	Grasping Ability levels 4-7 Holding Ability levels 1-5 Handling Ability levels 3-5
Moving to human levels of pick rates	Grasping Ability levels 5-8 Holding Ability levels 1-5 Handling Ability levels 3-5
Development of low cost human safe, and dextrous manipulators for logistics	Grasping Ability levels 3-6 Holding Ability levels 1-5 Handling Ability levels 3-5

2.7.12.7 Perception ability

Perception is a key ability for both logistic and transportation systems in several aspects: vehicles need to be capable of determining precisely their location with respect to the environment over long periods of time; to maintain consistent and up-to-date maps of their immediate surrounding; to identify target objects for loading and unloading operations; to identify humans and other dynamic entities and to track their position. Thus, high levels of perception ability is necessary for several components of logistic and transportation systems.

Target	Ability level required and related abilities
Accurate and precise long-term localization in dynamic environments	Tracking Ability Level 6 Location Perception Ability Levels 4-6
Autonomous localisation and position in GNSS or marker denied environments with moving agents	
Automatic map building and maintenance	Scene Perception Ability Levels 3-6
Object recognition and tracking	Tracking Ability Levels 2-5 Object Recognition Levels 5-11
Tracking of humans, understanding of human actions and intents	Scene interpretation 1-6 Object recognition 12-13 Tracking ability 6

2.7.12.8 Decisional autonomy

Automated control processes in future intra-logistics and transportation systems will be responsible for the continuous operation of fleets of vehicles. These will be subject to dynamic external requirements and will have to be addressed in real time. Such requirements include destinations to be visited, deadlines, map changes, and vehicle-level and infrastructure-level contingencies. Crucially, the adherence to such requirements must be guaranteed by the control processes in order maintain smooth running operations. For this reason, whether they are centralised or distributed, or whether they control the behaviour of one vehicle or of a fleet, automated control processes must be provided with high levels of decisional autonomy.

Target	Ability level required and related abilities
Autonomous navigation through diverse environments (e.g., from a distribution point to a store passing through roads, pedestrian zones, etc.)	Decisional Autonomy Levels 1-5
Automatic establishment of unload point for last-mile deliveries	Decisional Autonomy Levels 4-6
Coordination and task allocation with guaranteed formal properties (e.g., absence of deadlocks, adherence to temporal constraints and orderings, avoidance of “off-limits” zones)	Decisional Autonomy Levels 6-8
Continuous 24/7 operation of fleets, seamless vehicle substitution	Decisional Autonomy Level 3
Autonomous optimisation, rescheduling and planning of whole warehousing operations taking into account changing workloads	Decisional Autonomy levels 6-10

2.7.12.9 Cognitive ability

A wide range of Cognitive Abilities are critical to many of the logistics and transport functions. From scene interpretation through to object understanding and human interaction. Cognitive reasoning ability is critical to planning and reasoning around optimisation and scheduling of multi actor systems and in guiding behaviours both in distributed and centralised control. Cognitive Abilities are also critical in object handling and establishing grasp strategies and in interpreting the context of objects for manipulation.

Target	Ability level required and related abilities
Ability to semantically annotate the map of the fleet's working environment (e.g., the store, the warehouse, the road, etc.)	Interpretive Ability Levels 5-9 Reasoning Levels 3-6
Ability to autonomously monitor stock levels, pallet/container contents, and other products in the store/warehouse	Acquired Knowledge Levels 5,7,8,9 Reasoning Levels 3-5, Interpretative Ability Levels 2-6
Ability to self configure and adaptively deploy individual vehicles and fleets in diverse environments	Reasoning Levels 5-8 Envisioning Levels 2, 6 and 7
Automatic inference of traffic rules	Envisioning levels 7-8

	Reasoning levels 2-7
Automatic scene interpretation and object recognition for loading and unloading tasks	Action Ability Levels 5,8 Interpretive Ability Levels 3-7 Object Interaction Levels 3-7 Envisioning Levels 4,5,6
Integrated task scheduling and motion planning, fleet coordination, and vehicle control	Reasoning Levels 4-8, Envisioning Levels 1,2,4,5

2.7.13. Key technology targets

2.7.13.1 Systems development.

The use of standard robot frameworks and development of industrial grade standards based on current open source solutions are essential for quickly advancing industrial-relevant research. Reusable software components and modular integration schemes will enable a reduction of deployment costs and diminish the need for re-factoring efforts when presented with different domains.

System Design

- Modular software architectures for robotic platforms.
- Development of human safe, fast, low cost platforms to enable uptake in domain.

System Integration

- Tight integration of perception, motion planning, semantic mapping, task scheduling, mission planning, fleet coordination, human robot interaction, and vehicle control
- Simulating combined autonomous and human systems

Modelling and Knowledge Engineering

- Development of common knowledge representations for facilitating tighter system integration.

2.7.13.2 Human robot interaction.

Logistic and transport systems often operate in the presence of humans and human-driven vehicles. This entails high safety requirements and human-friendly behaviour.

Safety

- Algorithms for safe navigation and motion in the presence of people.
- Dependable people detection and tracking techniques as well as algorithms or techniques for motion prediction.

Human Machine Interface

- Human-robot interaction techniques which streamline operations, reducing overall cost.
- Intuitive and effective mission posting interfaces for fleet managers.

2.7.13.3 Mechatronics.

Sensors

- Development of low-cost sensors for robust human detection and navigation tasks.
- Low cost 3D range sensors with improved detection range, precision, accuracy and frame rate.

- Self-calibrating sensors (intrinsic and extrinsic).
- Combinable sensors, especially 3D ToF-sensors with new CDMA techniques.
- Development of new sensors which could work in adverse conditions, both indoor and outdoor.

Actuators

- Low cost, reconfigurable, dextrous grippers and manipulators for application specific handling of goods.
- Intrinsic safety for collaboration with people

Power Supply and Management

- Power system for continuous operation
- Low energy requirement system
- Wireless power transmission

2.7.13.4 Perception, Navigation and Cognition.

Sensing

- Scene interpretation by means of multi sensor systems using different physical phenomena.
- Multi robot perception in heterogeneous teams.
- Robust object recognition and shape/scene recovery in challenging scenarios (e.g., with sharp changes of luminosity, dusty places, fog).

Interpretation

- Techniques for maintaining consistent spatio-temporal representations.

Mapping

- Techniques for autonomous acquisition of semantic maps (creating and updating topological and dynamic maps of agents and places for AGVs in industrial environments).
- Life-long map maintenance by heterogeneous vehicles and sensors.

Localisation

- Precise and accurate infrastructure-free localization in dynamic environments.
- Collaborative localization in multi-robot systems (increasing the localization accuracy by detecting different vehicles and their relative positions)

Motion Planning

- Techniques for high-precision, on-line motion planning under differential constraints.
- New techniques for multi-robot motion planning including interaction with humans.

Cognitive Architectures

- Provably safe and efficient task scheduling, warehouse optimisation and coordination techniques.
- Techniques for autonomous deployment of logistic systems in new environments.

Learning Development and Adaptation

- Learning technologies for building and maintaining models of human-behaviour, including prediction of behaviour.

Knowledge Representation and Reasoning

- Common representations for enabling a tighter integration of perception, control, action and motion planning, and coordination.

Action Planning

- Methodologies for efficient on-line task allocation and scheduling.
- Methods for whole system optimisation and risk aware scheduling and rescheduling.

2.7.14. Technology combinations

Flexible grasping

Autonomous handling of goods is a key aspect of logistic systems. The next generation of systems in warehouse environments will need to address a wide variety of tasks, which go beyond simple pallet picking and transportation. For example, future systems will need to pick single items out of crates and containers, order pick from SKUs, assemble kits or pallets, transport and handle heterogeneous goods. These tasks require substantial grasping capabilities and thus need developments both in hardware (better and cheaper actuators and sensors), as well as advances in control and perception. The next generation of industrial robots in warehouse environments will need to be capable of carrying out complex tasks, such as unpacking, de-palletising, picking single items, kit assembly, packing, palletising, vehicle loading, joint handling with humans, and handling of deformable materials etc. Such tasks require high levels of dexterity and may require complex kinematic and dynamics solutions. This also includes the need for much faster robot operations, to reach human levels of manipulation speed in unstructured settings.

Mobile manipulation

Future systems for in-house logistics process automation will also need to be capable of performing mobile manipulation tasks. Many of the more complicated tasks currently performed by human workers require substantial levels of dexterity in manipulation: Picking and assembling parts into kits; selecting single items from crates, piles, or shelves; re-ordering items on a pallet; all of which require both manipulation capabilities and platform mobility. The mobile manipulation task in logistics and transportation is also constrained by strict safety requirements, as robots may need to work in close proximity with, or even in cooperation with human workers. Thus, a combination of new technological developments in sensors, actuators, control, human-robot interaction, perception and cognition are necessary to fulfil the future domain needs. Cost, safety and speed of operations in unstructured mobile manipulation are all key.

Collaborating robots, humans and management systems

Warehouse and logistics operations will increasingly require multiple robot systems to carry out the range of tasks required in a synchronised and collaborative way. For example; robots able to pick out of AGVs while they are driving or that are palletising on a pallet transported by an AGV while it is driving. Such high levels of collaboration between separate systems will impact on the design and operation of intra-logistics and warehouse operations. Current warehousing systems have sophisticated methods for stock control and scheduling of tasks. Autonomous scheduling, multi-robot planning and optimisation will need to be integrated with one another and eventually with these existing management systems.

Rapid Deployment in Realistic Logistics Environments

In order to gain wide acceptance in industry, autonomous robotic systems need to be capable of fast and cost-efficient deployment into novel warehouse environments. Future robot systems need to be able to operate without assuming a fixed warehouse layout, and should be capable of adapting to changes in the environment over time. In order to meet these requirements, future systems will need to use a combination of novel technologies in environmental mapping, planning, localization, and adaptation over time.

Outdoor Navigation

Transportation tasks in outdoor environments will be an increasingly important automation domain, which requires a combination of new technologies. The task of point-to-point delivery, in particular also the last-mile delivery task, requires autonomous navigation in semi-structured outdoor environments and through population centres, which poses a number of challenges. A combination of step changes in technologies such as perception, localisation, mapping and navigation through unstructured and dynamic environments will be necessary to make possible this kind of robotic applications.

2.7.15. Product visions

2.7.15.1 Warehouse Co-workers

A robotic warehousing system able to safely operate autonomously and in physical collaboration with human operators to pick and/or carry items in a warehouse and assist in the packing and unpacking of storage units. The system will require increased human robot interaction capabilities, be adaptable to environment and workload changes, and not require substantial re-engineering of the warehouse, and be easy to configure and secure. Such systems might be able to either carry, pick, pack and otherwise manipulate unknown objects; interface with other warehousing systems, as well as include or interface with warehouse scheduling and optimization algorithms, stock control software, etc.

2.7.15.2 Urban freight transport

The last-kilometre delivery problem involves many difficulties that could be resolved or mitigated using robotic technologies. For instance, common problems are traffic congestions and the lack of loading and unloading areas in urban centres.

Current and future opportunity

Interesting challenges for new systems would be:

- Reduce the occupancy time on loading and unloading areas when a transporter is carrying out a last-kilometre delivery using small autonomous delivery robots.
- New ways of capillary delivery with unmanned vehicles, especially UAVs.
- Technologies related with traffic supervision tasks that provide useful information for route determination methods.
- Collaborative delivery systems that combine autonomous robots, automated infrastructure and people.
- Support systems to transport heavy goods, e.g., high capacity oil bottles, butane or propane cylinders, refreshment drinks bottles, etc.

2.7.15.3 Multimodal freight transport

To increase productivity and safety, and to reduce carbon emissions it is important to shift from conventional long haul road transports (lorries) to rail freight systems. One of the current main difficulties lies with transhipment operations between transportation modes. Further improvements are required in the loading and unloading of pallets and boxes in containers, lorries and rail platforms. Improving operations in transportation areas like ports and airports are of capital importance to reduce congestion in the European transportation network [2].

Current and future opportunity

Simultaneous and parallelised loading tasks carried out by means of collaborative robots, using robot-robot and human-robot interaction techniques. Automatic load of transports while improving the occupancy factor of the transport.

2.7.15.4 Intra-logistics and Warehouses

The primary goal is to improve productivity and the quality of service delivery. Existing automated storage and retrieval systems require a high initial investment and have low flexibility. They also dictate the warehouse layout and the storage format.

Autonomous transportation within warehouses can currently be provided by commercial AGV systems. However these rely on a fixed infrastructure and pre-defined working patterns.

The increase in B2C trade requires systems capable of picking unitary elements in a warehouse, or able to facilitate the work of the person carrying boxes with objects to the picking cell. These demands require more flexible systems able to interact with human co-workers.

There are a large number of different application domains for this type of system provided that they can be shown to be economically viable.

- Stock control.
- Room-Delivery systems.
- Re-provisioning of shelves.
- Route picking (for customers).

Current and future opportunity

Reliable, flexible and low-cost navigation and localization methods will open a wide range of tasks to be performed inside buildings, for example hospitals, schools, offices etc. Ability to seamlessly locate items in indoors environments. Ability to semantically map a scene or interaction scenario.

2.7.15.5 Unmanned Ships

Maritime transport is the principal transport system in term of tons per miles moved. There is a significant opportunity to create fully autonomous shipping. The cost of crew is second only to the cost of fuel on cargo ships and in addition the crew support systems would no longer be required reducing energy usage and increasing cargo capacity. While there are regulatory barriers to the deployment of unmanned ships it is expected that these will be overcome. Remote operation and supervision is also an potential current opportunity.

Current and future opportunity

The continual progress in ICT and other technologies have had a great impact on the maritime sector, giving support to seafarers in facilitating their duties as well as reducing workload and stress.

Introducing robotics technology is seen as a natural progression of this trend that will further enhance safety both on-board and at sea, improve efficiency and reduce environmental impact. Systems able to automatically set the parameters of operation taking into account sea condition, weather and optimum energy use are a key enabler to improving efficiency.

The introduction of autonomous systems into the marine shipping industry is seen as a significant opportunity that will disrupt the current business models used in the industry.

2.7.15.6 Maritime Applications

Domain Overview

The maritime business generates revenues of more than $500bn, including Oil and Gas, Cruise & Ferry and Yachts. While automated shipping will eventually deploy in cargo operations this is only one area of application within the domain. Shipping support services will also benefit from robotics technology in terms of loading and unloading goods and supplies, refuelling and maintenance and inspection. On-board vessels there are opportunities to provide services using robotics technology including cleaning, service delivery, and catering applications. These may be particularly applicable on cruise ships.

2.8 Consumer Robots

Consumer robots are defined as Robots that are operated by, or interact with, untrained, or minimally trained people in everyday environments. Typically these robots will be bought or leased and used to provide services to individuals.

These robots will be considered to fall within the consumer regulatory framework. They are likely to be mass produced, although not in every application. The business models will typically be based on B2C transactions either on a purchase or hire basis.

2.8.1. Domain Overview

The domain can be divided into a number of different sub-domains:

- Domestic appliances
- Entertainment
- Education
- Assisted Living

Each of these sub-domains has particular characteristics.

2.8.2. Sub-Domain: Domestic Appliances

Robotics technology has wide applicability within the domestic appliances market. The addition of Robotics Technology typically enhances products by extending functions through providing a degree of autonomy. Over time there is a user expectation that robotic based appliances will be able to complete many household tasks autonomously. In the assistive care market assistance in everyday tasks such as food preparation and cleaning are fundamental to extending the utility of the home for the elderly and infirm.

Robotics technology has been applied to domestic appliances for over ten years, starting with pool cleaners, vacuum cleaners and lawn mowers. The market in these areas is now maturing and individual sales volumes are increasing. Europe has globally competitive domestic appliance manufacturers and there is extensive opportunity not only within the European market but in the global market for robotics technology. It is estimated that the Domestic Appliance market for robotics will grow to more than €10Bn by 2020. This is an area of high growth potential and an important sector within the robotics market as it also promotes the public awareness of robotics and has the potential to drive part costs down as a result of the volumes of units shipped thereby enabling other lower volume markets.

2.8.2.1 Current and future opportunity

Although the first robot vacuum cleaners started to appear in the mid 1990's they have still to reach the market penetration levels of manual appliances. Although Europe started this trend it has not held that lead to date. The current expectation is that a new wave of smarter cleaning machines based on improved technology will significantly grow the market taking it beyond current sales of low millions of units per annum. Even with current figures the numbers of units sold dominate the figures for service robot sales. Europe has strong domestic appliance manufacturers and it is expected that they will start to gain back a significant share of this market.

Applications in pool cleaning and lawn mowing are now also growing however it has taken the market some time to develop. Appliances that are able to map the space they are cleaning and make deliberate decisions about how to clean that space are only now becoming available. There is still considerable market fragmentation and therefore opportunity for consolidation.

There is an opportunity to apply current improvements in robot technology in order to bring appliances closer to the point where using manual appliances is no longer necessary. It is also expected that the market will broaden into delivering other types of appliance.

It is expected that the domestic appliance market will stimulate focused research and innovation and has the potential to develop a European supply chain.

Future market opportunity centres on the application of more advanced robot technology to domestic appliances to provide significant robot functions and step changes with direct consumer benefit. The market driven nature of this domain means that the development of technology will mainly concentrate on step changes that raise TRL and Capability levels. In particular dependability is critically important in the more advanced applications, appliances will need to be able to recognise failures and remain safe. Consumers are always quick to recognise what works and what does not, so fulfilling a genuine user need is essential.

Typical goals for advancing system function are:

- Extension of the robotic function to reach beyond the robot
- The development of multi-modal appliances. For example cleaning including specific dirt and stain removal actions.
- The ability to learning optimal paths, patterns and room layouts without the need for barrier devices or other types of marker.
- Systems that can take instructions to perform a range of different functions within a given context.
- Systems able to handle unexpected events in their environment.

In the longer term there are opportunities for the integration of manipulators with mobile bases, or in fixed appliances, such as a tumble dryer, in terms of combining clearing and cleaning functions. However the cognitive interaction between user and robot needs to increase to match the complexity of the environment and the objects to be cleared before a useful function can be achieved.

2.8.2.2 Key Market Data

The Domestic Appliance market is typically divided into small and large appliances and into cleaning and laundry. Robotic applications will therefore fall into different sectors within this market.

Technical consumer goods market in Europe is worth some €200bn per annum of which the European small appliance market is worth some €13bn per annum and the large appliance market €30bn. Robot products are likely to fall between these two markets and the consumer electronics market which is also some €30bn. Europe has three of the top five global suppliers in this market and several of the market leaders in individual sectors.

It is estimated that the Domestic Robotics market will be worth more than €10Bn in 2020 from its current base of €3bn. Sales of domestic robots including floor cleaning robots are experiencing double digit growth per annum.

The domestic vacuum cleaner market is currently dominated by the US based iRobot Corp. The global annual sales volume of cleaning robots is estimated at 2.5 million units per annum. There are an increasing number of “clone” products and a number are offering enhanced mapping. Dyson has entered the European market in 2016, after its Japan launch in 2015, with its 360 Eye product offering a better cleaning performance and advanced vision based mapping.

2.8.2.3 Relationship to other domains and markets

There is a strong relationship with the existing domestic appliance markets and some of the suppliers in the robot market are established domestic appliance manufacturers. Where there is a strong existing market for manual devices carrying out the same function there will be significant IP benefits in promoting collaboration between conventional appliance manufacturers and robotics technology companies.

There are strong links to the component supply industry because of the need to drive the down the cost of robot parts, mechanisms, sensors and associated sub-assemblies through mass production.

There are opportunities in collaboration with semiconductor manufacturers and silicon designers to incorporate dedicated processing and sensor integrated processing in order to reduce costs.

There is strong overlap with the assistive care market where systems that support the elderly population impact on domestic appliance functions such as food preparation, cleaning and house maintenance.

2.8.2.4 Europe’s Place in the Market

Europe has strong global domestic appliance brands and it is important that they are engaged with the inevitable shift to the integration of robotic technology within the domestic appliance market.

The domestic appliance market is a significant potential growth area for European companies.

2.8.2.5 Key Stakeholders

Europe has a number of key global players in the domestic appliance market. Notably Bosch, Siemens, Electrolux, Philips and Dyson together with a large number of smaller companies. In addition a number of US and Korean domestic manufacturers have extensive investment in Europe.

2.8.2.6 European Products

There are various robotics products made by European companies but to date none have gained a significant proportion of the European domestic robotics market let alone of the total domestic market.

The user expectation of product performance varies considerably form country to country across Europe as does sensitivity to price it is therefore likely that, as with conventional domestic products, manufacturers will experience different market penetrations across Europe depending on their point in the market.

A number of European manufacturers have used re-badging of far-east designed robotics appliances in order to test the market.

2.8.3. Sub-Domain: Entertainment

2.8.3.1 Domain Overview

The toy sector has always been a strong user of low level robotics technology. As the cost of robotics technology reduces there has been a corresponding increase in the level of sophistication in robot based toys. Although these are typically high value items, their perceived educational side effects are a driving market force.

At the other end of the entertainment industry, in theme parks, and museums the deployment of robotics technology to provide innovative interaction experiences has grown significantly. Many new theme park rides combine robotics technology with traditional roller-coaster rides to enhance the experience. Museums are increasing the levels of interaction through interactive animatronics in order to improve visitor experience.

The games industry has now grown to be larger than the Movie and Music business. Its current use of robotics technology is minimal with the exception of 3D sensing. There are significant opportunities both for game and promotional use of robotics technology.

2.8.3.2 Current and future opportunity

The low cost margins, high volumes and fast trending in the toy industry mean that robotic entertainment products have tended to dominate at the lower end of the market. More sophisticated toys have begun to emerge but market take up has not been strong. Much of the market concentrates on zoomorphic or humanoid forms, rather than on sophistication in terms of interaction and the deployment of robotic technologies. Most of the successful products occupy the market between entertainment and educational end use. The educational aspects providing a justification for higher price levels.

As part costs are reduced through increased volume the opportunity to produce autonomous products will increase and the increasing use of smartphone technology as the primary means of interaction will increase over time.

Swarm interaction between robot toys is in its infancy, there may also be applications for localisation and manipulation technologies.

Sports interaction robotics has long been explored in academia and as costs reduce may well become a significant new market joining Entertainment and Healthcare.

As robot human interaction becomes more dependable a range of high end entertainment robotics will emerge that provides physical and cognitive interaction.

2.8.3.3 Relationship to other domains

There are strong links to non-robotics sectors including the toy industry, the smart phone market and sports and leisure industry. The gaming market may increasingly use robotics as a way of extending user interaction. All of these sectors are highly cost conscious and require high levels of reliability.

There are also applications in the adult entertainment industry that have been exploited.

Within the robotics market there are strong links to the Educational domain and to a lesser extent the healthcare market, particularly in the preventative healthcare sector.

2.8.3.4 Europe’s Place in the Market

Europe leads in the exploitation of theme park robotics, and in the high end educational robotics sectors.

2.8.3.5 Key Stakeholders

Europe has a strong games industry both for computer games and conventional toy products. However US brands dominate the low and mid range toy market.

2.8.4. Sub Domain: Education

2.8.4.1 Domain Overview

The current education market is primarily concerned with the supply of kits and systems to both the school and higher education markets. In schools there is a trend towards teaching technology based subjects and robotics is often used as the basis for the practical side of this type of teaching. However there are no pan European standards for education and so the market is fragmented along national boundaries.

Typical systems embody a high degree of flexibility leaving the designed function up to the user, constrained only by the physical, sensing and computational limitations of the parts supplied. There is also a strong emphasis on linkage to educational goals, either specific to teaching in schools, colleges and University, or to general educational aspirations for home use.

Note: Robots also have a place in professional training, most commonly in the medical and search and rescue areas but these aspects are treated within the MAR sections of those domains.

2.8.4.2 Current and future Opportunity

The end market for educational systems ranges from pre-school education to university level. In the school market the supply of whole systems, for example "turtle" systems, tends to dominate the earlier years in education while free-form construction oriented kits dominate the later stages. In some cases these kits are assembled for users from a wide range of parts some of which are targeted at specific robot competitions. Typical examples use existing constructional toys as the basis for building robots.

Increasingly there are internet resources linked to particular educational kits.

Future opportunities centre around systems able to integrate with the internet and be extended by third party applications and 3D printing.

Key to many robotics educational activities is the combining of robotics kits with national and international competitions. Numerous examples of such competitions exist at all levels of education from the Little Lego League to University level competitions exemplified through the Robo-cup, euRathlon and RoCKIn projects. Extending the reach and visibility of these competitions is a key target for expanding robotics education and public engagement in robotics.

2.8.5. Sub Domain: Assisted Living

2.8.5.1 Domain Overview

Assisted Living addresses the challenges of robotics technology support for **independent living at all ages, social innovation and inclusion** and **ageing**. The main settings of this are the house, the town, and daily human-inhabited environments; on the other side the relative actors are mainly **healthy persons**. The sub-domain of Assisted Living is closely related to the Healthcare Domain however its focus is on non-medical applications and on an ageing society. The market is defined by non-medical consumer customers, such as individual citizens, elderly persons, their families and caregivers. As with many other areas of consumer purchase and particularly healthcare related purchases key stakeholders include public and private service providers, voluntary associations (NGOs), retail, technology producers, IT infrastructure developers, policy makers, insurers, public administrations and standards and certification organizations.

This sub-domain address robotic solutions and technologies that aim to improve the quality of life by enriching the environments where humans live and work. These new technologies need to provide end-users with dependable, acceptable and sustainable support and assistance including where necessary individually tailored systems.

Europe is facing important challenges as an ageing populating and increasing health costs impact on society. These societal needs will drive innovation and create disruptive opportunity. Europe has the opportunity to play a leading role in this new global market.

Robotics technology has the potential to impact on this societal need.

It is generally recognised that this involves multiple step changes in terms of both human robot interaction, cognition and perception as well as mechatronics in order to create co-workers and companions able to provide an identified benefit to Users. The primary abilities for this type of robot system are safe and intuitive interaction and configurability to each User's needs. In order to create such systems new design and development processes will be needed together with certification and testing able to provide guarantees of performance in everyday environments.

This requires also an integrative approach to science and engineering in order to overcome the bottleneck affecting traditionally engineered mechatronic modular systems, that are in most cases built as simple sums of components. The creation of such systems will require significant advances in system abilities particularly in dependability and safety and cognitive and interaction ability. Advances in these system abilities should be pursued together with the definition of new strategies and approaches aiming at endowing the new robots with highly integrated sensorimotor architectures and morphologies.

The core of providing assistive care is the development of sustainable systems designed around the human being that address the questions and challenges of the ageing society. This may ultimately result in a new ecosystem of sustainable consumer service-products. This will not be realised unless there is an increase in the acceptance of robots in society with respect to elderly care. Such a vision is still far in the future and within the medium term research horizon it is important to establish the underlying elements that will be required to deliver and deploy such systems and to develop trials and platforms able to benchmark and establish performance baselines.

These assistive care robots will eventually impact on a wide range of different functions. These can be characterised into a number of different areas:

- Domestic services, including cleaning, clearing, security and food preparation.
- Social companionship covering both social interaction, healthcare monitoring and tele-presence.
- Extended living applications including personal hygiene, cognitive assistance and wellbeing, health monitoring and emergency assistance.
- Mobility both in terms of personal mobility assistance inside and outside of the home and transport over longer distances.
- Personal motivation to achieve as much as a person is capable of while providing protection and assistance.

While it is expected that individual products may well cross these boundaries in their provision of functions it is highly likely that where all of these functions are required multiple interacting systems will be needed that also communicate in the cloud. It is even conceivable that in certain applications the robot is controlled via tele-operation for critical parts of its function so that critical decisions are made by human operators.

In a number of the above functions, and particularly in domestic services, systems will be developed for the wider consumer market, but which will in turn have a significant impact on assistive care. Similarly the provision of wide spread autonomous transport will have a higher positive impact on elderly mobility by removing the need to be fit to drive.

2.8.5.2 Current Opportunity

Tele-presence robots

Current opportunities: Tele-presence robotics combines the technologies of communication with robotic platforms, in order to provide a greater interaction with and presence within the remote environment. Such systems let health-care workers check on patients and children who are homebound because of injuries, illnesses, or physical challenges can go to school. Such systems already exist but can be enhanced both in terms of their ability to remotely manipulate the environment, feedback haptic sensations, and thereby extend the range of interactions.

Barriers and limitations: While there are concerns about such systems in professional work environments and the long term reliability for elderly people and their carers and relatives such platforms can provide an alternative means of communication. However privacy and consent are critical, and in a commercial use of such devices to monitor the elderly safeguards would need to be put in place.

Personal wellbeing services

Current opportunities: The demands of a n ageing population and increased pressure on centralised healthcare mean that there is increased interest in services delivered at home. Robotics technology has the potential to act in a diagnostic and therapeutic role. Promoting wellbeing at home through improved exercise, diet and monitoring could have considerable health benefits and is preferable to the provision of central services. There is the added benefit that such systems are able to carry out multiple functions and provide continuous monitoring in a home setting, as opposed to sporadic checks in hospital outpatient departments. In the future it is possible the robots may be able to assist in cognitive and mental wellbeing by providing cognitive support even in assessing and reducing stress.

Key to the success of these devices is the development of acceptable and effective sensing systems. Many physiological measurements require physical contact and measuring emotional state or behavioural traits, critical for the diagnosis of progressive conditions, requires continual monitoring and interpretation.

Barriers and limitations: If personal wellbeing management robots are to be successful, they need to be accepted by users. Acceptance is defined as the robot being incorporated into person’s life. For acceptance of robots to occur, there are three basic requirements: motivation for using the robot, sufficient ease of use, and comfort with the robot physically, cognitively and emotionally

Robots for personal mobility

Current opportunities: Mobility is a key element in the maintenance of a healthy life and a lack of mobility contributes to the onset of many age related health issues. Robotics technology has the potential to provide a wide range of different types of mobility aids from assistance in standing and sitting to preventing falls and helping with personal hygiene.

Autonomous transport and assistance in mobility outside of the home is critical to extending social integration and maintaining a healthy life. The development of mobility aids for walking that increase confidence in moving over longer distances is also an important objective. Smart mobility aids may also be enhanced through wider connection to sources of data in the cloud to ensure safety and the delivery of localised services.

Barriers and limitations: Of critical importance to the utilisation of such devices is their ergonomic acceptability coupled to the cost of deployment and ethical and legal issues, especially legal liability. Systems that are justified though cost saving will need to demonstrate continued and sustained performance over extended periods of time. Validating and certifying systems will also be critical to acceptability. Which this type of system there area also ethical and societal consequences to their use and deployment, particularly if this is wide spread. Public engagement and debate will be an essential apart of developing such systems.

2.8.5.3 Key Market Data

Demographic changes – with a combination of increasing life expectancy and a reduction in the birth rate the ratio in Europe between elderly persons and workers will pass from the 26.8% (about one senior citizen to four workers) in 2012 to the 52.6% in 2060 (about one senior citizen to two workers). This trend will cause significant shifts in social structure. Having more persons in need of help and assistance means to increase costs of the health- and social- cares for the community with the burden resting on fewer people of work age.

Across Europe geographic differences and the balance between urban and rural life mean that the type and provision of services for the elderly will vary significantly from region to region. Currently isolation in rural communities can be addressed through the local community, as the proportion of elderly people increases these localised care may become less especially if the trend for urban living continues to increase. In an urban setting access to more advanced healthcare may be easier but isolation may be more acute. Such issues will shape the provision of systems for mobility and care and it is important to take such factors into account when proposing systems.

Healthcare management in public and private contexts - Eurostat studies [22] show that in 2011 the 20,5% of EU27 elderly population is at risk of poverty or social exclusion however this increases significantly in the European countries suffering more from the economic crisis such as Bulgaria (61,1%), Romania (35,3%), Greece (29,3%), Portugal (24,5%), Italy (24,2%) and Spain (22,3%). While there is little that current robotics technology can contribute to this particular issue it highlights an important factor, that as funding for healthcare is reduced the care of the elderly suffers in proportion. It is therefore critical that systems designed to have a wide spread impact on elderly care must provide a net economic saving in addition to delivering effective services. This will require systems that integrate into existing care provision and services.

Children with special needs - It is estimated that, overall, between 500 and 650 million people worldwide live with a significant impairment. According to the World Health Organisation (WHO), around 10% of the children and young people in the world, about 200 million, have sensory, intellectual or mental health impairment. This brings to high costs for the Healthcare system (e.g. the average lifetime cost of Cerebral Palsy was calculated to be €860k for men and €800k for women). Children will benefit from assistance provided by robots both in terms of increased mobility and in the long-term management of various conditions. Studies have already shown that robots can have an impact on children with autism and further studies are needed to investigate extending the use of robots to other conditions such as ADHD. Also Robot Assisted Learning can have several benefits for children with special needs and give extra stimuli and support to children with special learning difficulties.

2.8.5.4 Barriers to Market

In this sub-domain there are a number of barriers to market apart from the technical complexity of many applications. Providing evidence of cost effectiveness is critical in any public health application, and this must also be accompanied by safety and dependability guarantees. With systems that will operate closely with a user over long periods of time privacy and security also become important.

With the future demographic changes the use of robots in elderly care has the potential to raise significant ethical questions about the nature of that care and about the wider impact it will have on society.

Key to any potential deployment of assistive care systems will be acceptance by users and more importantly in many applications their families and guardians.

In addition to these specific concerns the user interaction with assistive robots is fundamental to many applications. This is a complex problem where the robot needs to interact in a cognitive and social context as well as physically. Proper validation and certification is required but to date there is no clear process for achieving approvals in terms of the cognitive and social performance of a system.

At the core of user acceptance are good and well-founded standards and regulatory systems that drive the process of certification. Developing these in conjunction with care providers and non-robotics experts will be a critical part of the development process.

For acceptance of robots to occur, there are three basic requirements: motivation for using the robot, sufficient ease of use, and comfort with the robot physically, cognitively and emotionally. Regardless of age the user should understand their role in the system, this helps in the acceptance of the services offered. In many applications a stronger body of evidence is required to attract further investment.

Acceptability

The acceptability is defined as “the demonstrable willingness within a user group to employ technology for the tasks it is designed to support”.
The acceptability aim is to understand the users' acceptance and intention to adopt the assistive robotics, and determine if an effective system improve the feeling of autonomy and security in a given context.

The acceptability concept consists of three parts:

Attitude - Attitude is a broad concept with different interpretations and definitions and it could be described as the tendency to act positively toward assistive robotics

Usability - The evaluation of interaction between assistive robots and humans from a social and psychological point of view in order to evaluate the effectiveness, efficiency and satisfaction

Acceptance - The acceptance is a set of subjective parameters which are able to give the assistive robot the highest degree of acceptability. The aspects, which could be investigated, are the aesthetic, the impact of user's life and user's

2.8.5.5 Key Stakeholders

An overview of all possible stakeholders involved in the domain of Robot Companion for Assisted Living includes several heterogeneous actors, coming from different fields, such as end-users, service providers, producers and organizations. Particularly, these stakeholders could be described as:

- Primary Stakeholders: end-users (i.e. principal owners of the robot or service, elderly persons, their families informal caregivers, etc.);
- Secondary Stakeholders: organisations offering services (i.e. service providers for social services, voluntary associations, shopping service stores, security services, etc.);
- Tertiary Stakeholders: organisations supplying goods and services (i.e. enterprises producing technologies, IT infrastructure developers, etc.);
- Quaternary Stakeholders: organisations analysing the economical and legal contexts (i.e. policy makers, insurances, public administrations, Standardization organizations, etc.).

2.8.5.6 Current Key Projects

- *WiMi-Care, (Supporting the Knowledge Transfer for a Participative Design Sector through Microelectronics) http://www.wimi-care.de/eng/, 2008-2011*
- *SRS, (Development and prototyping of remotely-controlled, semi-autonomous robotic solutions in domestic environments to support elderly people), www.srs-project.eu*
- *ASTROMOBILE, (Assistive SmarT RObotic platform for indoor environments: MOBILity and interaction), http://www.echord.info/wikis/website/astromobile*
- *Robot-Era (Implementation and integration of advanced Robotic systems and intelligent Environments in real scenarios for the ageing population), January 2012 - December 2015, www.robot-era.eu*
- *AALIANCE2 (Next European Generation Ambient Assisted Living), www.aaliance.eu*
- *ACCOMPANY (Acceptable robotiCs COMPanions for AgeiNg Years), October 2011- September 2014, http://accompanyproject.eu/*
- *DALI (Devices for Assisted Living), November 2011- October 2014, http://www.ict-dali.eu*

- *GIRAFF+ (Combing social interaction and long term monitoring for promoting independent living), January 2012- December2014, http://www.giraffplus.eu*
- *HOBBIT (The Mutual Care Robot), November 2011 – October 2014, http://hobbit-project.eu/*
- *SILVER (Supporting Independent LiVing for the Elderly through Robotics), January 2012 – September 2015, http://www.silverpcp.eu/*
- *PARLOMA (Improving life quality of deaf-blind people), Italian Smart Cities and Social Innovation Initiative, 2013 – 2016, http://www.fanpage.it/edu/parloma/*
- *ALIZE (Adaptive Strategies for Sustainable Long-Term Social Interaction) www.aliz-e.org*
- *DREAM (Development of Robot-Enhanced therapy for children with AutisM spectrum disorders) www.dream2020.eu/*
- *CareToy (A Modular Smart System for Infants' Rehabilitation At Home based on Mechatronic Toys) www.caretoy.eu*
- *Companionable, (Integrated Cognitive Assistive & Domotic Companion Robotic Systems for Ability and Security), January 2008 – Juli 2012, http://www.companionable.net*
- *AALias, Product development of a mobile robot system that interacts with elderly users, monitors and provides cognitive assistance in daily life, and promotes social inclusion by creating connections to people and events in the wider world, http://www.aal-alias.eu, 2010 - 2013*
- *Florence, Improve the well-being of elderly (and that of his beloved ones) as well as improve efficiency in care through AAL services supported by a general-purpose robot platform, http://www.florence-project.eu/, 2010-2013.*
- *SERROGA, Development of a robot-based health assistance service with robot demonstrators in different roles, http://www.serroga.de.*
- *ALMA, support the autonomous mobility, navigation, and orientation of the mobility-impaired person, http://www.aal-europe.eu/projects/alma/*
- *DOMEO, Domesti Robot for Domestic Assistance, http://www.aal-domeo.org/, 2009-2013*
- *Michelangelo (Michelangelo (Patient-centric model for remote management, treatment and rehabilitation of autistic children)*
- *SCRIPT (Supervised Care and Rehabilitation Involving Personal Tele-Robotics), November 2011-October 2014, http://scriptproject.eu*
- *ExCITE (Enabling SoCial Interaction Through Embodiment) http://excite-project.eu/, July 2010 - December 2013*
- *NANOBIOTOUCH (Nano-resolved multi-scan investigations of human tactile sensations and tissue engineered nanobiosensors) www.nanobiotouch.org*
- *Mobiserv (An Integrated Intelligent Home Environment for the Provision of Health, Nutrition and Well-Being Services to Older Adults), December 2009 – September 2013, http://www.mobiserv.info*
- *SHELL NATIONAL CLUSTER ON TECHNOLOGY FOR AMBIENT ASSISTED LIVING ("Shared Interoperable Home Ecosystems for a Green, ComfortabLe and Safe Living"), Italian Cluster Initiative, 2013 – 2015*
- *JADE (Joining innovative Approaches for the integration and Development of transnational knowledge of clusters policies related to independence of Elderly), February 2011 – January 2014, http://www.jadeproject.eu/*
- *R3COP (Resilient Reasoning Robotic Co-operating Systems) funded by the ARTEMIS Joint Undertaking as well as from the National Funding Authorities http://www.r3-cop.eu*

- *CORBYS (www.corbys.eu) focus is on robotic systems that have symbiotic relationship with humans. Such robotic systems have to cope with highly dynamic environments as humans are demanding, curious and often act unpredictably. CORBYS will design and implement a cognitive robot control architecture that allows the integration of i) high-level cognitive control modules, ii) a semantically-driven self-awareness module and iii) a cognitive framework for anticipation of, and synergy with, human behaviour based on biologically-inspired information-theoretic principles as well as a Brain Computer Interface (BCI).*

2.8.5.7 European Products

There are a number of assistive robot manufacturers within Europe these are typically start-ups or SMEs. Most notably in the tele-presence application area. To date major healthcare companies have chosen not to enter the assistive robotics market.

2.8.6. Key System Abilities

Intuitive user interfaces, efficient and effective operation, high functional dependability, good 3D sensing and interpretation of the working environment.

2.8.6.1 Configurability

Intuitive simple configuration	Level 1 - Start-up Configuration
Configuration without technical knowledge	Level 3 - Run-time Self Configuration
Downloadable configurations from the internet	Level 3 - Run-time Self Configuration
Self-organising sensing/action/cognitive abilities	Level 3, 4

2.8.6.2 Adaptability

Adaptation to changing environments	Parameter Adaptability Level 3 - Multiple parameter adaptation
Learning of optimal paths and process sequences	Component Adaptability Level 3 - Process chain adaptation
Learning of household object locations per room and per house.	Task Adaptability Level 2 – Single task adaptation
Systems able to self modify and adapt behaviour in accordance to environmental and individual user changes (adaptability)	Task adaptability Level 2-3

2.8.6.3 Interaction Ability

Interaction with wide age range and human intelligence range	Social Interaction Modality Level 2
Physical interaction and collaborative object	Ability target – Collaborative

handling.	manipulation.
Conversational interfaces, even in limited contexts	Social Interaction Extent: Level 1
Situational prediction: Social context-defined human-robot interaction patterns.	Social learning Level 1
Robots as social partners	Level 4 to 8 HRI Level Level 1 to 6 Safety Levels
Whole body interaction	Level 4 to 8 HRI Level Level 1 to 6 Safety Levels
Social situational awareness	Social Modality Level 2
Context standardisation and classification. The robot should adapt to various context which demands different social behaviours (work environment, house environment, hospitals, elderly vs children)	Social Interaction Extent Level 3

2.8.6.4 Dependability

Guaranteed process performance	Level 5 – Task dependability
High levels of product reliability in domestic environment.	Levels 5-6
Dependable physical interaction with the environment and users	Environmental Dependability and Interaction Dependability – Level 4 Graceful Degradation
System with appropriate taken countermeasures to handle unexpected and hazardous catastrophic consequences on the users and the environment (safety), to preserve integrity and confidentiality of data (security), to provide readily (availability) and continuously (reliability) correct services to the users	Level 7 – Predictive Dependability

2.8.6.5 Motion Ability

Human intuitive motion	Dependability Component – Motion Dependability
Fast dynamic motion (Entertainment)	Constrained Motion Level 5
Service Robots should work with person in every context, they should be designed to move on different kinds of ground, go uphill,	Level 2 to 7

recognize obstacles (both static and dynamic) present along the path and change their way in order to avoid them or even interact with them, when the obstacle cannot be avoided (obstacle negotiation).	

2.8.6.6 Manipulation Ability

Household object manipulation	
Autonomous manipulation of unknown objects	Level 8
Efficient handling of complex objects with varying properties e.g. soft, dynamic, heavy, large, extremely small	Level 5 to 7

2.8.6.7 Perception Ability

Recognition of user defined spatial areas	Location Perception Level 5 – Mapped Location
Recognition of user defined objects	Object Recognition Level 5 – Parameterised Object Recognition
Coding of intention of a person	Level 8 - perception ability
Coding of interaction with materials, objects and environment	Level 3 to 7 - perception ability Level 2 to 5 - Tracking Ability Level 2 to 6 - Object Recognition Levels
Classification of objects vs. active agents. This has an enormous impact on the interaction patters. Robot system should be able to perceive situations where is possible to interact or not with the environment.	Level 6 to 7 - perception ability Level 2 to 5 - Tracking Ability Level 2 to 6 - Object Recognition Levels
Identification of social signals	Level 8 - perception ability
Body awareness	Level 6 to 8 - perception ability Level 3 to 5 - Tracking Ability Level 9 to 13 - Object Recognition Levels
Context based perception. Sensory modalities are modified according to the context.	Level 2 to 5 - perception ability Level 4 to 6 - Levels of Scene perception
Autonomous development of perceptual skills	Level 3 to 7 - perception ability

Efficient, relevance-based interpretation of the sensory world	Level 6 to 8 - perception ability

2.8.6.8 Decisional Autonomy

Process optimisation against limited resources	Level 7 - Constrained task autonomy
Dynamic decision making for critical responses	Level 9 Dynamic autonomy
Highly dependable decision making	Functional Dependability
Robot should be able to interact autonomous and socially intelligent with humans	Level 7 to 10 and Social Interaction extent Level 2.
Decision making on incomplete information	Level 8 to 10

2.8.6.9 Cognitive Ability

Understanding the context of a wide range of domestic objects	Interpretive Ability Level 4 - Object category interpretation
Human intention understanding and prediction	Cognitive Human Interaction Level 7 - Intuitive Interaction
Prediction of action outcomes	Envisioning Level 2 - Dynamic motion prediction
Autonomous acquisition of new capabilities and generalized knowledge	Acquired Knowledge Level 9 - Interaction acquisition

2.8.7. Key Technology Targets

Because of the high volumes and the need for high reliability, and user satisfaction the market is inherently cautious of new technologies. Cost effective functions, manufacturability and IP status are key criteria in the assessment of new technologies. Value for money impact on the end product in terms of added user value is a key assessment criteria.

2.8.7.1 Systems Development

Systems Design

- Safety and dependability designed in.
- Ethical behaviour designed in

Systems Engineering

- Low cost mass production

Systems Architecture

- Well defined common architectures to allow modularisation.

Systems Integration

- Common APIs to allow module development and component market.

Modelling and Knowledge Engineering

- Realistic user environment simulation.
- User interaction models.
- Room maps with embedded semantic information.
- Complex user environments.

2.8.7.2 Human Robot Interaction

Human Machine Interface

- Minimal intuitive interfaces
- Reliable natural language, including both speech and gestures.
- Emotional and appealing interfaces.
- Interfaces encouraging social interactions

Safety

- Designed in. Certification.
- Variable impedance.
- Wearable technology for context awareness.
- Sensory and external action prediction.
- Reactive and predictive safety measures for real-time interaction with the world
- Social human robot interaction:
- Collaborative action
- Reasoning and human intention prediction
- Autonomous Interaction pattern generation and identification

2.8.7.3 Mechatronics

Mechanical Systems

- Light weight energy efficient motion.
- Human compatibility.
- Impact absorbing surfaces and mechanics to guarantee safety physical human interaction.
- Integrated sensing in mechanical joints and links:
- multi-modal surface sensors
- soft and deformable surfaces
- intrinsic elasticity
- Mobile manipulators
- manipulation in unforeseen environments
- dual-arms manipulation under unknown conditions
- dynamic dual-arms mobile manipulators
- Dexterous manipulation
- manipulation of fragile objects
- fine manipulation (e.g. like with the skills of a watchmaker)
- dual hands/arms dexterous manipulation

Sensors

- Low cost robust sensing.
- Integrated sensing and actuation.
- Bio-Sensor and Lab-on-chip
- Sensor miniaturization
- Whole body sensation based on multi-modal sensor fusion
- Multi-modal, high density sensor distribution for low cost (power, weight, computation, price)
- Implantable sensors

Actuators

- Low cost robust actuators, rotational and linear.
- Low cost multiple DOF mechanisms.
- Human musculoskeletal system-based actuators
- New-strengthened bio-artificial muscles

Power Supply and Management

- Whole day usage.
- Energy harvesting for reducing wiring
- Power optimisation and action evaluation.
- Smart power management Energy harvesting for maximal energetic efficiency

Control

- Human-like full-body manipulation control
- Variable stiffness control Design of new control architectures for hyper-redundant robots with multi-modal sensors

Communications

- Integration into existing wireless protocols. APIs for status display and command and control.
- Secure wide area communication
- Human body communication, using the body as a communication medium with low energy consumption

Materials

- Novel actuation and sensing
- Exploration of new materials with different physical properties (mechanical, electrical, etc.)
- Integration of soft, deformable and durable surfaces with sensing capabilities

2.8.7.4 Perception

Sensing

- Robust low cost 3D sensing
- User health sensing.
- Biocompatible surface and materials
- Pervasive sensing to provide computing and sensing capabilities in order to create smart environment
- Multi-modal sensor data fusion and fusion (multi-modal input and output).

- Biological inspired sensor-actor integration

Interpretation

- Obstacle and object identification.
- User's object recognition. Location identification.
- Recognition of critical situations

2.8.7.5 Navigation

Mapping

- Maintaining long term maps.
- Mapping and remapping of indoor and outdoor environment
- Real-time reconstruction of moving structures

Localisation

- Sub cm localisation in 3D over whole day.

Motion Planning

- Smooth motion in dynamic environments.
- Motion in complex dynamic environments with multiple DOF mechanisms.

2.8.7.6 Cognition

Cognitive Architectures

- Neuro-morphic architectures for coding and processing sensory information
- Neuro-morphic architectures for closing sensory-motor loops

Learning, Development and Adaptation

- Adaptation to user's environment.
- Learning user preferences, user's objects, and patterns of usage.
- Autonomous active learning based on artificial curiosity

Action Planning

- Coordination of multiple different appliances in complex tasks.
- Optimisation of path and resource
- Whole day planning.
- Action abstraction
- High-level abstract description of tasks and plans decoupling the Problem Space from the Solution Space

Knowledge Representation and Reasoning

- Knowing object context.
- Grasping user's objects.
- Ontology based self-adaptation. Knowledge based capable to combine information from different sources (visual, tactile, force, etc.)
- Self-adaptable and scalable Knowledge Management

Natural Interaction

- Managing longer user interactions.
- Action/Reaction to surface events

- Intuitive interaction interfaces for teaching and collaboration
- Full body physical interaction
- Intuitive, emotive end-user friendly design

2.8.8. Key Technology Combinations

Integrated healthcare sensing

Sensing human health parameters provides a valuable source of data for the decision making systems within assistive robots. In many cases these parameters require physical contact to allow accurate measurements to take place. The integration of this bio-sensing into the sensing systems of a robot and the development of robot behaviours that minimise the intrusiveness of measurements are required to make use of this valuable source of data.

Access to the Internet of Things

Assistive robots will in some applications need to sense not only the user but obtain information from the ambient and embedded systems around them, either data collected by smart sensors or by other smart devices in the environment. Protocols and standards for the enhancing of this data between multiple devices will be critical to the use of this data.

Cloud data processing

Given the unstructured and unknown environments that assistive robots are likely to face it is highly likely that some processing will be carried out in the cloud. For example the recognition of novel objects, or advice about strategies or decision making that may involve clinical judgement that cannot be pre-programmed or the interpretation of social context. All of these complex interpretation and interaction tasks may well sit more effectively in the cloud where their drivers and enablers can be collated from a wider range of experience than any one robot may encounter. Establishing standards for these high level cognitive and social interactions will be critical to their wide spread enhancement of assistive robots. Interacting between products by different manufacturers will be critical to wide adoption and deployment.

Dependably safe systems

Dependability and safety must be designed into a system. In assistive robotics systems will need to prove that they are dependably safe within their operating parameters. Safety and dependability are not only provided through the interaction of multiple technologies but through the design process that creates the system. Both at requirements capture and through implementation and certification. Neither safety nor dependency can be “bolted on” after a system is produced.

Currently safety and dependability can be designed into the mechatronics of a system. This can be sufficient for simple industrial applications. However, as the system increasingly interacts with unknown and unstructured environments it becomes increasingly more difficult to guarantee performance without limiting the usefulness of the system, for example by limiting its momentum or the forces it can apply. Add to this the need to guarantee safety and dependability in a healthcare setting where the system must assess the user’s state and make autonomous decisions about its actions and there is clearly a significant gap in the technology required to build a functional system.

3. Robot Categories

The Strategic Research Agenda sets out a number of dimensions that should be considered when categorising robots. One of these dimensions is the operating environment. The following section details the main operating environments for robot technology. {*Note that future revisions of the MAR will expand on the other categorising dimensions.*}

3.1 Operating Environments

There are five primary operating environments for robots:

- On the ground
- In the air
- On or under water
- In space
- On or Inside the human body

Within each of these primary environments there are further sub categories, for example in-doors or outside, in the upper atmosphere or close to the ground. Each of these different types of operating environment presents their own challenges for robots and robotics technology.

Environments can also be characterised by collective environments characterised by function or interaction with people, examples include Smart Cities, Production environments, Retail outlets etc.

Environment may also contain hazards such as high temperatures, explosive atmospheres, corrosive chemicals, or natural hazards such as extreme weather or unstable ground.

Robots designed to operating in these different environments are shaped by them such that it is possible to characterise aspects of such a robot without categorising their function. Operation in a particular environment leads to common requirements for technologies, to common certification and regulation, common standards and benchmarks. These common elements create the potential for robotics organisations to focus on particular environments, producing products, systems technology and services that address the needs of a particular environment while working horizontally across the different market domains. The purpose of the following sections is to capture these common characteristics.

3.1.1. Characterising Environments

It is possible to characterise environments in more detail by parameterising what is meant by the different terms used to describe environments. It is possible to identify two different characterisations:

- How easy it is to interpret the environment.
- How dynamic the environment is.

These map into a spatial and temporal characterisation.

Spatial Characterisation

Spatial characterisation is based on the ability of the system to interpret the environment based on “sense data” with respect to the task at hand. This interpretation will take many different forms, from identifying and segmenting objects, to identifying safe places to move to, to identifying locations and affordances. It will also depend on the “certainty” of the sense data. In this context the “sense data” may be generated by the robot or acquired from other sources, the term “robot system” is therefore used to capture this wider gathering of data.

While this ability to interpret the spatial environment will vary between tasks it is possible to identify some fixed points within the range of possible difficulties. The environment can be described in the following terms:

Fixed: The operating environment of the robot does not alter, while the robot itself will have some physical effect on its environment, for example moving a piece of work from one place to another, the environment itself does not alter. This is typical of many industrial robot applications where there is minimal, almost zero, uncertainty in the sense data. The robot may not need to plan motion paths.

Structured: The environment around the robot contains objects and spaces that can easily be "identified" with a high certainty by the robot system with respect to the task. The environment has been structured to match the sensing capability of the robot system. The robot may need to plan motion paths.

Semi-structured: The environmental contains a mixture of objects and features. It contains "identifiable" objects, where the robot system can deduce knowledge of the objects from sense data and objects which can be identified with a reduced level of knowledge gained per object, for example non-rigid objects or natural objects. It is likely that the task relevant objects have been structured to be more easily identifiable, or the robot system has been sensitised towards correctly identifying these objects. The environment may also contain features that are beyond the interpretation capability of the robot system, for example highly reflective surfaces. As a minimum ability the robot will be able to sufficiently interpret the environment such that it can move safely within it, in the context of the task.

Unstructured: The robot cannot rely on the environment to aid its interpretation. The robot may encounter any object and it may need, within the task context, to deduce generic properties or characteristics from what it interprets with sense data. Object boundaries may not be well defined, for example unknown objects that need to be manipulated might have articulated joints. There may be a lack of distinguishable features, where object boundaries are unclear and most importantly there is no defined pathway or region on which the robot should move. The robot system will need to explore and safely "test" the environment.

Temporal Characterisation

Temporal characterisation is based on the predictability of the environment over time with respect to the perception capability of the robot system. This refers both to the dynamics of objects in the environment and of the sense data as a result of external variation, for example from changes in the weather.

Static: There is no significant variation in the environment beyond that which is made by the robot system. No external un-expected events occur that have to be handled beyond the need to maintain system safety. Variation in sense data is within the interpretation ability of the robot system.

Predictable: Other actions take place in the working environment that alter the environment and are not under the control of the robot system. However the effect of these actions is predictable, although their timing may not be. The robot system is able to alter its behaviour to carry out its task. Variations in sense data are mostly within the interpretation capabilities of the robot system and when they are not it is able to detect this and delay or alter its actions.

Dynamic: Other actions take place in the environment moment to moment that require the robot system to adjust its control and decision making in order to carry out or continue to carry out its task. Sense data may change as a result of external events and the robot system will need to distinguish between the different causal factors that have changed the sense data, for example the reflection of a flashing bright light is not interpreted as an object changing shape.

Unpredictable: Other actions take place in the environment that are not predictable but which alter the way the robot system must carry out its task, for example by altering the operating space or moving objects critical to the task. The robot must use the interpretation of sense data to deduce characteristics and generate a response that can safely mitigate these unpredictable events within the context of the task.

3.1.2. Smart Cities

It is widely recognised that robotics technology has a key role to play in the development of Smart Cities, from the delivery of services to the integration of transport. Robotics will also be a key component in the maintenance of infrastructure and in the data gathering needed to drive Smart City processes.

Europe is pioneering many of these developments and more information about the European Innovation Partnership on Smart Cities and Communities can be found here: http://ec.europa.eu/eip/smartcities/. Smart Cities in Europe include Copenhagen, Barcelona, Helsinki amongst others. There are Smart Cities and Social Innovation Under 30" programme of the Italian Ministry of Research and Universities through the PARLOMA Project. There are also smart cities such as the San Raffaele Smart City, a private compact urban district with 25,000 people.

Smart Cities will be able to utilise a broad range of robotics technology, and eventually will become shaped by that technology. For example, the layout of buildings, roads and access to buildings is strongly related to current transport modalities, autonomous transport will alter the character of that modality and thus the shape of the city. The location of buildings and their relationship to people who live and work there will alter and change over time. For example the use of smaller autonomous urban transport that is hired per journey will remove the need for parking spaces in retail areas.

Much of the use of robotics in Smart City will be in service delivery, waste disposal, transport, infrastructure maintenance etc. However in these applications and in applications related to social care, retail and recreation, social intelligence will play a key role in raising levels of acceptability and deployment. Robots able to exhibit social intelligence will create sustainability within the Smart City through persistent interaction that provides a social and functional gain. Social intelligence will provide robots with a higher degree of acceptability. One resulting challenge will be for robotic systems to exchange and communicate social intelligence so that a collective improvement is achieved.

Social intelligence is not confined to interaction, it will also assist in the interpretation of operating context for services and in filtering data gathered using socially relevant categorisations. There is a significant incentive to connect robots and smart city data systems. Initially this will reinforce the current links between Smart Cities and ICT such as the Internet of Things and Semantic Web by providing a wider means of gathering data. In time as robots become better at interpreting details of the social environment this information will improve the assessment of underlying social trends over time thereby allowing the city to respond. This will require greater cooperation among cross-disciplinary experts and will create greater opportunities for social applications of robotics technology.

3.1.3. On the Ground

The characteristics of robots that operate on the ground are so numerous that it is left to the individual market domain sections to detail what is required in the range of applications within each domain.

3.1.4. Wearable Robotics

3.1.4.1 Domain Overview

The list of potential Wearable Robotics (WR) applications is extensive and can be divided into different application areas (non-exhaustive):

- Worker support and prevention in factories, construction, logistics and delivery
- Emergency responders
- Rehabilitation and physical therapy
- Assistance in daily living environments
- Prosthetic limbs
- Recreational consumer devices
- Elderly person mobility support
- Human robot collaboration

All these applications share the characteristic that the robots are externally attached to the human body and interact with the sensorimotor system of a human user, for purposes of augmentation, assistance to, or substitution of human motor functions, such as locomotion or object manipulation, as well as interact with human body structures. Wearable Robotics as understood here, include for example exoskeletons, soft exo-suits, robotic orthoses and prostheses.

1.2.2. Current Opportunity

> *"There are many ongoing initiatives dedicated to wearable robotics, including conferences, special issues and international workshops. All of them demonstrate the growing interest in the topic. Overcoming the physical limitations of the body, whether natural, age-induced, or caused by diseases or traumatic events, with temporary or permanent effects, is an actual societal need. Finally, considering its highly inter- and trans-disciplinary nature, the value of wearable robotics for the education of young engineers should not be overlooked" – [Vertechy et al.,2014 IEEE RAM].*

Examples are "The International Workshop on Wearable Robotics" (WeRob), the Wearable Robotics Association (WearRA), with it's WearRAcon conference, special sessions and workshops at IEEE conferences like ICRA, IROS, ICORR and BioRob, as well as special issues in many robotic journals, such as IEEE Robotics and Automation Magazine.

Development of a new generation of Wearable Robots, is currently expected through the integration of diverse fundamental technical expertise and by developing cross-domain cooperation. Such a new generation of WRs will be characterized by better integration and adjustment to the human users, as well as to specific domains of application, which will allow WRs to become a mainstream type of technology and thus largely expand WRs societal benefits.

The cross-disciplinary knowledge required to develop wearable robotics is not generally integrated nor is there currently sufficient inter-disciplinary communication on their impact on WRs, a non-exhaustive list is:

- human biomechanics
- science of human sensorimotor control (understanding and modelling)
- human-robot interaction and interfacing
- robot-ethics and philosophy of technology
- application-related fields such as clinical medicine or industrial production
- modelling of (interaction with) human tissues
- mechatronics

- control theory
- wearable sensor technology
- system energetics
- system architecture and system integration
- soft robotics design
- ergonomics and human-centered design
- materials and component technology.

A critical challenge in Wearable Robotics is to integrate these critical domains to provide best practice and to develop technical synergies that will impact on the market.

3.1.4.2 Barriers to Market

Wearable Robotics are in most applications a novel type of product, which implies that Ethical, Legal and Societal (ELS) aspects may arise around their market introduction. In particular markets and their related regulatory environments are not currently well adjusted to wearable systems. For individual products this will pose a range of barriers to market introduction. Several efforts can be made on a general level to support market introduction of WR technology, of which some are listed in this section. However for many applications the technology is currently not mature enough to allow the applications to be commercially delivered. An analysis of the related technology roadmap is presented later.

Definition of performance targets and related benchmarks

In order to express and communicate purpose and performance of specific WR technologies, it is important to establish a framework that defines such concepts, and to define benchmarks that allow systems to be quantified. Such work will facilitate communication to potential clients, comparison of products and R&D efforts, and assist the definition of a safety and regulatory environment. Some current efforts in this field are:

- Benchmarking of bipedal locomotion working group http://www.benchmarkinglocomotion.org/
- Study group for IEEE RAS Standing Committee for Standards Activities, oriented at exoskeletons/WRs

Regulation and certification issues

The emerging WR technology poses potential specific safety threats that are currently not clearly addressed by existing regulation and certification frameworks.

Recently several efforts have started in standardization, especially:

- ISO 13482, a recently published standard on safety for personal care robots, including WRs, developed under ISO TC184/SC2/WG7 "Personal care robot safety", related to non-medical, non-industrial application of WRs.
- IEC SC62A & ISO TC184/SC2 – JWG 9 "Medical electrical equipment and systems using robotic technology", related to medical robotics (medical applications of WRs)
- IEC/SC 62D & ISO/TC 184/SC 2 – JWG36 "Medical robots for rehabilitation", also related to medical applications of WRs

Concerning certification, the FDA has for example recently started to classify exoskeletons for use outside of the clinic, a first occurrence of WRs being deployed in common environments. See FDA publication 2015-03692, 24-02-2015 on "Medical Devices; Physical Medicine Devices; Classification of the Powered Exoskeleton".[11]

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[11] https://www.federalregister.gov/articles/2015/02/24/2015-03692/medical-devices-physical-medicine-devices-classification-of-the-powered-exoskeleton

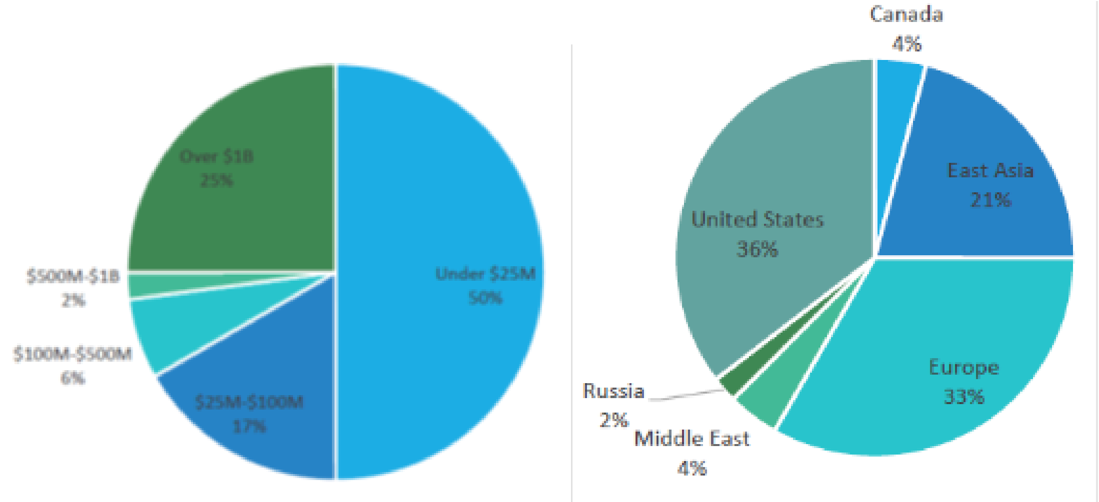
Consideration of ELS-Aspects

Because of the close coupled interaction WRs have with their users and the intrinsic “degree of autonomy” that such a robot could exhibit, it is important to consider Ethical, Legal and Societal (ELS) issues, especially as they may impede the societal acceptance of WRs. Thus, it is essential to consider user aspects during the design of WRs and to take into account, as early as possible during development, ELS issues that may impact the acceptance of a particular product. It is further essential to have a theoretical framework in place to discuss, identify and address ELS issues and facilitate communication between stakeholders.

3.1.4.3 Key Market Data

As stated before, the WR market consists of a conglomerate of different market segments. Currently, the market for ‘exoskeletons’ is the clearest emerging segment, and hence the best documented. The following quote characterizes this market segment:

> *“A relatively small group of companies are working hard to stake an initial foothold in what has been forecasted as a $2.1B market by 2021, with a 73% CAGR between 2014-2019. Of the 48 companies with a reasonable claim to participating in the exoskeleton business, half are still in the start-up mode with valuations that are less than $25M. One quarter are large global companies such as DaeWoo and Lockheed-Martin, who have made their names in other business lines and are interested in getting into the exoskeleton market. Many of the remaining quarter started as small firms spun out of research or university organizations that were bought up by larger companies.*
>
> *The three main areas of innovation are currently centred in the United States, Europe and East Asia. Those three regions account for 90% of the global market with much of the innovation linked to the vast research networks located within those business markets.*
>
> *In Europe as well as in the United States, much of the innovation and activity is occurring primarily at the smaller scale, emerging from research centres aligned with universities and from engineers in the industry deciding to step out on their own. While larger companies are involved in buying up the smaller innovative start-ups, much of the activity is still concentrated at the start-up level. The market in East Asia illustrates a very different trend with the majority of the action occurring in old line, well capitalized industry giants.”* [12]



Exoskeleton-companies by left-size, and right-geographical distribution (Source: WearRA - Wearable Robotics Association)

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[12] Information and quote from: http://www.wearablerobotics.com/profile-of-the-global-exoskeleton-business-landscape/

3.1.4.4 Relationship to Domains and Markets

Wearable Robots as a type of robot have wide applicability across numerous domains. Of primary interest are Manufacturing, Healthcare, Logistics and Consumer Applications. All of these markets are at an early stage of development.

3.1.4.5 Key Stakeholders

Europe has a wide range of stakeholders and End Users for Wearable Robotics. Stakeholders are becoming increasingly aware of the potential for applying WR however the identification of key products is still in discussion. This is supported by the growth in Wearable Robotics companies offering specific devices, by underlying changes in the regulatory environment driven by policy makers and industry and by the increase in available Wearable Robotic services.

3.1.4.6 Current Key Projects

So far Europe has played a leading role in the R&D effort on WRs. The European Commission has funded research activities in this field starting from FP4 (e.g. MANUS project), with increasing support from FP5 (e.g. GAIT project on lower limb exoskeletons or DRIFTS project on upper limb exoskeletons), through FP7-ICT with past (e.g. NEUROBOTICS, EVRYON, BETTER, MUNDUS, MINDWALKER, CORBYS, CYBERLEGs, SCRIPT) and on-going (e.g. SYMBITRON, BIOMOT, BALANCE, STAMAS, WEARHAP, WAY, WaNDER) projects, as well as under Horizon2020 (AIDE, RETRAINER), mostly focused on basic development as well as medical (therapy or assistance) applications of WRs. Additionally WR projects have been funded under the AAL program (EXO-LEGS, AXO-SUIT), focused especially on elderly users, and under the FP7-NMP (e.g. ROBO-MATE), focused on industrial applications. Moreover, many relevant projects on wearable sensors have been funded (e.g. INTERACTION, RUNSAFER, SUPRONICS, WI-SHOE, WEAR-A-BAN, WIISEL, SimpleSkin, CuPiD, AMYO, MYOSENS), or on relevant robotic aspects (interaction control: HUMOUR, COGIMON; soft actuation: VIACTORS, STIFF). Next to this EC funded work, many national research projects focusing on, or are relevant to, WR. (e.g. “Wearable soft robotics for independent living” – UK, Capio – Germany, LOPES – Netherlands, HYPER – Spain, ALTACRO – Belgium, among many others).

3.1.4.7 Key System Abilities

Wearable systems place very specific demands on Motion Ability, Perception Ability and Decisional Autonomy in addition to the requirements for safe and intuitive Human Robot Interaction.

3.1.4.8 Key Technology Targets

Key technologies that are likely to create Step Changes in the wearable robotics market include light weight dynamic mechatronics, improved energy sources and low noise actuation systems. Improvements in cognitive assessment of users and the environment will also help systems to interact more appropriately with both the user and the environment. It is also likely to step changes in materials technology and in control methods will impact on wearable technology.

3.1.4.9 Key technology Combinations

Key to the deployment of wearable systems will be the tight integration of sensing and actuation coupled to human compatible mechanisms. In particular systems that can be ether adapted or manufactured to fit the individual characteristics of a user will increase the mass market potential of wearable systems and this in turn may depend on the development of design systems able to include models of the end user, including the dynamics of their motion.

3.2 Aerial Robotics

3.2.1. Domain Overview

The list of potential Aerial Robotics applications is extensive and can be divided into a number of different application areas:

- Inspection and Maintenance
- Logistics and delivery
- Search and rescue
- Environmental Monitoring

The largest of these application areas is in inspection and maintenance and there are already products and service companies starting to develop the opportunities. Regulation is still one of the largest barriers and if a pan European market is to be established focus must be placed on the development of a harmonised regulatory environment across Europe.

Inspection and maintenance of facilities using Aerial Robots has a number of particular advantages. It can be low cost, interactive and can result in a map of data that has commercial value. The value of knowing the condition of a facility to its owner and being able to increase inspection frequency will reduce liability and allow maintenance operations to be planned with a higher level of certainty. This in turn reduces down-time and therefore costs. Taking a high value facility off-line to carry out an inspection tasks is highly undesirable and Aerial robots have the potential to provide a alternative lower cost solution.

Infrastructures that can be inspected include, power generation plants, offshore plant, industrial plant. In most cases the main advantage is that aerial robots are able to reach places that are hard to reach from the ground or which would be hazardous to humans. In the future it is envisaged that Aerial robots will gain manipulation ability and be able to carry out maintenance tasks in addition to inspection tasks.

In most inspection and maintenance applications aerial robots will be integrated with human operators. The goal is to build systems which complement and act as an aid to the human mission expert and are easily deployable system, able to provide information (e.g. the map of the workspace) while seamlessly and performing the tasks that do not require human input, thus reducing the cognitive load on the operator.

Key stakeholders for aerial systems are:

- Companies developing inspection and maintenance equipment
- Robotic manufacturers already in the market and manufacturers of aerial platforms).
- Companies providing inspection and maintenance services
- End users, owners or guardians of buildings, plant and equipment that might benefit from aerial inspection.
- Environment control organisations.

According to the report of the Hearing (Brussels, October 2009) on Light Unmanned Aircraft Systems (LUAS), with a Maximum Take-off Mass of 150 Kg), in 2009 there were 20 European Countries with a total of 169 Unmanned Aerial Systems manufacturers an developers, including 117 SMEs of which 104 manufacturers were producing LUAS.

Given the level of activity in this area of application these numbers are likely to have increased significantly since then.

The main barriers to market are regulatory and in particular the lack of pan European harmonised standards will currently fragment the market along national lines.

It should also be noted that there is a Roadmap for the integration of civil Remotely-Piloted Aircraft Systems into the European Aviation Systems.

3.2.2. Current Opportunity

The potential to reduce costs when inspecting critical infrastructure has been recognised and is driving much of the commercial development of Aerial systems. There is also a recognition that the data gathered has intrinsic long term value. This value increases when positional data is augmented with data from different types of sensors, for example the sensing of pollutants, radiation, chemicals; or through post processing able to classify structures or condition.

The types of infrastructure that may benefit from aerial inspection include the following:

- Distribution facilities: electrical lines and distribution centres, pipes and others
- Infrastructure: bridges, dams
- Power generation plants: indoor (boilers, chimney stacks) and outdoor (pipe works, cooling towers, dams, wind turbines, grid equipment).
- Pipes and other aerial components in thermal plants, solar plants, inspection and maintenance of wind energy generators, and others.
- Industrial plants with aerial facilities such as oil, gas and chemical industries
- Offshore plants: offshore oil and gas facilities, oil-drilling platforms, offshore wind plants, wave generation
- Indoor aerial inspection and maintenance of big parts in manufacturing, i.e. aeronautic manufacturing
- Support for decommissioning works carried out at civilian nuclear power reactors, nuclear and radiological laboratories, research reactors, enrichment plants, uranium mines and uranium processing plants, reactors that power ships (including icebreakers and aircraft carriers), power stations, and fuel processing facilities
- Surveillance of large process facilities (oil and gas refineries, chemical industry)

The current technical barriers are related to the characteristics of the platforms and the ability of navigation and positioning with enough accuracy for the kind of applications being considered here. The main commercial barriers are related to the cost of the equipment but mainly to regulations.

Development of the following activities in inaccessible (or very difficult and costly to access) sites, involving risk for workers.

- Industrial inspection and maintenance with actuation on the environment. Examples include non-destructive inspection by contact, taking samples, deployment of sensors, cleaning operations
- Aerial manipulation for a variety of applications including maintenance activities, dismantle and disassembly operations, construction works
- Aerial support (inspection, data acquisition or even future manipulation) to the increasing market of decommissioning of civilian nuclear power reactors (reactors that reach the end of their original design lives reviewed after the Fukushima Daiichi accident[13]), as well as to the oil and gas market due to the ageing offshore structures[14]

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[13] Closing and Decommissioning Nuclear Power Reactors Another look following the Fukushima accident. http://www.unep.org/yearbook/2012/pdfs/UYB_2012_CH_3.pdf

[14] Analysis of Terrestrial and Space Energy Technology Roadmaps, (ESA Contract 4000107937-13-NL-MV, Robotics and Remote Sensing)

3.2.3. Barriers to Market

Regulations and certification issues

The lack of regulations for small aircraft has impacted the development of the aerial robotics market. The new regulations for Light Unmanned Aerial Systems (LUAS) or Very Light Aerial Robotic Systems (VLUAS) already developed or being developed in many countries are eliminating the barriers. Thus, the International Civil Aviation Organization (ICAO) published in 2011 the Circular 328 AN/190 on Unmanned Aircraft Systems (UAS) addressing UAS systems and operations being considered for implementation in the United States National Airspace System. In the United States the Federal Aviation Authority recently (July 2013) published the Unmanned Aircraft Systems (UAS) Operational Approval (8900.227) devoted to regulate the operation of these systems within the National Airspace System. In Europe, the United Kingdom Civil Aviation Authority published in 2002 the CAP722, the UK policy for the certification and operation of UAV Systems, both military and civil. Since publishing CAP722, the CAA has further reviewed and developed its UAV policy, both in the light of recent experiences and as a result of changes in regulatory responsibilities since the formation of the European Aviation Safety Agency (EASA). CAP722 last issue was published in 2012 (5th edition), taking into account legal, certification, spectrum and security issues. Later several countries have developed similar regulations.

In the Roadmap for the integration of civil Remotely-Piloted Aircraft Systems (RPAS), published June 2013, it is pointed out (Annex II) that:

- *"currently, non-military RPAS operations are already known to take place in a significant number of European Union (EU) countries (Austria, Belgium, Bulgaria, Czech Rep., Denmark, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Netherlands, Poland, Portugal, Slovenia, Spain, Sweden, UK),as well as in Norway and Switzerland. Several of these countries have national rules and regulations in place permitting a limited variety of RPAS operations [Czech Rep., Denmark (has adapted Swedish rules), France, Ireland, Sweden, Switzerland, UK]. Several countries are preparing the publication of national rules and regulations [Belgium, Netherlands, Norway (will adapt Swedish rules)]. In most of other EU countries, non-military RPAS operations are currently being permitted on an exemption basis. By far the majority of the authorized RPAS operations that are taking place today are performed within Visual Line-of-Sight (VLOS). Beyond Visual Line-of-Sight operations are legally possible in France and have taken place in Denmark (Greenland) and Norway".*

Characteristics of existing platforms

Up to recently, the characteristics of the available platforms (heavy, unsafe, with very small payload) have limited the applications. The development of more reliable, safe and low-cost systems involving not only platforms but also communication, including dedicated command and control frequencies, and integration with the ground infrastructure, is also having a significant impact.

The development of new light small platforms will also promote new applications of flying robots in close proximity to people.

3.2.4. Key Market Data

Current products in the market are aerial robots and Unmanned Aerial Vehicles to perform basic functions for inspection. These inspection tasks can be carried out in a wide range of different market domains.

Where there is potential for novel and disruptive application of aerial inspection it is difficult to assess the market size, for example in agriculture or in environmental control activity, or in search and rescue. However in industrial inspection the market in certain areas can understood within the context of the market as a whole. In applications such as power plat inspection aerial robots have the potential to make a significant impact.

The market opportunities are very large due to the potential saving of costs and the substitution of human work in dangerous conditions. Thus, for example, the human inspection of plant can only be performed when the plant or critical subsets are stopped. In a 300 MW power plant the reduction in outage gains is about €0.75M per day.

The market data for maintenance of processing industries is also very high. Thus, for example, in 2008, companies spent more than $56Bn in the Hydrocarbon Processing Industry with $13.7bn in USA and $42.3bn outside USA. Furthermore, in the Power, Oil & Gas and Basic Chemistry industry, system sales vary up to €150m per year depending on the industry up to €400m per year for operation.

There are plans to close up to 80 civilian nuclear power reactors in the next ten years While many of these reactors are likely to have their operating licenses extended, they will eventually be decommissioned. Under a recent EU Directive15 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, all Member States are to ensure that funding resources are available for decommissioning[15]. At the global level, the need to have adequate resources available for decommissioning is being addressed by the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. The coming decade will probably witness the rapid expansion of decommissioning activity, costing tens of billions of dollars. The decommissioning industry's performance will be critical to the future of nuclear power generation.

The decommissioning sector has been steadily forming over a few years but it is expected to see some major progress over the next five to ten years. Hundreds of offshore oil and gas platforms will be recovered from the North Sea over the coming years. Analysis by industry body Oil and Gas UK and decommissioning agency Decom North Sea put the value of this work at £30bn over the next 25 years.

In mid-2011, 16 nuclear power plants (power and prototype reactors) were in different stages of decommissioning in Germany. At the end of 2011, another eight reactors were finally shut down and decommissioning will commence in the next few years. The remaining nine plants will be finally shut down in a stepwise process until 2022 due to the amendment of the Atomic Energy Act of July 2011; one plant each by the end of 2015, 2017 and 2019 and another three plants by the end of 2021 and 2022. These plants will also be decommissioned after their final shutdown. More than 30 research reactors of different size and more than 10 nuclear fuel cycle facilities were finally shut down and were or will be decommissioned. At the site of the Greifswald nuclear power plant (KGR), Europe's largest decommissioning project is being undertaken. The decommissioning of the Greifswald and Rheinsberg nuclear power plants of the former German Democratic Republic (East Germany) is financed from the federal budget[16].

Along with the Gulf of Mexico the North Sea is among the leading regions for spending on the decommissioning of offshore oil and gas infrastructure. The North Sea decommissioning market will see significant growth in the next decade, with many structures older than 20 or 30 years.

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[15] Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:199:0048:0056:EN:PDF

[16] http://www.neimagazine.com/features/featuredecommissioning-in-germany 27 March 2013.

3.2.5. Relationship to other Domains and Markets

There are relations with other markets such as industrial robots in industrial plants, mobile inspection robotics, space (flying robots for orbital robotics, exploration with flying robots), marine robots, agriculture (precision agriculture, monitoring, spraying), construction (mapping with aerial robots), and the relations with other markets such as transportation of goods will be apparent in the short future.

There are opportunities for joint initiatives with other topic groups. Thus, for example, a joint initiative is the teams of aerial, marine (surface and underwater) and ground robots for inspection and maintenance

3.2.6. Europe's Place in the Market

The position of Europe in the military and security UAV market is clearly behind USA or even Israel due to the lower investments on research, development and innovation for many years. However, this is not the case in the market for civilian and commercial applications where the position of Europe is better. In particular, the future markets of aerial robotics for industrial application and services could be better. Today Europe has relevant manufacturers of aerial platforms, sensors, navigation systems and industrial robots and can play a leading role in future markets such as the aerial manipulation.

According to the Annex 2 of the Roadmap for the integration of civil Remotely-Piloted Aircraft Systems, published June 2013,

- *"there is already a substantial RPAS industrial community in Europe. The following European Union (EU) countries conduct RPAS design and production activities (at systems level): Austria, Belgium, Bulgaria, Czech Rep., Finland, France, Germany, Greece, Hungary, Italy, Latvia, Netherlands, Poland, Portugal, Slovenia, Spain, Sweden, UK. In addition, Norway and Switzerland are also actively involved at systems level. It is of interest to remark that not all of these countries are traditional aviation industry countries. Currently, non-military RPAS operations are already known to take place in a significant number of European Union (EU) countries (Austria, Belgium, Bulgaria, Czech Rep., Denmark, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Netherlands, Poland, Portugal, Slovenia, Spain, Sweden, UK), as well as in Norway and Switzerland".*

However, it should be pointed out that, in addition of the above aerial platforms manufacturers, aerial robotics may activate the participation of robotics manufacturers and end-users (see Domain Overview above)

3.2.7. Key Stakeholders

Europe has a wide range of stakeholders and End Users within this domain. In many cases the potential for applying Aerial robotics is becoming increasingly understood both with End Users and with policy makers. This view is supported by the growth in Aerial Robotics companies offering platforms and associated technology, by the changing regulatory environment driven by policy makers and by the increase in service companies offering Aerial Robotic services.

3.2.8. Current Key Projects

The list of FP7 projects devoted to aerial robotics or with strong components of aerial robotics includes ARCAS (Aerial Robotics Cooperative Assembly System, Integrated Project developing aerial manipulation capabilities), AIRobot (aerial robotics for inspection), SFly (visual navigation, new aerial platforms), FP7 EC-SAFEMOBIL (Estimation and Control for Safe High Mobility Cooperative Systems, Integrated project, landing in mobile platforms, coordination of multiple aerial platforms, tracking), PLANET (PLAtform for the deployment and operation of heterogeneous NETworked cooperating objects, Integrated Project, integration of aerial robots with wireless sensors and actuators and with ground robots), FIELDCOPTER (GPS-EGNOS based Precision Agriculture using Unmanned Aerial Vehicles), MUAC-IREN (Multi-UAV Cooperation International Research Exchange Network, Marie Curie, long endurance cooperative aerial robotics), SHERPA (Smart collaboration between Humans and ground-aErial Robots for improving rescuing activities in Alpine environments), and ICARUS (Search and Rescue).

Previous related projects on aerial robotics have been FP5 COMETS (coordination and control of multiple heterogeneous aerial vehicles), FP6 AWARE (joint load transportation, deployment of sensors, cooperation of multiple aerial robots), FP6 MUFLY (Fully Autonomous Micro-Helicopter) FP6 MICRODRONES (Development of a new concept of completely autonomous flying robot equipped with monitoring sensors).

Current National projects are CLEAR (Cooperative Long Endurance Aerial Robotics, Spain), WSAN-UAV (deployment and operation of wireless sensors and actuator networks by using UAVs, Spain), ADAM (autonomous mobility, cooperation of multiple platforms, Spain) PERIGEO (research on space technology using UAVs, fault detection and recovery in aerial robots, Spain), PROMETEO (application of UAVs to forest fires, trajectory planning), SINTONIA (UAV with null environment impact, Spain), DEMUEB (research on key technologies and operational solutions for UAS, Germany), BLE UAV (research on UAV applications on vineyards, Germany), PEA DECSA (Development of navigation and perception algorithms for small drones in urban environment, France), ROBOTEX (National network of robotics platforms, France), senseSoar and AtlantikSolar (Solar UAV, Switzerland), Skye (Omnidirectional Spherical Blimp, Switzerland), Air-Ground Localization and Map Augmentation Using Monocular Dense Reconstruction (Switzerland), Distributed Flight Array, and Flying Machine Enabled Construction (Switzerland), SMAVNET (developing swarms of flying robots that can be deployed in disaster areas to rapidly create communication networks for rescuers, Switzerland),

It should be noticed that the above list of projects did not include the ones funded under FP7 Transportation Systems, SESAR, EDA or EDA/ESA

On the other hand, some decommissioning projects are, the Shell's biggest current project is the Brent field decommissioning. Brent was one of the UK's earliest and largest oil & gas development projects, with all four platforms (Alpha, Bravo, Charlie and Delta) coming on-stream in 1975-76. The Brent Delta ceased production at the end of 2011 and Wood Group PSN was awarded a Decommissioning Services Contract (DSC) by Shell to decommission the field. Decommissioning of all four platforms could take as long as ten years. ConocoPhillips's main decommissioning project at present is taking place at the Ekofisk field, offshore Norway.

3.2.9. European Products

Today, there are hundreds of Light Unmanned Aerial Systems and Aerial Robots produced by the European manufacturers. Thus, the above mentioned report of the Hearing on Light Unmanned Aircraft Systems (LUAS) (Brussels, October 2009) listed 252 unmanned aerial systems with a Maximum Take-off Mass lower than 150 Kg .

3.2.10. Key System Abilities

Aerial robots for inspection and maintenance will be able to flight outdoor and indoor in constrained environments, to interact cognitively and physically with other aerial robots, and eventually ground robots and marine robots, will have manipulation capabilities, and eventually morphing capabilities, will be able to perceive the environment for localisation, navigation and application (inspection and maintenance) and to take decisions based on these perceptions and in cognitive capabilities.

3.2.10.1 Configurability

Morphing aerial platforms	Level 4 – Autonomous Configuration
Ability to adopt different configurations depending of the environment and the state	Level 3 – Run Time Self Configuration

3.2.10.2 Interaction Ability

Interaction cognitively and physically with other aerial robots, ground robots and marine robots. E.g. in manipulation tasks	Robot Robot Interaction Level 5 – Team Coordination.
interpretation of human commands.	Human Interaction Modality Level 2 – Direct Interaction

3.2.10.3 Dependability

Designs intrinsically dependable	Dependability Level 5 – Task Dependability

3.2.10.4 Motion Ability

Ability to move indoor and outdoor avoiding obstacles and exerting forces	Unconstrained Motion Level 5 – Force constrained Path Motion
Ability to move fully autonomously in indoor and outdoor spaces with many obstacles	Unconstrained Motion Level 4 – Position constrained path motion
Ability of long term flights and afford hard environment conditions (i.e. wind)	Unconstrained motion Level 6 – Parameterised Motion

3.2.10.5 Manipulation Ability

Ability to perform aerial manipulation tasks.	Grasping ability Level 4-6, Handling Ability Level 2 - 3
Ability to perform complex manipulation and tasks requiring the application of significant forces	Manipulation Ability Target – Tool Manipulation

3.2.10.6 Perception Ability

Autonomous perception for object recognition, tracking and obstacle avoidance	Perception Ability Level 5
Integration of visual and range only localisation and Simultaneous localisation and mapping in GNSS denied environments	Location Perception Level 3
Fully autonomous on-board autonomous	Ability Target: Immunity to Natural

perception in outdoor complex environments with variable lighting conditions	Variation. Handling ability Level 5 – Positioning for placement.

3.2.10.7 Decisional Autonomy

On-board reactivity and planning including multiple- robot systems autonomy	Level 8 – Multiple Task Autonomy
On-board reactivity and planning including multiple- robot systems autonomy in complex indoor and outdoor environments	Level 8-9

3.2.10.8 Cognitive Abilities

Interpretation of scenes under uncertainty for aerial inspection and maintenance,	Reasoning Level 4. Object interaction Level 5
interpretation for manipulation,	Interpretative Ability Levels 3-5

3.2.11. Key Technology targets

3.2.11.1 Systems Development

Systems Design

- Enhancements in system-level robustness, ease of deployment and intuitive human-robot interaction. Standardized, modular hardware and software components.
- Assembly of aerial robots into systems of systems, potentially developed by several partners.

Systems Engineering

- Design of systems composed of multiple aerial, ground and marine robots
- Ability to cope with the variability of conditions of application scenarios occurring in a real mission, very easy to deploy systems

Systems Architecture

- Distributed architectures for multiple aerial robots and heterogeneous multi-robot systems
- Distributed architectures for multiple aerial robots and heterogeneous multi-robot systems with dependability and reconfiguration properties

Systems Integration

- Improved tools for hardware and software integration of aerial robots for inspection and maintenance.
- Improved tools for hardware and software integration of micro and nano aerial robots for inspection and maintenance.

Modelling and Knowledge Engineering

- Integrated modelling including kinematic, dynamic and aerodynamic interactions of one and several aerial robots in task involving physical contacts

- Tools for integrated modelling including kinematic, dynamic and aerodynamic interactions of one and several aerial robots in task involving physical contacts
- Integration of inspection and maintenance knowledge
- Databases for learning and decision making

3.2.11.2 Human Robot Interaction

Human Machine Interface

- Multimedia and virtual reality technologies for inspection and maintenance by means of aerial robots
- Advanced physically interacting interfaces with humans with multiple heterogeneous autonomous systems

Safety

- New aerial robots with soft materials and dependability
- New aerial robots with soft materials and dependability for minimization of damages in case of failures.
- Reliable system state estimation and autonomous decision making for emergency procedures

3.2.11.3 Mechatronics

Mechanical Systems

- Development of morphic platforms with the ability to change configuration (i.e. fixed wing and rotary wing) for different phases of the flight and operation (take off, approach, hovering, landing)
- Combination of ultra light micro- and nanostructures with high stiffness and flexible materials. Low cost individual construction and production for each particular customer and application

Sensors

- Sensors embedded in the structure of the aircraft and arms, for closed loop control as well as for inspection and maintenance activities.
- Intelligent sensors with embedded computation for inspection and maintenance.
- Light weight, low cost 3D-scanners. Optical sensors with extreme high dynamical range and high resolution.

Actuators

- Low cost, high performance actuators with redundancy. High grade of sensor integration.
- Low cost multiple DOF mechanisms, Individual, platform- and/or application tailored actuators

Power Supply and Management

- Aerial robots with extended endurance, Redundant power supply, utilization of sun and wind energy
- Persistent flight robots, Sources with high energy density

Communications

- Aerial robots with Integrated antennas in the structure, Long range (100 km) broadband links with moderate transmission power and minimal weight

- Secure wide area communication, Network infrastructure for reliable broadband communication at each location. Broadband networks based on stratospheric flying platforms

Materials

- Application of new materials and parts with embedded sensing capabilities, Low cost composite materials
- Micro- and nanostructures tailored for particular platforms and applications

Control

- Local positioning and reactive control loops involving interactions with the environment.
- Methods for utilization of all dynamical capabilities of the platforms.
- Coordinated control of hybrid (aerial, ground and underwater) robotic teams.
- Reliable reconfiguration and adaptation for different situations including emergency
- Distributed control of large swarms for inspection and maintenance

3.2.11.4 Perception

Sensing

- Distributed sensing of multiple aerial robots for inspection. Low cost small 3D sensing
- Improvements in low cost 3D sensor robustness and reliability, Reliable perception of natural environment in real time

Interpretation

- On-board interpretation of images and data for inspection and maintenance Reliable obstacle and object identification and recognition in working space
- Fully autonomous reliable complex scene interpretation for inspection and maintenance, situation awareness and autonomous decision making

3.2.11.5 Navigation

Mapping

- On board 3D mapping for inspection and maintenance
- Simultaneous localization and mapping in complex large GNSS denied industrial environments

Localisation

- Accurate localisation of aerial robots for inspection and maintenance
- Very accurate (sub cm) long term 3D localisation in GNSS denied environment, reliable localisation in wide range natural environments.

Motion Planning

- Safe motion planning of multiple aerial robots in constrained environments for inspection and maintenance
- Reduction of high-dimensional configuration spaces for online motion planning.

3.2.11.6 Cognition

Cognitive Architectures

- Definition of a cognitive architecture for inspection and maintenance by means of aerial robots

- Reliable behaviour.

Learning, Development and Adaptation

- Basic methods for learning from human operators in inspection and maintenance tasks
- Learning application preferences, objects, and patterns of usage.

Action Planning

- Distributed task allocation for multiple aerial robots in inspection and maintenance, Formal description of tasks/missions, planning based on advanced search techniques
- On-board optimal planning and re-planning in complex environments, task and mission planning as a combination of sensing, situation awareness (interpretation) and motion planning.
- Grasp planning of aerial manipulators for maintenance applications
- Real-time grasp planning of complex objects
- Fully distributed planning of teams of heterogeneous robots for safe and efficient inspection and maintenance
- Fully distributed planning of large teams of heterogeneous robots with communication constraints

Knowledge Representation and Reasoning

- Application of cognitive knowledge of inspection and maintenance when interpreting scenes and situations for planning and control
- Application in real time of cognitive engineering for inspection and maintenance with multiple cooperative robots
- Extract knowledge from inspection and maintenance applications to be used in new applications
- Knowing object context.

Natural Interaction

- Collaborative aerial robots for inspection and maintenance
- General purpose cognitive robotic platform for inspection, maintenance and decommissioning.

3.2.12. Key technology combinations

Medium Term Requirements

- Combination of aerial robot navigation and positioning with on-board manipulation capabilities for maintenance applications
- Integration of inspections sensor technology with position and navigation data to create inspection data maps
- Visual servoing for navigation in inspection applications and aerial manipulation in maintenance applications.
- Integrated sensing in the structure of the aerial robots for navigation and inspection applications
- Integrated sensing in mechanical joints and links of very light on-board manipulation
- On board integration of new 3D cameras in very light robots for inspection and maintenance applications
- Integration of new material technologies for the design of micro and nano aerial robots for inspection

- Integration of radio based positioning technologies and range only SLAM for indoor and outdoor navigation without GNSS in inspection and maintenance

Long Term Requirements

- Swarms of intelligent micro aerial robotic vehicles built with new materials, with cognitive capabilities, interacting physically with the environment and with other aerial vehicles, for inspection and maintenance.
- The lack of safety properties would present a significant barrier that can be overcome by means appropriate design and new technologies to increase the safety.

Impact and dependence

- Future light aerial robots for inspection and maintenance will be built with new materials, integrating sensitive properties, will be able to perceive, plan, and react to external stimulus, will use bio-inspiration, will be able to cooperate with other robots, and will be integrated in future internet to acquire inspection and maintenance knowledge and to provide the results.

3.3 Marine Robotics

3.3.1. Domain Overview

The Oceans cover more than 70% of the earth's surface and support an estimated 90% of the life forms on our planet. They constitute one of the main resources for food, employment, and economic revenue, and a potential source of still unknown living and mineral resources, as well as alternative energies. The oceans also harbour a vast cultural heritage in the forms of archaeological sites yet to be found and explored. However, the oceans remain largely unknown. This is especially true in the case of the deep ocean: deep, dark, vast, and subject to tremendous bar pressure, the bottom of the oceans is the largest component of the solid surface of our planet and yet it is also the least known. Marine robotics technologies play a key role in a wide range of functional applications including:

- environmental surveys, monitoring, and assessment;
- oil and gas surveys;
- harbour and border surveillance and protection;
- underwater intervention;
- critical infrastructures inspection (e.g. wave and wind offshore energy installations)
- deep sea mining;
- scientific data collection and sampling;
- underwater farming and fish-farming;
- underwater archaeology and cultural heritage conservation;
- transport systems safety (ship structure inspection, emergency towing systems);
- highly automated vessels;
- companion robots for divers;
- search & rescue.

In the last years, pioneer research has been carried out aiming at the development of autonomous marine robots able to monitor deep and surface sea waters, to increase the safety of sea transport and to execute underwater intervention operations involving grasping, manipulation and transportation, as well as assembly activities. The use of marine robots in industry, research and service applications has dramatically increased in the last 20 years. The market for underwater systems is among the most valuable within professional service robots.

Yet there are both technical and non-technical market barriers that need to be addressed on a medium as well as long time scale. These include:

- lack of legislation for autonomous marine vehicle operation (non technical);
- lack of systems to monitor all the parameters required by the EU Water Framework Directive (technical/non technical)
- autonomous anti-collision systems (technical);
- autonomous, automatic, light green-sensor devices for water pollution assessment (technical);
- very low bandwidth-based remote operation (technical);
- underwater optical and acoustic communications, vision, & localisation (technical);
- low cost, easy to use, systems for persistent autonomous surveillance and monitoring operations (technical);
- energy harvesting systems for persistent autonomy at sea (technical)
- automatic AUV launch, recovery and docking systems for energy recharging and massive data transfer (technical)
- systems for cooperative navigation and motion control of surface and underwater vehicles (technical)
- combined vehicle-manipulator systems for underwater infrastructures inspection (technical)

According to the key market data presented in a following section, the potential market size of unmanned marine vehicles, including remotely operated and autonomous underwater and surface vessels, will be on the order of $3bn between 2015 and 2019. However, considering that because of the economic value of the oceans, about $40.4bn is spent annually collecting data and doing ocean operations, the above-mentioned estimate is largely pessimistic according to some analysts.

Research and advances in marine robotics technology will contribute to several scientific and societal aspects such as the sustainable management of ocean and coastal resources, through the improvement of climate modelling, better and safer use of European fossil resources, acceleration of the exploitation of marine energies, and availability of new food resources, the preservation of cultural heritage, and the improvement of sustainability and safety of transport.

Moreover, from a scientific and technological point of view, the methodologies for autonomy developed in the marine environment can be shared and transferred to other fields of applications, e.g. space and air.

3.3.2. Current Opportunity

As discussed in the Douglas-Westwood AUV Gamechanger Report 2008-2017 the distinction between autonomous and remotely operated underwater vehicles is getting less clearly defined with AUVs working with manipulators or carrying an ROV to a location. In particular, in order to support oil and gas operations, AUVs should include the ability to work at 3,000m depth, reliable long-range electrical power and navigation systems that can tackle long missions with infrequent positioning updates, safe and reliable launch and recovery systems for variable sea states, and a set of robust fail-safe mechanisms. They will operate within an infrastructure including underwater docking stations as well as acoustic positioning and communication links. AUVs will execute routine mapping of deep-water oil and gas fields, and cable and pipeline routes linking the sites to the shore. Accurate manipulation and manoeuvring abilities are fundamental for protecting and exploring deep wrecks in archaeological applications.

The United Nations Convention on the Law Of the Sea requirements for the identification of national seabed boundaries such as the foot of the continental slope open the market to a massive use of AUVs operating in addition to conventional hydrographic vessels for high resolution hydrographic survey of vast areas of seabed. The extension of European national seabed boundaries around, for instance, Portuguese islands on the Mid Atlantic ridge or French islands close to Mozambique, offers dramatic opportunities to Europe for deep water mining. Activity that requires the development of specialised robotic vehicles and tools for intervention and operations.

Deep ocean mining and resource exploration also requires adequate environment monitoring and marine ecosystem impact assessment. This will also provides market opportunities for robotic systems in prior data gathering, operation monitoring and post operations assessment.

The European Marine Strategy, committing each Member State to provide a detailed assessment of the state of the environment, a definition of "good environmental status" at regional level and the establishment of clear environmental targets and monitoring programmes, offers the opportunity of developing and marketing Autonomous Underwater and Surface Vehicles for the environmental monitoring of coastal zones. Cooperative low cost multi-node data collection systems, possibly integrated with remote (aerial and satellite) sensing systems, can represent an appropriate technical solution to the problem of extended, both in space and time, monitoring of coastal areas able to support their environmentally compatible anthropization, e.g. for sand beaches refurbishing.

Shallow water AUV and USV systems can be very useful for port and harbour authorities to detect silting next to docks and to identify areas that need dredging.

Marine science and ocean monitoring continue to be a driver market for marine robotics: AUVs and USVs will be an integral part of ocean observing systems, providing flexible and mobile sensor platforms for researchers; AUV teams and swarms can monitor large area such as fish stocks and health, requiring long-endurance capabilities, and fast phenomena such as harmful algal blooms.

Maritime transport safety can be dramatically increased by the use of robotic systems for routine repeatable standardise inspection of vessel hull and internal structure. Further development of control and anomaly detection software will help robotic vehicles to identify objects or items of interest and then change plans as necessary and communicate as required with remote human supervisor/inspector.

With the increasing stress on the fishing resources and disadvantages of inshore aquaculture, offshore aquaculture expected increase (both in volume, area, and variety of species) will lead to new market opportunities for robotic systems. These will provide exploration, management and security support to an increasing set of new automated aquaculture systems and offshore aquaculture facilities.

In addition to marine applications, freshwater bodies offer new market opportunities to underwater vehicles. Though fresh water makes up only around 1% of Earth's water resources, freshwater bodies (rives, lakes, bogs, bonds) are in densely populated regions, they are of high economic interest and under severe environmental pressure. This environment (very shallow water, low visibility, rapid currents) pose different challenges to vehicles design (such as small size and very good manoeuvrability).

Generally speaking, high demand for research vessels and cost is making Autonomous Marine Vehicle-based research more attractive to many organisations.

Moreover the growing interest and the influx of funding in the field of marine robotics in general foster the investigation of disruptive design and methodologies.

Major barriers to market development have been summarised in the previous section.

3.3.3. Future Opportunity

- Spawned by increasingly challenging scientific and commercial demands, the market is expected to witness the transition of many of the above systems from the laboratory to the real world. Namely, in what concerns multiple robotic systems for ocean exploration and exploitation, as well as advanced systems for intervention in underwater structures. Type of stimulation needed: initiatives aimed at fostering close interaction and partnerships in the scope of end-user driven projects involving research institutions, commercial operators, and stakeholders.
- Networked cooperative control of multiple autonomous vehicles: the combination of acoustic communications, absolute and relative navigation (using acoustics and vision), and control algorithms to make a group of marine robots keep a formation in the presence of adverse environmental conditions or change its formation to better adapt to the tasks being performed (e.g., marine habitat mapping in complex, non-structured 3D environments).

3.3.3.1 Scientific Opportunities.

Design and development of marine robots and technological systems for:

- Ocean/climate studies,
- Ocean exploration at unprecedented scales
- Deep ocean habitat studies (including those near hydrothermal vents)
- Deep ocean observatories deployment and operation
- Environmental surveying and monitoring
- Sustainable exploitation of marine resources
- Detection and monitoring of marine pollutant spills
- Archaeological surveying (for cultural heritage preservation)

3.3.3.2 Commercial Opportunities.

Advanced marine robots and systems to afford commercial operators the tools needed to substantially improve the means available to:

- Monitor critical infrastructures (e.g. ocean harbours)
- Monitor ocean energy production facilities (e.g. offshore wind and wave energy generation plants)
- Detect and monitor the effect of hydrocarbon spills
- Assess the size and type of fish stocks,
- Assess the extent of mineral. oil, and gas deposits
- Carry out and monitor the impact of underwater mining activities
- Increase the efficiency and safety of gas and oil exploration and exploitation activities
- Increase the safety of human operations underwater
- Enhance the safety of human and vessel rescue operations

On a longer time scale, new relations in terms of human presence on the sea, either by the extending current limited continuous presence in the sea (as in offshore oil platforms) with the establishment permanent sea cities, recreational, scientific on the surface and underwater human inhabited structures, will foster and expand the global market needs in all the SRA defined domains: civil, consumer, commercial, transportation and military with relation to marine robotics.

3.3.4. Barriers to Market

The main barrier to opening the market of marine robots in daily civilian coastal and harbour applications is given by the lack of rules on the operations of unmanned vehicles at sea and the consequent legal issues, in particular concerning liability in the case of accident. This aspect concerns, in particular, unmanned surface vehicles whose use in surveying and monitoring of shallow waters by, for instance, environmental agencies and harbour authorities is thus dramatically reduced. Moreover, the lack of approved protocols for remote inspection and maintenance of ship structures is currently closing several market opportunities for dedicated robotics systems. In this case, however, the introduction of robotic inspection tools, characterised by lower operating costs, can allow a more detailed planning of maintenance operations with a dramatic cost reduction for ship-owners and service companies.

The definition of good experimental methodologies and practices for at-field qualification of new marine robotics technology, as well as the study of the related legal issues, is a key mitigation action to reduce these barriers. On the other hand research priority on technical issues strictly related to legal barriers, e.g. design and development of reliable autonomous anti-collision systems, will contribute to their overcoming.

In a similar way, research on the development of autonomous, automatic, light green-sensor devices for water pollution can mitigate the barrier to civil market given by the lack of monitoring capabilities of all the parameters required by the EU Water Framework Directive.

On the other hand, the main technical barriers, transverse to general market opportunities, are listed in the following together with the corresponding mitigation actions:

- reliable medium bandwidth underwater communication systems: improvement of acoustic communication techniques; development of new technologies for short range communications, including optical communications.
- robust vision-based perception and motion estimation: development of cognitive perception algorithms for unstructured environments supported by low cost, size and consumption hardware
- reliable localisation systems: combination of multiple existing techniques
- very low bandwidth based remote operation: development of multi-level adapting tele-operation systems
- automatic AUV launch, recovery and docking systems for energy recharging and massive data transfer;
- low cost, size and weight energy harvesting and production systems
- low cost, easy to use, systems for persistent autonomous surveillance and monitoring: the overcoming of the above-mentioned technical barriers is fundamental

3.3.5. Key Market Data

The main market sectors for the unmanned marine systems and marine technologies are offshore, security and research. Main market drivers in the three sectors are listed in the table below.

Market Drivers for Offshore oil and Gas

- growing offshore exploration and production programmes;
- deeper waters (remote and harsh environments);
- potential for life-of-field inspection solutions;
- high costs of pipeline inspection using conventional systems;
- drives for efficiency and cost reduction with respect to vessel time.

Market drivers for security applications

- security industry faces budgetary cuts;

- literal zone operations;
- fleet reduction strategies promoting the use of multi-role platforms;
- integrated MCM systems with a single command control interface;
- quieter submarine propulsion require new detection methodology;
- higher resolution sensors;
- widespread acceptance of unmanned technology
- Market drivers for Research Applications
- catastrophic events (e.g. the Macondo oil spill and the Japanese Tsunami bringing new focus and funding into marine science);
- regional, national & international research ocean observation systems;
- large-scale, long-term global issues such as climate change;
- local, small-scale research activities;
- desire for increased density and frequency of observations;
- research needs in previously hard-to reach areas such as under-ice
- study and preservation of underwater cultural heritage

Other market sectors to mention are Food sector comprising Fisheries and Aquaculture, Civil infrastructure and law enforcement and Entertainment.

In the marine food sector, fisheries and aquaculture have different requirements and different robotics value chains. The traditional fisheries uses a relatively low level of robotics systems. The fishing process mainly incorporates marine sensors (such as echo-sounders) for detection from surface boats.

Upon catch the remaining industry vertical line (processing, transport and distribution) has in many cases a high level of automation and is similar to other food processing industries. Here robotics market opportunities rely on process optimization and with transport.

At sea fish tracking can benefit from increased use of robotic systems (namely AUVs) capable of detecting shoals and eventually from new catch support systems (here with advantages brought by robotics in terms of lowering environmental impact of to open new forms of more selective fish collecting).

Offshore aquaculture clearly provides a promising market for marine robotics. With a value chain structured in B2B relationships, both with robotics products sold to aquaculture industries or services provided, opportunities arise either on the exploration process, with the possibility of efficiently and with reduced cost monitoring large areas or on the security and surveillance of the installations themselves.

In civil infrastructures monitoring and law enforcement the main robotics End Users are either government institutions or organizations entrusted with functions. The markets here comprise both underwater systems as ROVs for inspection and maintenance and AUVs for patrolling and protection and unnamed surface vehicles surveillance and monitoring. These can also be used in other law enforcement activities such as large area patrolling with reduced costs in comparison with standard manned vessels.

The prospects of using advanced and innovative marine robotic systems and technologies are very promising, especially in the offshore business. The offshore operations and maintenance world spend is expected to exceed $330bn from 2010 to 2014. In addition to that, strong growth in offshore wind is underway - in 2010 the capital expenditure was £3.1bn (370 turbines), while in 2015 capital expenditure is expected at £10.6bn (914 turbines). UK is aiming to source 31% of electricity from renewable by 2020 (currently 9%). Global demand for subsea vessels is expected to climb beyond 310,000 days for the forecast period 2011 - 2015 – a 28% increase on the previous five years.

The marine robotics technology development will influence the existing robotic as well as non-robotic market by introducing "de-manning" to reduce costs & increase safety; reducing the impact of high vessel costs; improving reliability of remote systems; introducing advances in autonomous technology; increasing awareness & acceptance of unmanned systems.

ROV MARKET AND TRENDS

Global ROV vehicle sales in 2010 totalled approximately $850m and the ROV operations market is expected to grow from $976m (2011) to **$1.5bn in 2015**. Drilling will remain the biggest market sector and the ROV days for drilling support are expected to grow at near 14% CAGR (compound annual growth rate) which implies a need for an extra 221 work-class units in the period 2011-2015. Construction support days growth is estimated at 6% CAGR while IRM activities will rise at 7%.

In 2010, oil and gas purchased approximately 50% of ROVs, while ROV sales for defence & security and scientific research equalled 25% for each sector.

Market drivers for ROVs are offshore drilling, the security environment, and the need for ocean data. The prospect for offshore drilling varies by location, yet offshore exploration in Brazil, Nigeria, Indonesia, and the Gulf of Mexico are expected to be strong. In the security market, ROVs are routinely used for forward observation, reconnaissance, and mine counter-measures by the military. ROVs will increasingly be adopted by organizations charged with ocean rescue and port security seeking effective tools for scanning and observation, including hull inspection. The need for data on the oceans is driven by the need for creating detailed maps for navigation and minerals extraction, particularly in the Arctic.

AUV MARKET AND TRENDS

The AUV market is smaller than the ROV market - according to industry interviews conducted by the Duke University Centre on Globalization, Governance and Competitiveness (CGGC), the global annual expenditure on AUVs is roughly $200m, dominated by U.S. manufacturers. The market is expected to grow to **$2.3bn by 2019**. Even though the compounded annual growth rate of 30% is optimistic, the growth potential of AUVs is clearly large.

Currently, the military/security market makes up approximately 50%, the scientific research market approximately 30% and the oil and gas market approximately 20% of AUV sales. By 2016, military & research sectors will hold 89% of AUV market (CAGR 12% & 8%), and commercial sector 11% market, but with CAGR of 20%.

The World AUV Market Prospects for 2010- 2019 (includes oil & gas, research and military applications) in the most likely scenario the forecast gives that a 1,142 AUVs are required over the next decade: 394 large, 285 medium, 463 small units. Unit sales forecasts through 2019 estimate that the majority of sales will occur in small AUV sales. However, large AUVs will dominate the projected $2.3bn sales because of their high unit costs.

The AUV emerging markets are renewables, site survey, Life of Field (LOF), rig moves and hydrography. Long-term subsea operations such as LOF demand new technology. AUVs will increasingly be used in the oil and gas market, primarily due to the cost of using ROVs. The increased functionality in AUVs and the demand for floating oil production systems and remote fields are also drivers for adopting AUVs.

USV MARKET AND TRENDS

Since unmanned vehicles are cheaper and faster to produce than manned vehicles, Unmanned Marine Vehicles (UMVs) and Unmanned Ground Vehicles (UGVs) end up being very attractive during periods of financial uncertainty and are in fact one of the few recession resilient sub-sectors of the defence industry. Global Unmanned Marine and Ground Vehicles market is thus foreseen to reach **$1.96bn by 2017**. This trend is confirmed by the experience of European SMEs whose estimates, based on requests of quotations for available products, set to 200-300 units of light vehicles in Europe annually the USV market volume for inland waters only.

It should be noted that the above market values relate to vehicles only and do not include the costs of development programmes, deployment systems, ship-borne data processing systems and other ancillary equipment.

3.3.6. Relationship to Domains

Marine systems have extensive application across the Civil and Commercial Domains. There are also applications in transport and in the consumer sector mainly in terms of recreational activities.

3.3.7. Europe's Place in the Market

The global production of ROVs and AUVs is located in a very few countries, namely USA and UK and USA and Norway respectively.

As summarised by the following examples Europe plays a key role within the marine robotics market, including services and sensors and instrumentation.

- Out of top 10 ROV manufacturers in 2000-2010, 5 are from EU, 4 from USA and one from Japan.
- Out of top 10 AUV manufacturers in 2000-2010, 4 are from EU, 5 from USA and one from Canada.
- Two out of five larges ROV service operators are located in the UK, two in USA and one in China.

The key end-markets for ROVs are oil and gas, defence, and scientific research. The oil and gas industry uses ROVs for pipeline inspection and burial, underwater construction and repair, and detailed ocean mapping. The defence uses ROVs for detecting and neutralizing underwater mines. ROVs also are used for a variety of security applications, including port security (hull inspections) and water rank inspections at nuclear facilities. Scientific applications of ROVs include ocean data gathering, mapping, and exploration.

The main end-users of underwater sensors and instrumentation are:

Offshore energy (offshore oil and gas exploration and development and the emerging renewable energy sectors, tidal and wind energy development);

Marine defence: The largest market for underwater acoustic technology is marine defence (IBISWorld 2011). Relative to acoustic sensor chains, navies and coast guards do not provide a key end-market in the non-acoustic underwater sensor technologies global value chain.

Scientific research: Underwater sensors are used in scientific research to detect the depth of a water body, measure water currents, temperature, as well as the presence or absence, abundance, distribution, size, and behaviour of underwater plants and animals.

Aquaculture: As the fastest growing food sector on earth, with an average annual growth rate of 6.6% from 1970 to 2008

3.3.8. Key Stakeholders

Europe has a highly developed marine industry, most European countries have extensive sea boarders and there are considerable levels of marine based trade that operate from within Europe including major shipping routes and cargo terminals. Europe is also engaged in oil and gas extraction from under sea resources and has a considerable fishing industry. There is a well developed marine supply chain and robotic technology is already in use in some niche sectors of these markets. There is considerable awareness of the potential for marine robotics amongst marine focused stakeholders and there are wide range of SMEs and service companies designing building and deploying marine robotic systems.

3.3.9. Current Key Projects

CON4COORD	http://www.c4c-project.eu	ICT-2007.3.7.(c): 223844	2008-2011
UAN	http://www.ua-net.eu	FP7:225669	2008-2011
HydroNet	http://www.hydronet-project.eu/	FP7-ENV-2007-1: 212790	2008-2012
Co3AUVs Cooperative Cognitive Control for Autonomous Underwater Vehicles	http://robotics.jacobs-university.de/projects/Co3-AUVs	FP7-ICT-2007-3 GA 231378	2009-2012
FILOSE	www.filose.eu	FP7:231495	2009-2012
SHOAL	http://www.roboshoal.com	FP7:231646	2009-2012
MINOAS	http://www.minoasproject.eu	FP7 SST.2008.5.2.1	2009-2012
TRIDENT	http://www.irs.uji.es/trident	FP7:248497	2010-2013
CLAM	cordis.europa.eu/projects/rcn/95346_en	FP7: 258359	2010-2013
CFD-OctoProp		FP7-PEOPLE-2010-RG	
NOPTILUS	http://www.noptilus-fp7.eu	FP7:270180	2011-2015
CART - Cooperative Autonomous Robotic Towing system		CART-285878-FP7-SME-2011-1	2011-2013
MORPH - Marine robotic system of self-organizing, logically linked physical nodes	https://www.facebook.com/morphfp7project	FP7-ICT-2011-7 GA 288704	2012-2016
PANDORA	http://cordis.europa.eu/projects/288273	FP7:288273	2012-2014
ICARUS	http://www.fp7-icarus.eu	FP7:285417	2012-2015
ARROWS		FP7-ENVIRONMENT	2012-2015
EUROFLEETS2		FP7-INFRASTRUCTURE	2013-2017

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ROBOCADEMY		Marie-Curie Action	2013-2017
EURATHLON	http://www.eurathlon2013.eu	FP7-ICT	2013-2015
PETROBOT		FP7-ICT	2013-2016
CADDY - Cognitive Autonomous Diving Buddy	http://www.caddy-fp7.eu/	FP7-ICT-2013-2 GA 611373	2014-2016
SUNRISE	http://fp7-sunrise.eu/	FP7-ICT	2013-2017
WiMUST Widely Scalable Mobile Underwater Sonar Technology	http://www.wimust.eu/	H2020	2015-2018
DexROV	http://www.dexrov.eu/	H2020	2015-2018
ROBUST	http://eu-robust.eu/	H2020	2015-2020
BRIDGES	http://www.bridges-h2020.eu/	H2020:635359	2015-2019

National funded projects

COMAS - COnservazione programmata, in situ, dei Manufatti Archeologici Sommersi (Planned conservation, "in situ", of underwater archaeological artefacts)	Italy	MIU: PON01_02140	2011-2014
TRITON	Spain		2012-2014
PICMAR - Intelligent Platform for Multimodal Characterization of the Seafloor and Submerged Structures	Spain	MICINN-INNPACTO: IPT-2012-0463-310000	2012-2015
MARIS - Marine Autonomous Robotics for Interventions	Italy	MIUR PRIN: 2010FBLHRJ	2013-2016
RITMARE	http://www.ritmare.it/ Italy	BANDIERA cofund	2012-2016
MEDUSA DEEP SEA	PORTUGAL http://www.medusadeepsea.com/	EEA Grant	2015-2017

3.3.10. European Products

There are a wide range of different European marine robotic products ranging from whole systems to specialised sensing and software delivery companies. Europe has a long marine history and many global marine equipment companies are based in Europe.

3.3.11. Key System Abilities

3.3.11.1 Configurability

In order to be tailored to different application scenarios, field unmanned marine robots must be **reconfigurable** at different levels. They should be able to use interchangeable sensor and/or tool skids payloads. State of the art commercial system, programmed at way-point level should evolve to more advanced programming systems based on the desired mission goals. Modular Robots: Sensor Suite / Tool skids Payload

- Way-point/Event-based programming
- Distributed Heterogeneous Robot Teams
- Goal Oriented Programming

3.3.11.2 Adaptability

Marine robots must **adapt** their behaviour to their operational environment. Underwater robots should be able to adapt their trajectories to the 3D topography even at short distances to gather optical imagery. This also applies to robots operating in more structured environments were the vehicles must survey 3D artificial structures on the seabed. Adaption to environmental conditions taking into account the presence of currents, wind, sea state is also very important for field operation vehicles.

- To 3D Structured / Unstructured Environments
- To Environmental Conditions: Currents, Wind, Sea State, Optic (light/illumination)
- To faulting components (fault tolerance)
- Intelligent “Motivation Dynamics” with temporarily changing priorities (situation-specific priorities)

3.3.11.3 Interaction Capability

Robots should **cooperate** and **interact** with operators, divers, other robots and/or submerged infrastructures. State of the art HMI for commercial ROV systems are predominantly based on real-time optical and acoustic imagery of the operational environment. More advanced HMI where the robot is shown to the operator within the actual 2D/3D scene reconstructed online from the opto/acoustic video stream, are desirable to make users aware of the robot situation within the operational environment. Docking will be necessary in different fields: 1) to allow recharging for long term deployment, 2) to simplify the launching and recovery, 3) to allow for broad band communications through cabled subsea infrastructures and 4) to enable manipulation in underwater infrastructures. In spite of recent achievements with new underwater modem technologies, like optical or electromagnetic modems, current technology is still far to achieve high data-rate wireless networking at large distances, being this one of the major difficulties limiting the interaction capabilities of current systems.

- Interaction to: Operators, robots, subsea infrastructures, ships, divers.
- Advanced HMI for Tele-operation, Tracking & Supervision.
- Docking / Recharging
- Interoperability of underwater communication systems and integration with underwater sensor networks
- Trans-media access (radio-acoustic link) and combination of satellite-radio-acoustic communications

- Broad-band Large Range Wireless Communication
- Networking

3.3.11.4 Dependability

Since deep ocean is an hazardous environment, robot **dependability** is a key concept in marine robotics. Safe recovery of the robot after a mission is the major goal. To this aim, safety assessment, fault tolerance during the operation are a must. Robot dependability is expected to play an important role to make long term/range deployment unsupervised systems a reality.

- Robot healthy/safety assessment
- Fault Tolerance
- Long Term (Permanent?) Deployment
- Long Range Deployment

3.3.11.5 Motion Ability

Marine robots move predominantly on the sea surface or through the ocean water. Multiple cooperative vehicle operations involving surface, underwater and aerial vehicles are expected to increase in the future. At a longer term, hybrid vehicles being able to navigate on surface as well as to dive, or even being able to fly and dive have an interesting potential for long range operations. Key motion capabilities include dynamic positioning, (cooperative) 3D motion/path following close to the seafloor in potentially high relieve 3D terrains and/or across submerged artificial 3D structures.

- 3D Terrain Compliant Path Following
- 3D motion at visibility distance (5m to 1m).
- Dynamic Positioning
- Motion across heterogeneous media (Air/surface/underwater)

3.3.11.6 Manipulation Ability

Although the **ability to manipulate** objects underwater has been extensively used in intervention ROVs, the level of automation is very far from those exhibited by state of the art industrial or mobile robots. ROVs and HROVs may potentially benefit from advanced sensor aided tele-manipulation, visual servoing and force feedback. Automated docking to subsea infrastructures for maintenance, as well as into smart launch and recovery systems to improve deployment is desirable. Together with docking, increased levels of automation during the intervention are necessary in both structured and unstructured environments, progressively evolving from advanced tele-manipulation systems towards autonomous multipurpose manipulation robots.

- Sensor Aided Tele-manipulation
- Visual Servoing
- Force feedback
- Autonomous Manipulation in Structured and unstructured Environments
- Docking to subsea infrastructures
- Smart Launch & Recovery Systems
- Shape adaptive grippers
- Multipurpose Autonomous Manipulation
- Cooperative Manipulation
- Systems for cooperative grasping and transportation of heavy objects.
- Improvement of the sensitivity and accuracy of underwater manipulators.

3.3.11.7 Perception Ability

Moving across a 3D world, the vehicles must be able to **perceive** it using multiple sensing modalities. Multi-sensor multi-modal data fusion is necessary to allow the robot to be aware of its environment and current situation. Self localisation is one of the most important abilities as it provides the basis for controlling the vehicle as well as for geo-referencing the data. State of the art methods based on DVL navigation possibly aided with a form of acoustic transponder networks (SBL, LBL, USBL, GIB) should be complemented with more advanced methods requiring less infrastructure like single beacon navigation. With the increasing number of multiple vehicle operations, cooperative navigation will also play an important role. Of particular interest are the methods not requiring external infrastructure but taking profit on a priory maps (Terrain Based Navigation) or self built maps (SLAM). Potentially they will allow the vehicles to move in un-confined areas. High resolution wide range seafloor imaging in 2D (photo-mosaicking, FLS sonar mosaicking, SSS mosaicking), 2.5 D bathymetry and textured bathymetry, and their natural evolution to 3D representations (for instance using stereo, structure light or 3D sonars) is one of the principal abilities required. 4D mapping to represent temporal evolution is also needed in scientific and fisheries applications. The ability of combining maps from different missions or simultaneously gathered with multiple vehicles is necessary to obtain the best possible cartography. Although of high interest, multiple vehicle mapping online, would require a break-through in the communications since it has broadband requirements. Together with long term (permanent) navigation in unconfined environments and high resolution wide area 3D mapping, these are considered long term goals.

- Multi-sensory Perception, sensor & data fusion.
- DVL Navigation Aided with Acoustic Transponders
- Cooperative Navigation
- Map-Based Localization (with and without a priory maps).
- 3D sensing (stereo, structure light, 3D sonars…)
- Mapping in 2D, 2.5 D, 3D and 4D using different sensing modalities (optical/acoustic).
- Map fusion (multimodal, multi-vehicle, multi-session)
- Change detection.
- Long Term Localization in Unconfined environments
- High Resolution Wide Area 3D Mapping
- Cooperative Mapping (break through in communications required)

3.3.11.8 Decisional Autonomy

As autonomous entities, marine robots require a high level of Decisional Autonomy. They need to be able to assess their own situation within the context of the operation and decide how to behave to ensure their safety while guiding the robot through the mission objectives. Since robot resources (sensors, actuators, energy…) are limited an optimal use of them should be scheduled. Key abilities include: 1) smart sampling (decide where to sample to improve the overall quality of the outcome data), 2) Mission planning and 3) Multi-objective coverage/path planning taking into account the robot constrains. Only with a high level of robot autonomy will be possible to face the long term goal of achieving persistent deployment of marine vehicles

- Optimal use of limited resources
- Situation Assessment
- Smart Sampling
- Mission Planning
- 3D Coverage planning
- Multi-objective Path Planning with constrains
- Persistent Deployment

3.3.11.9 Cognitive Ability

Cognitive abilities like object detection and identification, semantic mapping and grasp planning/learning, may have a potential for target applications in structured environments like subsea infrastructures. Without the need to target full autonomy they may also play an interesting role in increasing the levels of autonomy of how underwater manipulations is done by robot operators.

- Interactive probing for interactive prediction of dynamics systems
- Detect Objects and their context
- Semantic mapping
- Grasp Planning / Learning

3.3.12. Key Technology Targets

Technical Advances Needed.

The advent of a new generation of advanced marine robotics systems - capable of revolutionizing the means available to carry out increasingly challenging commercial and scientific missions at sea - must be necessarily rooted in solid technical advances.

3.3.12.1 Systems Development

Systems Design

- Hydrodynamic design of energy efficient autonomous robots
- High-density energy systems
- Energy-efficient propulsion systems
- Simple and reliable systems for the deployment and retrieval of marine robots
- Hydrodynamic design of energy efficient autonomous robots

Systems Engineering

- Tools and methods to better understand and manage the complexity inherent to the design, development, and operations of multiple, heterogeneous robotic vehicles.

Systems Architecture

- Software and hardware architectures for multiple robot systems.
- Embedded systems for seamless sensor, actuator, and decision making systems integration

Systems Integration

- Acoustic and vision-based sensor integration
- Payload integration

Modelling and Knowledge Engineering

- Vehicle modelling
- Networked hardware-in-the-loop (HIL) for multiple vehicle simulation

3.3.12.2 Human robot interaction

Human Machine Interface.

- Systems for seamless mission specification and mission programming.
- Enhanced systems for seamless robot mission programming and execution with human operators in the loop.

- Systems for mission follow-up and post-mission analysis
- Natural human machine interface methods

Safety

- Fault tolerant systems
- Fault detection systems

3.3.12.3 Mechatronics

Mechanical Systems

- Marinisation of equipment (including actuators, energy sources, and computers) for deep water operations.
- Deep water vehicle hulls
- Automatic buoyancy control systems
- Miniaturized acoustic and vision sensors for installation in small platforms.
- Miniaturization of current marine capable systems (when appropriate) leading to reduced equipment costs, commoditization, and new large scale robotic swarm systems.
- Advances in bio-inspired swimming robots

Sensors

- Acoustic sensors for remote sensing and map building applications
- Acoustic-base systems for underwater obstacle detection and avoidance
- Vision sensors for marine habitat mapping and inspection of underwater infrastructures
- Laser-based systems for map building
- Advanced sensors for long-range underwater vehicle navigation
- Development of new chemical and physical sensors with low energy consumption footprint, reduced or no maintenance, and tailored for marine sensing requirements such as specific hydrocarbons, water nutrients, pollution compounds, etc.
- Biological sensors

Actuators

- Energy efficient propulsion systems
- Enhanced manoeuvrability for non-stationary navigation.

Power Supply and Management

- High-density energy generation and monitoring systems
- Energy management systems
- Energy harvesting systems for extended periods of operation at sea.

Communications

- Acoustic networked systems for multiple vehicle communications and relative positioning
- “Open-architecture” communication systems
- Reduced dependency on low-bandwidth communications
- Optical-based networked systems for multiple vehicle communications and relative positioning
- Technical advances in sensing and high bandwidth communications for safe monitoring of underwater vehicles manoeuvring in the vicinity of submerged structures.

Materials

- Advanced composites for vehicle hull and container fabrication
- New materials for deep water and water column exploration (such as variable form for hydrodynamic task adaptation, reduced weight and lower deployment costs)

Control

- Cooperative control of multiple heterogeneous platforms, including air, surface, and marine robots.
- Range-based multiple vehicle formation control
- Under-actuated systems
- Adaptive systems for reliable multiple vehicle control in the presence of shifting sea currents and large vehicle parameter uncertainty.
- New range-based and vision-based control systems for multiple vehicle formation keeping.
- Improvement of control systems allowing for the deployment of autonomous and semi-autonomous robots operating in harsh environments (e.g. sea currents, waves, and turbulence).

3.3.12.4 Perception

Sensing

- Sensing of chemical and biological variables of interest
- Sensing of pollutants
- Sensor technology and perception capabilities leading to human body detection and localization in difficult weather and long distances (for search and rescue market opportunities arising from an increasing human activity at sea)

3.3.12.5 Navigation

Motion Planning

- Systems for single motion planning in the presence of known current fields and obstacles. Need to take into account temporal and energy-related constraints.
- Systems for cooperative, multiple vehicle motion planning in the presence of currents and obstacles. Need to take into account temporal and energy-related constraints, inter-vehicle communication constraints, and vehicle navigational capabilities.

Mapping

- Off-line mapping (2D, 2.5D, and 3D)
- On-line mapping
- Marine habitat mapping in complex, non-structured 3D underwater environments
- Underwater mapping in coastal areas and critical infrastructures
- Long term mapping, and techniques capable of coping with large volume of mapping information
- Semantic mapping and interpretation for long term autonomy and reliability.
- Advanced systems for marine habitat mapping in complex, non-structured 3D underwater environments

Localisation

- Single beacon localization
- Optimal acoustic sensor placement for single and multiple underwater localization

- Development of navigation systems for long term operations, exploiting recent developments on geophysical and terrain-based navigation.
- Acoustic networked systems for multiple vehicle communications and relative positioning

3.3.12.6 Cognition

Cognitive architecture

- Cognitive and perception architectures for a high degree of autonomous decision making required for a long term ocean presence

Action Planning

- Advanced systems for multiple vehicle cooperative task and mission planning
- Grasp Planning
- Systems for operator-assisted manipulation
- Systems for autonomous intervention in underwater structures
- Systems for cooperative grasping and transportation of heavy objects.
- Systems for cooperative, multiple vehicle motion planning in the presence of currents and obstacles. Need to take into account temporal and energy-related constraints, inter-vehicle communication constraints, and vehicle navigational capabilities.
- Networked systems enabling joint operations of air, surface, and underwater vehicles for persistent monitoring of the sea surface and the water column.

Learning, Development and Adaptation

- Adaptation with respect to shifting current fields and sea state conditions
- Adaptation to large vehicle parameter variations

Natural Interaction

- Cooperation and interaction among air, surface, and underwater vehicles
- Human-Machine Interfaces (HMI) for the operation of ROVs and Hybrid ROVs.
- HMIs for joint operation of air, surface, and underwater vehicles
- Systems for human-robot interaction and joint operations underwater

3.3.13. Key Technology Combinations

Beyond those technology combinations already listed in the SRA, other combinations of a particular interest in the marine robotics domain include:

***Cooperative Navigation*:** The combination of acoustic communications and range measurement with the solution of the localization problem of the entities involved in the communication process. This includes ranging to fixed and/or mobile beacons.

Broadband Communication: One of the major long term requirements which would represent a significant step in the field is long-range broad-band communications. State of the art systems are only able to provide a few bytes second at kilometres distance with acoustic technology, 1 MB at a 100 m distance using optical modems in deep clear water, or 10 MB at 10 m distance with electromagnetic modems. Hence, wireless video transmission is only possible at very close distances, for instance. For this reason tele-operated robots underwater must be tethered. The possibility of having wide band communications through water would eventually simplify the operation of tele-operated systems, but also facilitate the early adoption of autonomous vehicles in new fields of operation like the gas and oil infrastructures. It would allow supervisor operators to take the control of the robot if needed, which is paramount in these installations due to safety constrains.

Visual Servoing, Mobile Manipulation and Dexterous Manipulation technology combinations have a potential impact at short term into current ROVs, at medium term to the recent HROVs and at longer term to upcoming I-AUVs. Current manipulation systems mounted in ROVs and HROVs exhibit a low level of automation, being mostly based in joysticks and or small master-slave haptic (at joint level) interfaces for tele-operation. Therefore, advanced tele-manipulation technologies have a great potential of innovation. Integrated sensing in mechanical joints and links may have an impact in the design of advanced underwater mobile manipulation systems. In particular if they are modular systems easy to encapsulate to protect from the hostile underwater environment.

Cognitive human-robot interaction is relevant for diver companion developments, with recent and current on-going research projects in that direction. With a big professional and amateur diving market, diver companions have a significant potential. The design and development of advanced multi-modal human machine interfaces for tele-operation as well as for supervision of single and multiple autonomous robots, is also of general interest for the domain.

Underwater robot localization is an enabling technology for underwater robots where GNSS are not available. Another key technology is mapping since survey and cartography is one of the major outcomes of nowadays marine robots. Their combination into Simultaneous Localization and Mapping underwater is a key technology with high potential impact and which is much less developed in the underwater environment that in other domains of mobile robotics. This is mainly due to: 1) the research community in underwater robotics is very small, 2) the information provided by the sensor is much poor and 3) the difficulty experimenting and the related high costs. Finally, it is worth noting that an evolution of state of the art communications systems to significantly increase the band to achieve for instance real-time video transmission for instance, has a big impact potential. The combination of communication, navigation and mapping has also a significant impact potential to achieve cooperative navigation and mapping enabling new applications.

4. System Abilities

Robot systems operate through the integration of a wide range of different technologies. In addition to the characterisation of each of these technologies it is also important to characterise the overall performance of the system. This set of system abilities capture the important system level performance characteristics of robots. Abilities allow the state of the art to be identified and future targets to be set for the functional performance of robot systems.

The different system abilities are defined in a way that is independent of any particular robot configuration or market domain. Abilities provide a basis for setting performance metrics and for application providers to specify desired levels of system performance.

Each ability captures one specific aspect of the operation and behaviour of a robot system. For each different type of robot and application there will be critical abilities that can be identified. By establishing the state of the art it is possible to benchmark progress and target R&D&I activity towards next step targets. The list of abilities is intended to cover all the different types of ability that robots possess.

Within the Roadmap each ability is described together with the current state of the art, and the expected targets that might be reached by 2020. The Roadmap provides extended detail and explanation of these targets. Cross referencing these targets with the ability needs identified in each domain provides an insight into where R&D&I activity may have domain impact. Similarly different capabilities in each technology will impact on the abilities and step changes in technology can be expected to impact on key ability targets.

The core System Abilities are:

- Configurability
- Adaptability
- Interaction Ability
- Dependability
- Motion Ability
- Manipulation Ability
- Perception Ability
- Decisional Autonomy
- Cognitive Ability

4.1 Configurability

4.1.1. Description

The ability of the robot to be configured to perform a task or reconfigured to perform different tasks. This may range from the ability to re-program the system to being able to alter the physical structure of the system. (e.g. by changing a tool).

Configurability applies to different aspects of a robot system:

- To the configuration of software modules and components
- To the configuration of sensing and other electronic systems
- To the configuration of mechanical structures of the system.

The ability to configure a robot system must be designed into the system. In most cases software systems inherently contain a degree of configurability, electronic and mechanical systems require configurability to be designed in.

Configurability must be carefully distinguished from Adaptability and Decisional Autonomy which relate to how a robot system alters its responses (Adaptability) and how it changes its behaviour as it performs an operating cycle.

4.1.2. Current Technology Drivers

The following technology areas currently impact on the configurability of a system

- System Design
- System Architecture
- Mechanical Systems
- Human Machine Interface

4.1.3. Ability Levels

4.1.3.1 Mechatronic Configuration

There are some robot systems that contain modular components allowing mechatronic configuration prior to the operation of the robot. Typically these modules are assembled into a form specific to the task.

Level 0 - Static Configuration

The configuration files or mechatronic configuration are set prior to installation and cannot be altered by the user.

Level 1 - Start-up Configuration

The configuration files, or the mechatronic configuration can be altered by the user prior to each task in order to customise the robot system in advance of each cycle of operation.

Level 2 - User Run-time Configuration

The configuration, both in terms of software operating parameters and mechatronic configuration can be altered by the user during the cycle of operation. For example a robot may have an end effector changed part way through an operating cycle.

Level 3 - Run-time Self Configuration

The system can alter its own configuration within a pre-determined set of alternative configurations designed into the system. For example it can change its own end-effectors, or alter configurations based on the set of plug and play modules in use.

Level 4 - Autonomous Configuration

The system can alter its own configuration in response to eternal factors, for example altering its morphology in response to the failure of a sensor or actuator. Note that altering configuration must be carefully distinguished from actions taken as a part of the normal autonomous operation of the robot system.

Configuration mechanisms

Configuration of a system can take place via a number of different mechanisms. For the higher ability levels more than one of these mechanisms will be used.

- Design time configuration. Configuration settings are fixed as the system is designed.
- Configuration files are used to set configuration parameters in software. These may also impact on mechatronics via the controllers in the system.
- Skilled operator interaction. A skilled operator is able to alter the software configuration or mechatronic configuration.
- Unskilled user interaction. An unskilled user is able to alter the configuration.
- Configuration is automatically set by the arrangement of plug and play modules in the system (software and mechatronic).
- Remote Communication of configuration (Single system). The system configuration is communicated remotely to a single robot system.
- Remote Communication of configuration (Multiple Systems). The system configuration is communicated remotely to a set of robots.

4.1.4. Ability Targets

The following ability targets for configurability have been identified:

- *Design time configuration:* The development of system design processes and methods that enable and promote system configuration as a part of the design process. The development of standard means by which design time configurations can be captured and altered.
- *Verifying configuration validity:* The development of system design processes that enable and promote system configuration by ensuring that consistent, safe, and dependable configurations can be validated at run time.
- *Plug and play standards:* The development of standardised interfaces, both software and mechatronic that can support configuration at each of the identified levels but particularly in the development of plug and play systems.
- *User configuration interfaces:* The development of configuration interfaces, both HMI, software and mechatronic, that allow unskilled users to alter the configuration of a robot system while maintaining consistent, safe and dependable operation.
- *Mechatronic configuration:* The development of configuration systems able to handle a diverse range of impacts on system operation caused by significant changes in mechatronic and mechanical configuration. For example surgical instrument tool changing where tool function and morphology may necessitate alternative control and sensing strategies, or in agriculture where general purpose robot systems can be made crop specific, or where a platform changes its locomotion from wheels to legs.
- *Distributed configuration:* The development of configuration mechanisms where common configurations can be distributed to robot systems with different mechatronic configurations and mechanical morphologies.

4.1.5. Key Barriers

Plug and play architectures require standardised interfaces and the identification of system interconnection points that do not compromise system integrity or function.

Barriers can be created by the long time scales on the adoption of standards.

4.2 Adaptability

4.2.1. Description

The ability of the system to adapt itself to different work scenarios, different environments and conditions. Adaptation may take place over long or short time scales. It may relate to local control systems or actions, or to the whole system or to interaction.

Adaptability implies that the system performs optimisation against some performance criteria. This requires defined performance metrics that can be used to drive the adaptation process.

Adaptability can be applied many different aspects of a robot system:

- Adaptation of sensor processing to account for different environmental conditions, for example a vision sensor adapting to a failed sensing element.
- The control parameters of a controller adapting to account for changes in the specific properties of an actuator (increased friction, reduced power etc.).
- Adaptation of the intrinsic and extrinsic parameters of sensor configuration as they change over time due to wear and tear
- The adaptation to a new environment with respect to the strategy used to achieve a function. For example adapting a cleaning scan pattern to optimise time in a room after examining performance metrics.

Adaptability must be clearly distinguished from Configurability and Decisional Autonomy. Adaptability involves the altering of parameters over time based on experience with the goal of optimising performance.

It is particularly important to distinguish between Adjustment and Adaptation. Adjustment is the result of Decisional Autonomy based on sensing or perception. A platform will “adjust” to a changing environment (e.g. Walking onto a slippery surface) as a result of perception and the decisional autonomy mechanisms in the platform. Over time it may “adapt” its response to slippery surfaces based on the number of times it falls over.

Adaptation takes place over time based on an accumulation of experience. The time scale for adaptation will depend on the process being adapted. For example a PID controller operating at 1kHz may be adapted over a period of a second or more, where as task adaptation may take place over a period of days or weeks. The time scale of adaptation therefore depends on the cycle time of the process being adapted.

It is also important to distinguish between adaptation and knowledge acquisition where a robot changes its behaviour because it has acquired knowledge about the environment by using perception and cognitive abilities.

4.2.2. Technology Drivers

The following technology areas impact on the adaptability of a system;

- Learning and Adaptation
- Perception
- Cognition

4.2.3. Ability Levels

Adaptability is composed of three different types of abilities within a robot system:

- Parameter adaptability
- Component adaptability

- Task adaptability

The following are identified as different levels of adaptation within a robot system. Many current robots operate with little or no adaptation.

4.2.3.1 Parameter adaptability levels

Level 0 - No Adaptation

The system does not alter its operating behaviour in response to experience gained over time.

Level 1 – Recognition of the need for adaptation

The system recognizes the need for parameter adaptation. For example a PID controller realizes that there is oscillation and the D term is incorrect. The system identifies the problem but does not yet know how to correct it.

Level 2 – Individual Parameter adaptation

The system alters individual parameters in any part of the system based on assessments of performance local to the module on which the parameter operates. For example in a controller the differential term constant in a PID controller is altered to maintain stability, where stability is measured in relation to the oscillation in the control term.

Level 3 - Multiple parameter adaptation

The system alters several parameters based on the aggregate performance of a set of interconnected or closely coupled modules. For example the tuning of feature extraction filters over time to optimise performance in the environment.

Level 4 - Communicated parameter adaptation

The process of adaptation is carried out between multiple independent agents. The adaptation is communicated between agents and applied individually within in each agent. Agents can be both real and simulated and of different types including non-robotic agents.

4.2.3.2 Component adaptability levels

Level 0 - No Adaptation

The system does not alter its operating behaviour in response to experience gained over time.

Level 1 – Recognition of the need for adaptation

The system recognizes the need for component adaptation.

For example a visual navigation system detects inconsistencies between its visual and ego motion. The system identifies the problem and the failing components but does not do anything to correct the problem.

Level 2 – Adaptation of individual components

The system selects one of several processing components based on online feedback during operation. For example, a visual navigation system may switch from point features to line features based on the applicability to particular environments, identified at runtime.

Level 3 - Process chain adaptation

The processes applied to achieve a function are adapted over time, or over position, to optimise the outputs from a process chain. The adaptation may alter, over time, the weight applied to different processing outputs in a decision making process, or change which alternative or additional processing stages are switched into a process chain as a result of the long term assessment of performance. These adaptations have a degree of permanence with respect to multiple operating cycles and are controlled by long-term observations of the behaviour, state or effectiveness of the process outputs.

Level 4 - Communicated component adaptation

The process of adaptation is carried out between multiple independent agents. The adaptation is communicated between agents and applied individually within in each agent. Agents can be both real and simulated and of different types including non-robotic agents.

4.2.3.3 Task adaptability levels

Level 0 - No Adaptation

The system does not alter its operating behaviour in response to experience gained over time.

Level 1 – Recognition of the need for adaptation

The system recognises that the performance of a particular task could be optimised according to some metric, but no adaptation is performed.

Level 2 – Single task adaptation

A single task performed during the process cycle is adapted over time to optimise a particular metric. This adaptation is achieved by strategic overview of the performance of the system while carrying out the task. Adaptation is the result of accumulated experience.

Level 3 – Multiple task adaptation

A set of tasks performed during the process cycle is adapted over time to optimise a particular metric. This adaptation could include the reordering of tasks or adaptation of individual tasks. This optimisation is achieved by strategic overview of the performance of the system while carrying out the set of tasks. Adaptation is the result of accumulated experience.

Level 4 - Communicated task adaptation

The process of adaptation is carried out between multiple independent agents. The adaptation is communicated between agents and applied individually within in each agent. Agents can be both real and simulated and of different types including non-robotic agents.

4.2.4. Ability Targets

Level 0 and 1 are well understood in the context of controllers. Higher levels of adaptive ability are less well understood and targets for improving the adaptability of robot systems should concentrate on advancing adaptability levels within diverse applications.

- *Resource allocation adaptation:* Adaptation in complex dynamic environments to seek out optimal solutions to resource allocation problems and scan pattern problems. For example in warehouse picking and packing tasks.
- *Long-term self-calibration of robotic systems*: The development of algorithms to estimate the intrinsic and extrinsic calibration parameters without the intervention of expert operators.
- *Adaptation API:* Development of generic interface mechanisms for the adaptation of multi-stage processes particularly in sensor data processing and in planning.
- *Distributed Adaptation:* Development of mechanisms for the communication of adaptation within heterogeneous multi-agent systems, including the use of cloud computing.
- *Adaptation drivers:* Development of systems with internal modelling able to provide outputs to drive the adaptation of systems to improve performance over time.

4.3 Interaction Ability

4.3.1. Description

The ability of a system to interact physically, cognitively and socially either with users, operators or other systems around it, including other robots. The ability to interact may be as simple as the use of a communication protocol, or as advanced as holding an interactive conversation in a social context.

The ability to interact is critical to many areas of application. Interaction depends on both the medium of interaction and on the context and flow of the interaction. The ability to interact takes place in three distinct ways physical interaction, cognitive interaction and social interaction. The description of the levels of Interaction Ability include these three types of interaction.

4.3.2. Physical Interaction

The ability to physically interact covers four specific areas of interaction:

- Human-robot interaction
- Human-robot interaction feedback
- Robot-robot Interaction
- Interaction safety

Each of these four types of interaction require a set of ability levels. In a number of application scenarios two or more of these types of interaction abilities will be mixed.

Technology Drivers

The following technology areas impact on the interaction capability of a system;

- Human-Machine Interface
- Human-Robot Collaboration
- Communications
- Perception
- Cognition

4.3.2.1 Human-Robot Interaction Levels

The following set of levels relate to the interaction between users and the robot system. This set of ability levels are distinct from the cognitive human-robot interaction levels as they define the method of interaction independently of the cognitive context:

Level 0 - No interaction

It is possible that some robots will effectively have no operational interaction with a user.

Level 1 - Direct control

The user provides control of the robot moment to moment. The system can translate, alter, or block these controls within parameters set by the user or system. The user controls are in the form of parameters that alter the control of the robot. These parameters may be continuous quantities, for example a steering direction, or binary controls.

Level 2 - Direct physical interaction

The user controls the robot by physically interacting with it. The robot reacts to the user interaction by feeding back physical information to the user via the contact point. For example the user teaches a motion sequence to the robot, or feels the surface of an object the robot is in contact with.

Level 3 - Position selection

The system is able to execute pre-defined actions autonomously. The user selects the subsequent action at the completion of each action. For example a robot is able to move between defined waypoints in its environment, or carry out a fixed action such as releasing an object, as commanded by the user.

Level 4 - Traded autonomy

The system is able to operate autonomously during some parts of a task or in some tasks. Once this task or sub-task is complete the user will either select the subsequent task or intervene to control the system by direct interaction to carry out a task. This results in alternating sequences of autonomous and direct control of the system by the user.

Level 5 - Task sequence control

The system is able to execute sub-tasks autonomously, these sub-tasks will involve a higher level of decisional autonomy than the pre-defined tasks in Level 3. On completion of the sub-task user interaction is required to select the next sub-task resulting in a sequence of actions that make up a completed task.

Level 6 - Supervised autonomy

The robot system is able to execute a task autonomously in most operating conditions. The system is able to recognise when it is unable to proceed or when it requires user input to select alternative strategies or courses of action. These alternatives may involve periods of direct control.

Level 7 - Task selection

The system is able to autonomously execute tasks but requires the user to select between strategic task alternatives in order to execute a mission.

Level 8 - Mission Goal setting

The system is able to execute tasks to achieve a mission. The user is able to interact with the system to direct the overall objectives of the mission.

Parameters

These interaction levels are also modulated by parameters of the interaction. These factors can increase or decrease the difficulty of achieving levels of interaction ability:

- *Interaction time:* The length of time over which the interaction takes place. Longer sequences of interaction will in general be harder to achieve than shorter interaction times.
- *Interaction Environment:* The environment where the interaction occurs will also affect the difficulty. Interactions in controlled environments will be easier than interactions taking place in work or every day environments where the robot needs to focus attention on the user. Highly dynamic or hazardous environments will also significantly affect the interaction.
- *User expectation:* The level of expectation of the user, the level of user experience and training will impact on difficulty. Trained users able to understand how to command the robot and users that have realistic bounded expectation, or experience, will reduce the difficulty in achieving a particular level of ability.

4.3.2.2 Human-robot interaction feedback

The ability to command a robot depends on the user's perception of the state of the robot. This set of levels defines how this state information can be fed back to a user who is operating the robot.

Level 0 – No feedback

The robot system does not provide any feedback to the user

Level 1 – Visual feedback

The user is able to assess the state of the robot by direct observation. The robot system does not provide any means of feeding back information to the user.

Level 2 – Vision data feedback

The system feedbacks visual information about the state of the operating environment around the robot based on data captured locally at the robot. The user must interpret this visual imagery to assess the state of the robot or its environment.

Level 3 – Simple haptic feedback

The robot system is able to feedback a physical force that represents the forces at the end effector of the robot. The force feedback is delivered to the user via a single point of contact, for example a joystick.

Level 4 - Augmented haptic feedback

The system is able to feedback to the operator signals and forces that augment the force information from the end effector such that the augmentation enhances the interaction between the user and the robot.

Level 5 – Multiple point feedback

The robot system is able to feedback to the operator signals and physical forces that represent multiple forces at the end effector of the robot. The force feedback is delivered to the user via multiple points of contact, for example to each finger of the operator’s hand.

Level 6 – Augmented multiple point feedback

The robot system is able to augment with additional information the feedback of a set of physical forces that represent the forces at the end effector of the robot. The force feedback is delivered to the user via a multiple point of contact, for example to each finger of the operators hand. This augmentation enhances the interaction between the user and the robot with additional information which may be derived from additional sensing or additional interpretation.

Level 7 – Tele-presence

The system is able to provide multi-modal feedback to the operator such that they experience tele-presence. Typically this requires close synchronisation between different feedback channels.

Level 8 – Augmented tele-presence

The system is able to augment the experience of tele-presence with additional information that enhances the interaction between the user and the robot.

Parameters

The ability to achieve these levels of feedback will depend on a number of different application dependent parameters, these are:

- *Interaction Environment*: The environment where the interaction occurs will affect the difficulty. Highly dynamic or hazardous operating environments will also significantly affect the interaction.
- *The communication lag*: In a number of operating scenarios there may be significant communication lag between the operator and the robot.
- *Task complexity*: The complexity of the task being undertaken will affect the quality of the interaction and the need for high quality.

4.3.2.3 Robot to Robot Interaction Levels

The following set of levels relate to the interaction between robots in carrying out a task or mission. No distinction needs to be made between separate robots that communicate and systems of dependent robots that carry out a task. However there is a distinction between systems that rely on a central controller and those that use distributed decision making.

Level 0 - No interaction

The robot operates on its own without communication with another robot.

Level 1 - Communication of own status

Two or more robots communicate basic status information and task specific status. Status information is pre-defined for the task. The information communicated only relates to the state of the robot within the task.

Level 2 - Communication of task status

Two or more robots are able to communicate information about the task they are performing in terms of task completion, time to completion, and information about task barriers, resources etc. This information is at a high level and will impact on the planning of a common task, or tasks in a common space.

Level 3 - Communication of environment information

Two or more robots share information about their local environments, or share wider scale information that they have acquired or been given. The robots are able to assimilate the information and extract task relevant knowledge from it.

Level 4 - Team communication

Two or more robots are able to communicate task level information during execution of the task such that it is possible to implement dynamic planning between the robots in the team. Each robot carries out its own tasks with awareness of the other robots in the team.

Level 5 - Team coordination

Two or more robots are able to collaborate to achieve a task outcome that could not be achieved by either robot alone, or by each robot operating independently.

Level 6 - Capability Communication

Robots are able to communicate their own task capabilities and utilise cooperative working between teams of heterogeneous robots where there is no prior knowledge of the composition of the team.

Robot-Robot Interaction Parameters

Robot to robot interaction is governed by the parameters of the interaction channel. At a basic level this is governed by the standard communication channel parameters of:

- Communication bandwidth
- Communication latency
- Noise levels.

The values of these parameters are fundamentally governed by the communication medium which in turn will be determined by the environment of operation for each task.

The level of achievement in robot to robot interaction is also modulated by the level of generalisation in the task being undertaken. For tasks that are specific and well defined it is easier to achieve the higher levels of ability. Similarly in systems with a central control node task specific communication mechanisms are likely to have been designed in.

4.3.2.4 Human-Robot Interaction Safety Levels

A third aspect of interaction ability is the level of safety within the interaction. While safety technology will focus on the delivery of specific safety mechanisms it is the system as a whole that expresses the level of safety for the task.

The following levels only apply to robots that have an inherent level of un-safety. For example if a robot is safe at Level 0 then there is no need for it to reach Level 1 safety. For this reason each successive level relates to systems that exhibit increased levels of potential harm.

It is assumed that all robots meet safety criteria appropriate to their operating environment with respect to electrical and battery safety requirements, typically specified by European CE marking criteria. It is also expected that appropriate safety criteria have been applied with respect to consumables used by the robot. For example heated liquids, liquids under pressure, or chemical agents.

Level 0 - Intrinsic safety

The mechanism of the robot is safe because by design it cannot exert a force that is damaging to a person at any time during its operating cycle. The maintenance of this level of safety does not depend on software.

Level 1 - Basic safety

The robot operates with a basic level of safety appropriate to the task. Maintaining safe operation may depend on the operator being able to stop operation or continuously enable the operating cycle. The maintenance of this level of safety does not depend on software.

Level 2 - Basic operator safety

The robot is made safe for the operator by physically bounding the operating space of the robot. Access gates trigger stop commands to the robot. The robot will not operate unless the bounding space is closed.

Level 3 - User detection

The robot is informed when a user enters the work zone. The robot operates in an safe way while the user is present in the operating zone.

Level 4 - Work space detection

The robot operates within a well defined space where a zone of safe operation is identified to the operator and programmed into the robot. While the robot is occupying the safe zone it will control its motion such that it is safe. The system may also use sensing to detect that the user does not enter the unsafe zone.

Level 5 - Dynamic User detection

The robot or its support systems detect users within its operating zone and dynamically defines a safe zone that envelopes the user where the robot controls its motion to be safe.

Level 6 - Reactive safety

The robot is designed to be safe under all reasonable circumstances such that if it impacts a person the impact forces are minimised below the level that may cause injury during the impact.

Level 7 - Dynamic safety

The robot is able to exert strong forces as a part of an interaction task with a user, but recognises when the use of these forces may endanger the user. In this case the robot alters its motion to ensure safe operation.

Level 8 - Context dependent safety

The robot is able to recognise circumstances where it needs to behave in a safe way because it is uncertain about the nature of the environment.

4.3.3. Social Interaction Ability Levels

4.3.3.1 Description

Social Interaction ability is the ability of a robot to interact with humans, by understanding their individual social signals and cues and responding appropriately, in order to facilitate 'natural' human-robot interaction. This builds on both the other interaction Ability Levels as well as Cognitive Ability Levels. Social/natural Interaction goes beyond Physical Interaction Ability. As an example, consider a robot that works as part of a team on a construction site, carrying materials to workers. A robot that is capable of physical interaction would, for example, be able to manoeuvre through the space without colliding with humans, and, if it had a high level of dexterity, hand the materials to human workers. A robot with a higher degree of social ability would, for example, know that it should not interrupt the recipient if that person is engaged in a conversation with another human, but should wait until the conversation is over (unless it is an urgent situation). A robot with no social ability would not know this and would attempt to hand the material over as soon as it was able to do so.

For the purpose of this definition we refer to people interacting with robots that have some degree of awareness of humans in terms of sensing abilities and/or interfaces and abilities to interact and communicate with people. This distinguishes the human interaction from interaction with physical objects that lack these features.

4.3.3.2 Technology Drivers

The following technology areas impact on the social/natural interaction capability of a system:

Perception

- perceiving and tracking the social environment (e.g. recognition of individual people based on their faces, emotional expressions and utterances, behaviour and other characteristics)
- detecting social cues and behaviours (e.g. for social interaction and communication and interpretation of situations and human activities, visual auditory, speech, others)
- robust recognition/detection and monitoring of salient social cues in an interaction context in order to facilitate bi-directional human-robot interaction

Action

- generating social behaviours and expressions, expressing social cues (e.g. gestures, head nods etc. in a natural way), contingent with interaction partner
- social goals and interpretation of the social environment need to be translated into executable actions
- interaction modes and modalities adapted to task, role, functionality of robot etc. (verbal and non-verbal means of interaction), producing gestures, poses, behaviours, emotional expressions etc.
- communication verbally and non-verbally
- language abilities (perceive, process and understand linguistic interaction and generate verbal language, grounded in and appropriate to context)

Cognition and Social Intelligence

- reasoning (includes adaptation and action selection): reasoning about what to do given knowledge about the social environment and context, perceptual information and abilities to produce actions
- social cognition: e.g. knowing when and what social behaviours are appropriate
- spatial cognition, proxemics: e.g. knowing how close you can get to a human
- Social Learning: the ability to learn by social interaction and observation.

Achieving these step changes in the technology drivers will impact on the achievement of the social ability levels.

A robot capable of social ability will need to perceive its environment (perception) and to process information about it, requiring cognition and social intelligence. This is likely to require the ability to detect social cues (both verbal and non-verbal) and to reason about the world from the perspective of others. The ability to physically interact (interaction) and to engage in communication are also likely to be required, though not essential for all levels of social ability. Social abilities at many levels require highly dynamic, micro-managed activity, and other related capabilities for example turn-taking and the ability to respond contingently.

4.3.3.3 Human interaction levels of extent

These levels define the effect of integrating information gathered by the robot during progressively extended interactions.

Level 0: No social interaction with humans

The robot system does not utilise any form of social interaction with humans, other forms of interaction may take place.

Level 1: Temporally restricted interactions

The robot interacts with people only a small number of times while carrying out a task, and interactions are brief. The robot's social behaviour follows a pre-defined script. The robot does not use information exchanged in the interaction to change its social behaviour towards that person. The robot's social behaviour follows rules and conventions expected for specific pre-defined interactions.

Level 2: Temporally extended interactions

The robot interacts with a person over an extended time period, interactions are brief but may be repeated. The robot is able to utilise information given by the person during the interaction to change its interaction with the person in order to personalize its behaviour within a range of a priori defined options.

Level 3: Behaviour modulated interactions

The robot interacts with a person over an extended time period, interactions are brief but repeated. The robot is able to recognise a set of pre-defined human behaviours during the interaction. The robot uses this information, together with information supplied by the person to change its interaction with that person in order to personalize its behaviour within a range of a priori defined options.

Level 4: Long-term interactions

The robot interacts with the person repeatedly over extended periods of time. The robot can identify the person from the person's behaviour and/or appearance over repeated interactions. The robot forms a model of the person that it can use to reason about the person. The robot uses this knowledge to personalize its behaviour and to adapt its behaviour over time from the history of interaction with the person.

Level 5: Task modulation through interaction

The robot interacts with the person repeatedly over extended periods of time. The robot can individually identify the person from the person's behaviour and/or appearance. In addition the robot is able to infer short term goals, basic intentions and desires from its observations during the interaction. The robot uses this knowledge to alter its interaction and the tasks it carries out.

Level 6: Accumulated personal knowledge through interaction

The robot interacts with the person repeatedly over extended periods of time. The robot can individually identify the person from the person's behaviour and/or appearance. In addition the robot is able to accumulate knowledge about long term characteristics of the person from its observations during the interaction, such as preferences, habits, goals, and beliefs. The robot uses this knowledge to alter its interaction and the tasks it carries out.

Level 7: Multi-party long-term interactions

The robot is able to extend its interactions to multi-party situations. This requires awareness of the dynamics and interactions among groups of people, and a model of relationships among the humans and towards the robot.

4.3.3.4 Interaction complexity levels

These levels define levels of interaction complexity that arise as the cognitive/social complexity of the interaction is raised.

Level 0 – No interaction

The robot operates on its own without social interaction.

Level 1: Single task interaction

The robot carries out a clearly defined task, or a small number of tasks. These require the robot to socially interact with people in an acceptable way but the range of its interaction abilities are limited to the task and do not depend on knowledge of the human interaction partner(s) outside of the context of the task.

Level 2: Multiple defined task interaction

The robot carries out a range of tasks, and needs to be able to engage with humans in a number of these tasks in a socially appropriate manner. These interactions need to take into consideration knowledge about the individual human it is interacting with and the different context of each task. The robot acts according to its Human Interaction Level.

Level 3: Undefined parameterised interactions

The robot interacts with a human partner according to its Human Interaction Level. During and through interaction the human partner can modify the robot's behaviour, skills and knowledge about the domain in order to allow it to deal with new or unexpected situations.

Level 4: Unconstrained, open-ended

The robot cannot a priori predict precisely which interactions the human will engage in at any given point in time. The robot needs to be able to use extensive knowledge, knowledge about interaction histories with the user and extensive social signal processing abilities in order to determine the context of the interaction (e.g. to determine and appropriately respond to dialogues on various topics), and to respond with appropriate and socially acceptable behaviour. The robot needs to be able to monitor, adapt to and learn from changing user's preferences and needs.

4.3.3.5 Human interaction modality levels

These levels describe different modalities of human robot interaction.

Level 0 – No Human Interaction

The robot does not interact with humans in a social context.

Level 1 - Commanded tasks

The robot carries out tasks on command given by a human user. The robot does not seek interaction with the user until it reaches pre-defined points in the task.

Level 2 – Direct interaction

The robot carries out tasks through direct interaction with a human. The interactions may modulate the task or the sequence of tasks. The robot uses pre-defined interaction patterns.

Level 3 – Socially acceptable commanded interaction

The robot operates as an assistant to a person by carrying out useful tasks. These tasks are commanded but in a way that is socially acceptable to the person. The robot needs to take into consideration a variety of verbal and non-verbal modalities of interaction, and will utilise knowledge of the context and scope of its application domain to interpret and execute the commands.

Level 4 – Interaction as an assistant

The robot operates as an assistant to a person observing what tasks need to be carried out without necessarily being commanded. The robot is able to observe the context of the person and the social environment and within a limited range of tasks it is able to decide how and when to execute tasks.

Level 3 - Interaction as a personal companion

The robot operates as a personal companion to a person by carrying out useful tasks for them. The robot adapts to and learn from its changing roles over the course of long-term interactions with the person. The robot is able to change its tasks depending on changes in the persons' needs, abilities, interests and preferences.

Level 5: Socially situated companion robots

The robot is able to operate as a personal companion to a group of people who interact socially. The robot understands the dynamics between the group and is able to interact with each member of the group in a socially appropriate way.

4.3.3.6 Social interaction learning levels

This set of levels define how a robot learns through its interactions with a person.

Level 0 – No interaction learning

The robot does not learn from its interactions with people. It may learn in other ways.

Level 1 – Learning social sequences

The robot directly learns from specific sequences of social interaction and socially intelligent behaviour that take place during interactions with a user.

Level 2 – Social learning by observation

The robot learns over an extended period by observing the social interactions it has with its own interaction partners

Level 3 – Third party learning

The robot learns by observing third party interactions between people or between people and other robots. The robot is able to extract social interaction knowledge from these third party interactions and utilise this knowledge within the context of its own function.

Social Interaction Parameters

Social interaction ability levels are modulated by a number of external parameters that are not related directly to the interaction but are significant:

- *Number of interaction partners*: Having to interact with multiple partners, even if this is carried out sequentially, will provide an added level of complexity.
- *Complexity of the environment*: If the environment makes perception and interpretation of the environment harder, for example outdoors, or in a noisy environment then achieving interaction levels will be more difficult.
- *Predictability of the environment*: if the environment contains a high level of dynamic behaviour, for example the interaction partner is engaged in a continuing activity while communicating, or there are frequent interruptions due to external events this will increase the difficulty of interaction.

4.3.4. Ability Targets

The primary targets for interaction ability are concerned with providing increasing levels of interaction ability in the sets of levels set out above for physical, cognitive and social interaction. In particular the improvement of ability against the interaction parameters outlined above will be key in some areas of application. In addition to this general progression of ability the following R&D&I activities have been identified:

- *Certification and Classification of Safety Levels:* Methods need to be developed that are able to classify, and provide certification for, the safety levels needed within different domain contexts.
- *Interaction Design:* Interaction design has been used extensively in the design of everyday technical objects. The added physical element in robotics will require new interaction design methods to be developed particularly in applications requiring physical interaction. This has particular relevance in smart manufacturing and assistive robotics.
- *Robot Communications:* Robot to robot interaction will rely on communication protocols able to handle dynamic peer to peer networking. The higher levels of robot to robot communication may need additional protocols or layers over and above that currently being developed. Early engagement in the establishment of these protocols will be important particularly in the communication of robot centric information and information with a local context.
- *Establishment of Cloud based services*: In some applications robots may be able to rely on Cloud based services for the processing of information. Methods will need to be developed to allow the communication of information that preserves semantic and cognitive content.

Commentary

At each Ability Level different degrees of complexity of human-robot interaction may arise, benchmarking on each level will need to provide proof of progress within each level and how to advance to the next higher level in terms of the underlying technology required for social ability and the externally perceived social ability. The goal is to not only enhance the robot's functionality but also to enhance the robot's perception and acceptability by its human interaction partners. So on each level, psychological, cultural and other factors that influence the way people interact with and perceive machines will have to be examined since they impact people's expectations of human-robot interaction, the roles robots adopt in such interaction, the way humans adapt to robots in an interaction context, and the human-robot relationships that may be facilitated. Similarly, each level implies a level of social intelligence/social cognition of the robot, with the increasing need of the robot to be able to recognise and reflect upon intentions, goals and other mental and emotional states of its human interaction partners and to use such knowledge in order to behave increasingly socially intelligently. This involves perspective taking, joint attention and other aspects of 'mindreading'. Last but not least, ethical issues of human-robot interaction need to be considered.

4.3.5. Key Barriers

The user acceptability of interaction, and the establishment of interaction norms will represent key barriers to establishing and raising the level of user interaction. In safety critical tasks the certification and validation of systems will present a significant barrier to deployment.

4.4 Dependability

4.4.1. Description

The ability of the system to perform its given tasks without systematic errors. Dependability specifies the level of trust that can be placed on the system to perform. This may be in terms of a MTBF or that we trust it to look after a person for a day.

4.4.2. Technology Drivers

The following technology areas impact on the dependability of a system;

- Systems Development
- Perception
- Cognition

There are four fundamental elements to dependability:

- *Failure Dependability:* The system remains dependable when it fails.
- *Functional dependability:* The system is dependable in the tasks it performs. Performance is consistent and of a standard appropriate to the task.
- *Environmental dependability:* The robot is dependable in its interaction with the operating environment.
- *Interaction dependability:* The robot is dependable in its interaction with users and other independent robots.

Critically the dependability in a robot system must be at an appropriate level for the task being carried out. Not all tasks require very high levels of dependability. Part of the design of any robot system must be to assess the level of sufficient dependability for each task.

4.4.3. Current Ability Levels

4.4.3.1 Dependability Levels

Level 0 - No dependability

All useful robots are dependable to some degree, even laboratory prototypes. This level exists for completeness.

Level 1 - Mean failure dependability

The dependability of the robot is based on the mean time to failure of its components. The dependability is based on the design of the robot. The robot is not itself able to increase its dependability. For Failure Dependability this relates to the failure of all component parts of the robot including software components. For Functional dependability this relates to the frequency of failure of the system functions with respect to the task being undertaken, and for environmental dependability it relates to the failure of the robot to correctly interpret the environment, for example falling down a step, or failing to detect a hazard. For Interaction dependability it relates to the failure of the robot to interact with a human or another robot in a functional or intuitive manner that is appropriate to the task.

Level 2 - Fails Safe

The robot design is such that there are fail safe mechanisms built into the system that will halt the operation of the robot and place it into a safe mode when failures are detected. This includes any failures caused by in-field updates. Dependability is reduced to the ability to fail safely in a proportion of failure modes. Fail safe dependability relies on being able to detect failure.

Level 3 - Failure Recovery

The robot is able to recover from a proportion of failures by restarting or resuming its operation.

Level 4 - Graceful Degradation

The robot is able to recognise the impact of a proportion of failures on its function and operation and is able to compensate for the effect of the failure to maintain dependable operation. Function effectiveness or the ability to achieve optimal working may be impacted.

Level 5 - Task dependability

The robot system is able to recognise the impact of a failure on the overall task it is undertaking and re-task activities in order to minimise the impact of the failure on the task. This may also include self repair as an alternative task.

Level 6 - Mission dependability

The robot is able to recognise the impact of a failure on the overall objectives of a mission and communicate the nature of the failure to other systems and robots to minimise the impact on the mission objectives. In turn the robot is able to receive and interpret mission failures from other robots and systems and re-task its actions to compensate.

Level 7 - Predictive dependability

The robot system is able to predict that a planned future action may result in a loss of dependability, or that the effect of the partial failure of a component can be mitigated by altering future actions. Thus the robot is able to extend its dependability by taking action in advance of failure in order to reduce the effect on dependability.

Dependability components

In addition to the above generic levels there are specific aspects of dependability that have a varying significance depending on the task being carried out. In essence each of the other abilities also inform a specific level of dependability in addition to the four outlined above.

- *Motion dependability:* The level of motion dependability defines the dependability that can be placed on the motion of the robot. Certain applications require very high levels of motion dependability in order to provide high levels of operational safety guarantee. Motion dependability is a key element in both functional and environmental dependability. It may also be an important part of physical interaction dependability.
- *Manipulation dependability:* A robot that relies on the manipulation of objects as a part of its function will require a level of manipulation dependability that relates to the success of the manipulation of objects. This is a key element of environmental, functional and interaction dependability
- *Cognitive dependability:* A robot that requires some level of cognitive understanding to achieve its task will require a level of cognitive dependability. This will range from the success with which the context of objects in the environment is correctly handled to the correct interpretation of user states from cues.

Dependability Parameters

Achieving high levels of dependability will be affected by a number of parameters that are task dependent:

- *Failure criticality:* The relationship between mean time to failure and mission or task duration has a critical impact on the dependability of a system. This can be characterised in three levels; “non critical” where the time to failure does not impact on the task or mission; “task critical” where meantime to failure must be much greater than the typical task time; and “mission critical” where meantime to failure must be much greater than typical mission time. Ensuring a system achieves the desired criticality rating is strongly related to the System Design technologies.

- *Time scale:* The length of time a robot needs to perform a task will affect its dependability. A robot carrying out a short repetitive task is more likely to have a higher level of dependability than a robot with equivalent technology that carries out a longer task. For a number of proposed applications the ability to achieve long term dependability is important.
- *Task or mission risk:* The risk level of a particular task or mission will impact on the dependability of a system. High risk activities on the limit of ability will necessarily result in lower levels of dependability. For example trying to balance plates one on top of the other while moving across a room.
- *Environmental variability:* Robots that operate in environments with high levels of variability, both in terms of objects and in terms of dynamics, will inevitably display lower levels of dependability for a given technology level than robots working in structured and near static environments. Extremes of operating environment, for example working in poor visibility, will also impact on dependability.

4.4.4. Ability targets

In addition to the goal of developing systems and methods that are able to implement higher levels of dependability, and extend dependability over a wider range of above parameters the following aspects of dependability require R&D&I action:

- *Assessment:* To develop the means by which different dependability components, outlined above, can be assessed.
- *Certifiability:* To develop a system of certification that can provide guarantees about dependability sufficient for deployment in high risk or safety critical tasks. Notably this is most critical in physical human interaction tasks in Healthcare, Manufacturing, Agriculture and Civil tasks.
- *Design for Dependability:* Much of the dependability of a system is intrinsic to the design process. Methods need to be developed that identify the key parts of the design process that support design for dependability and can analyse a system during its design for dependability risks. In particular task assessment methods able to identify sufficient levels of dependability for a given task that take into account the different components of dependability and the dependability parameters identified above.
- *Intrinsic dependability:* While a significant part of dependability is embedded within system design, there is also a runtime component to the maintenance of ongoing dependable operation. The identification of methods and mechanisms for increasing this intrinsic dependability, particularly over long time periods is of interest for many different application areas and particularly in those performing long term high risk tasks and missions, particularity in the Civil and Healthcare sectors.
- *Post failure analysis:* The development of mechanisms and methods that allow analysis of the operation of a complex robotic system leading up to a dependability failure, and the development of tools to meaningfully deconstruct the behaviour of the system will be critical to improving system dependability.

4.4.5. Key Barriers

The key barrier to establishing higher dependability levels is the testability of system for dependability. Dependability can be designed into a system through appropriate design processes, but the testing of dependability on tasks and missions requires real world exposure to the working environment.

4.5 Motion Ability

4.5.1. Description

The ability of the system to move. Motion may be highly constrained where ability is measured by the precision of the motion, or its repeatability. Alternatively motion may be unconstrained and is measured by the ability to move effectively in different media or between media. For example in unstable environments such as on ice, sand, air or water this might specify the ability to maintain balance or achieve effective motion.

Motion ability includes the ability to maintain a position. Maintaining a position typically involves motion unless the position is statically held when the system is stationary.

It is important to note that all aspects of the motion of a robot are constrained by the mechanical operating envelope of its design.

4.5.2. Technology Drivers

The following technology areas impact on the motion capability of a system;

- Mechanical Systems
- Actuators
- Planning and Control
- Sensing and Perception
- Localisation and mapping
- Materials

4.5.3. Current Ability Levels

The following are a set of ability levels for motion:

4.5.3.1 Unconstrained Motion

Level 0 - No motion

All robots move in their environments, movement defines a robot. This level exists only for completeness.

Level 1 - Pre-defined open loop motion

The robot carries out predefined moves in sequence. The motion is independent of the environment and events in the environment. The robot may not be able to maintain a position if subject to external forces, may be able to statically rest at a given position.

Level 2 - Pre defined closed loop motion

The robot carries out predefined moves in sequence where each motion is controlled to ensure position and/or speed goals are satisfied within some error bound. So for example a robot can move to and maintain a position (within some error margin) against forces less than the resultant motive force at the point of contact. A platform will similarly be able to execute fixed motions where the accuracy of these motions in the environment will depend on other abilities such as its perception ability.

Level 3 - Open path motion

The robot can execute a motion that follows a path with a given path accuracy. This path is described by a specific point on the robot. The robot is able to return to any given point on the path with an accuracy that is appropriate to the task.

Level 4 - Position constrained path motion

The robot can execute a path motion where the path is constrained by physical objects or by defined zones that must be avoided. For example a robot arm that can operate through a physically constrained region such as a hole in a wall, or a platform that can move to avoid a known area of the environment such as a step down. The robot is able to execute a path to an unvisited location obeying constraints.

Level 5 - Force constrained path motion

The robot can execute a path motion while applying a specified force in a given direction related to the motion. For example moving over the surface of an object while applying a force perpendicular to the surface as might be required when polishing a surface.

Level 6 - Parameterised motion

The robot can execute a path move that optimises for a parameter. For example a path that reduces energy consumption, covers an area, or constrains the angle range of a joint, or the torque or force in a joint or linkage.

Level 7 - Position constrained parameterised motion

The robot can operate through a physically constrained region while at the same time optimising a parameter or set of parameters that constrain the motions of the robot. For example a robot arm may be able to reach a high shelf while maintaining a centre of gravity, or a platform robot operate in a room away from a charging station while optimising power usage.

4.5.3.2 Constrained Motion

Level 0 – Un-reactive

The robot does not respond to external forces acting on it.

Level 1 - Compliant motion

The robot can execute motions that change in response to external forces applied to the robot such that the force exerted on the external body is controlled. The robot is able to maintain position and path in the absence of any external force. The force is working on the robot only at the intended tool tip, and the environment is static and rigid.

Level 2 - Reactive motion

The robot is able to react to externally applied forces contacting any part of the robot, not just at the intended tool tip.. The reaction may result in stiffening to resist the force or in lowering stiffness to reduce impact effect. The system is able to apply a force in a given direction and maintain that force against a rigid or semi-rigid body.

Level 3 - Soft medium motion

The robot is able to move into and within a soft medium, with passive dynamics. It is able to maintain a position and path within this medium while optimising motion and force parameters as demanded by the task.

Level 4 – Multiple soft medium motion

The robot can move through multiple soft but passive environments, e.g., water and mud, during the same motion.

Level 5 - Dynamic motion

The robot is able to alter its own dynamics of motion in response to multiple active external dynamic forces in order to optimise motion parameters; the robot can identify the interaction dynamics of the external forces.

Motion Parameters

The above levels of ability define a framework for assessing motion ability. The motion ability of a whole robot is also assessed according to a set of motion parameters:

- Accuracy, repeatability, path error
- Speed, acceleration.
- Degrees of freedom (physical form)
- Load carrying capability
- Applied force/torque range
- Robot size and scale

The exact figures for these parameters will vary with each task. Achieving the higher levels of ability with extreme values of the motion parameters will be harder.

4.5.4. Ability Targets

The primary objectives are in raising the ability level of systems in order to expand the market. In addition the development of systems that usefully push the boundaries of the motion parameters significantly beyond current values for a given task may result in step changes in applicability. In particular the smaller and larger ends of the size scales, the range of environments and maintenance of stability are all key goals. In addition the following R&D&I objectives can be identified:

- *Operation in air and water or other dynamic environments:* The ability to maintain a position or velocity both absolute and relative to other robots or objects in the air or under water against the natural forces of the environment is fundamental to a number of key application areas. Similarly the ability to apply or resist a given force or impulse in a particular direction in the air or underwater to another object will also be fundamental to many applications.
- *Transition Environments:* The development of motion systems able to operate in transitionary environments for example in waterlogged ground, mud, sand, gravel etc. also in environments with varying temperature and pressure and in transition between environments, for example between air and water or across boundary regions.
- *Terrain following in 3D:* The development of control systems able to maintain a controlled distance during the motion of a robot (of any physical form) and to do so with smooth motion in a dynamic environment. For example following an unknown terrain in air and under water, including the case where the terrain involves high relief structures.
- *Develop motion control capable of stable modal switching*. For example between autonomous direct motion and compliant motion compatible with physical human interaction.
- *Exploitation of kinematic redundancy:* To develop systems able to use kinematic redundancy as a part of achieving parameter constrained motion.
- *Load transfer*: To develop mechanisms and control systems able to transfer load to fixed surfaces in the environment and make use of this to control constrained motion.
- *Interaction motion:* Development of systems able to execute motion against objects that have constrained motion. For example the development of systems required to open any door, or be compatible with human interaction.
- *Constrained space operation:* Development of systems able to operate in confined spaces, such as inside pipes or flexible tubes, or where the environment severely constrains the motion path.
- *Motion in flexible materials:* The development of systems able to operate within flexible objects and soft objects and react appropriately to textural changes and object density

changes. These systems have special relevance in healthcare and in in-vivo surgical robotics in particular, and in manufacturing where robots operate within materials of variable density and flexibility.

- *Human compatible motion:* The development of systems able to deliver human compatible motion and interaction, both in terms of impact, the ability to realistically mimic human motion in terms of range reach and capacity. This is of particular importance in assistive robotics and where human compatible interactions are required, and in environments where human scale motion is required, for example climbing stairs or working in a kitchen.
- *Cognitively aware motion:* The development of cognitively aware motion where a system is able to react to changes in the cognitive context of an interaction using motions that can be interpreted by a user. For example the reaching out of a robot arm to steady an elderly person must not frighten them with a sudden unexpected movement.

4.5.5. Key Barriers

The primary barriers to achieving high levels of motion ability are technology limitations, actuation technology, high resolution sensors, power densities, mechanical constraints, high strength, light weight materials etc. Users also expect durable motion systems appropriate to the task as well as other reliability and dependability attributes such as maintainability.

4.6 Manipulation Ability

4.6.1. Description

The ability of the system to handle objects. Where end effectors are fixed or specific to the task this will specify the accuracy and repeatability of the manipulation, for example the ability to absorb tolerances in parts. For dexterous manipulation it might specify the ability to discover how to hold and move unknown objects, or the ability to match two objects together in specific ways. (e.g for joining or stacking)

4.6.2. Technology Drivers

The following technology areas impact on the manipulation ability of a system;

- Systems Engineering
- Actuation
- Sensing
- Modelling and Knowledge Engineering
- Control
- Localisation
- Perception
- Cognition
- Materials

Manipulation ability is the result of a combination of other abilities. As a result each of the levels of manipulation ability relies on particular prerequisite abilities. The following defined ability levels concentrate on describing the ability to grasp, manipulate and move a single object. It is a natural consequence of being able to manipulate one object that the system is able to manipulate multiple objects by executing sequential manipulation actions. This is captured by the phrase “within the context of a task” in the following level descriptions. For example the context may be the movement of a single known object or a sequence of object moves. The process of deciding how to execute the sequence is not a part of manipulation ability but a part of Decisional Autonomy and Cognition. Similarly human collaborative manipulation results from abilities in Interaction, Manipulation and Motion working together.

4.6.3. Current Ability Levels

Manipulation ability is composed of three distinct sets of ability levels:

- Grasping Ability
- Holding Ability
- Handling Ability

4.6.3.1 Levels of Grasping Ability

The following set of levels refers to the ability of a system that has a grasping mechanism to grasp hold of an object.

Level 0 - No Grasping Ability

Many robots will not require the ability to grasp objects.

Level 1 - Simple pick and place

The robot is able to grasp any object at a known pre-defined location using a single predefined grasp action. The robot is then able to move or orient the object and finally un-grasp it. The robot may also use its Motion Ability to move the object in a particular pattern or to a particular location. Grasping uses open-loop control.

Level 2 – Known object pick and place

The robot is able to grasp a known object at a known pre-defined location using a pre-defined grasp action. The robot is then able to move or orient the object and finally un-grasp it. . At the same time, the robot should ensure grasp stability, i.e., not accidentally lose the object even when moving. The robot may also use its Motion Ability to move the object in a particular pattern or to a particular location. Grasping uses open loop control.

Level 3 - Tolerant grasp

The robot is able to grasp a known object that is not located at an exact location, may have some orientation variation and is in the general location within the span of the gripper from some known location. Tolerance in the grasp action is able to absorb the difference in location or orientation. The operation is able to compensate for the differences in the picking location without affecting the required placement accuracy.

Level 4 - Tolerant grasp with sensors

The robot is able to grasp a known object that is not located at an exact location, may have some orientation variation and is in the general location within the span of the gripper from some known location. Tolerance in the grasp action is able to absorb differences in location or orientation. The operation is able to compensate for the differences in the picking location without affecting the required placement accuracy. The grasping uses sensors to control the grasping operation.

Level 5 - Location unknown pick

The robot is able to pick up a known object where the location and orientation of the object are not pre-defined. The robot may use Perception Ability to locate the object and Decisional Autonomy to plan and execute the grasp action in the context of the task.

Level 6 - Generic pick

The robot is able to pick up an object belonging to a certain parameterised type where the dimensions, location and orientation are unknown. The robot may use Perception Ability to locate the object and Decisional Autonomy to plan and execute the grasp action in the context of the task.

Level 7 – Complex object grasping

The robot is able to pick up an object belonging to a certain parameterised type where the object can be articulated, or consists of multiple separate parts.

Level 8 – Pick up unknown object

The robot is able to grasp a geometrically unknown object - an unknown object at a known pre-defined location selecting a grasp action online. The robot is then able to move or orient the object and finally un-grasp it. During the whole operation, grasp stability must be guaranteed. The robot may also use its Motion Ability to move the object in a particular pattern or to a particular location.

4.6.3.2 Levels of Holding Ability

The following set of levels characterise the ability of a robot system to retain its grasp of an object within the context of a task.

Level 0 - No Holding Ability

Many robots will not require the ability to hold objects.

Level 1 – Simple holding of known object

The robot retains the object as long as no external perturbation of the object occurs.

Level 2 – Dynamic holding of known objectives

The robot can retain a grasp on a known object under some defined maximum level of external perturbation of the object.

Level 3 – Simple Holding of modelled object

The robot can retain a grasp on an unknown but modelled object as long as there is no external perturbation of the object.

Level 4 – Dynamic holding of modelled object

The robot can retain a grasp on an unknown but modelled object under some defined maximum level of external perturbation of the object..

Level 5 – Holding unknown objects

The robot can dynamically adapt to the characteristics of the object and retain a grasp up to defined maximum levels of perturbation.

4.6.3.3 Levels of Handling Ability

The following set of levels characterise the ability of a robot system to handle and place an object within the context of a task.

Level 0 - No Handling Ability

Many robots will not require the ability to handle objects.

Level 1 – Simple release

The robot is able to release an object at a known pre-defined location, but the resulting orientation of the object is unknown. The object should not be prematurely released.

Level 2 – Moving to orientation

The object can be placed at a predefined place with a fixed orientation.

Level 3 - Variable placement

The robot is able to alter its placement action to accommodate small changes in location of the destination for a picked object. For example it is able to join two parts where the positional tolerance of the mating part is greater than the accuracy needed to place the part correctly. The placement variation is derived from sensor data on-line during the handling process. The robot may use Decisional Autonomy during placement.

Level 4 - Compliant placement

The robot is able to use compliance in the placement process to fit a picked part into a statically held part. For example the insertion of one part into another where the insertion forces vary during insertion as a result of friction. The robot may use Perception Ability and Decisional Autonomy during placement.

Level 5 – Positioning for placement

The robot is able to orient and align a known object and then place it within the context of a task.

Level 6 – Generic positioning for placement

The robot is able to orient and align a known parameterised object where the dimensions, location and orientation and surface properties are unknown and place it appropriately in the context of the task.

Level 7 – Complex part placement

The robot is able to manipulate an object belonging to a certain parameterised type where the object can be deformable, fragile, articulated, or consists of multiple separate parts. The robot is able to exercise the articulations of the object or disassemble it within the context of a task.

Level 8 - Unknown Object Handling

The robot is able to determine the generic grasping properties of an unknown object. It is able to use those properties to determine how to handle and place the object. The robot may use Perception Ability and Decisional Autonomy during placement.

Level 9 – Understanding object through handling

The robot is able to deduce properties of an object through handling of it. For example if it contains a liquid, if it can be articulated, to determine its centre of gravity, or estimate its dimensions.

Manipulation parameters

The following parameters significantly affect the assessment of manipulation ability:

- Object scale and form
- Object shape complexity
- Object properties; surface texture and material (smooth, rough, transparent, soft, hard, sticky, electrically charged, magnetic, wet, etc.)
- Object dynamics; Object motion under load, compliance, stretch, flexibility and other motion properties.

In assessing manipulation ability it is important to ensure that the identified levels of ability are suitably technology independent. The mechanical nature of manipulation ability will be significantly affected by the specific gripper and sensing technologies employed. The development of these elements of manipulation is covered by technology capability targets and therefore do not form part of the classification of manipulation ability.

4.6.4. Ability Targets

In addition to the on-going development of systems that raise ability levels the following have been identified as R&D&I objectives:

- *In-hand manipulation and re-grasping:* The ability to orient a part while it is being held “in-hand” using a process of un-gripping and re-gripping will be fundamental to the ability to orient and align everyday objects particularly when interacting with users and handing over objects for collection.
- *Contextual assistance:* Significant information can be gained about an object while manipulating it. Information can be gained from direct tactile sensing of the pressures but also from the dynamics sensed as the object is moved (for example the slosh of fluid in a bottle, or the sound emitted by an object when it is grasped). In some cases object may simply be picked up and replaced in order to gain contextual information.
- *Tool manipulation:* The use and manipulation of tools allows generic manipulators to carry out a wider range of tasks. The ability to handle variable material densities, apply forces and orient tools are key to their use.
- *Single finger manipulation*: Exploiting interaction forces existing in miniaturized robotics to perform manipulation with only one finger. The target is to position and orientate object precisely and efficiently despite limited motion capability.
- *Non contact manipulation:* Manipulation of objects (position, orientation, trajectory) using non-contact force fields (magnetic, optic, electric, acoustic…) in different environment (air, liquid, vacuum…). The key goal is high speed trajectory control and multi-component manipulation.
- *Human level dexterity:* Everyday objects have the characteristics of human dexterity built into their design. Instilling human compatible dexterity and manipulation ability is a key goal for the effective manipulation of everyday objects within any human compatible task particularly where interaction is necessary.

- *Collaborative manipulation:* There are many manipulation tasks that require collaboration either between users and robots, between robots, or simply between multiple manipulators on the same robot. Each presents a challenge to manipulation ability in terms of the grasping and exchange of objects.
- *Adaptive plans for dynamic objects:* Robots operating in manufacturing, in healthcare and in everyday environments will need to be able to handle and manipulate dynamic objects, objects that deform, or move independently. The ability to handle dynamic objects will mark a significant step change in ability.
- *Manipulation sequences:* While the ability to carry out sequences of manipulation actions depends on decisional autonomy and cognitive abilities the focusing of these abilities on tasks related to manipulation is an important goal. Of particular importance to numerous applications is the planning and execution of sequences involving multiple objects, occluded objects and objects that require multiple grasp strategies. The ability to pick out objects with minimal disturbance to other objects and the ability to select and grasp specific objects from a collection containing repeats will be a significant step change.
- *Haptic SLAM:* The ability to discover the shape of an object and establish grasp properties purely or mainly from haptic information provided by the process of touch and manipulation.
- *Hazardous material handling*: The ability to safely handle and manipulate hazardous materials or when working in a hazardous environment over extended periods of time. For example working with radioactive or chemically reactive materials, working in an explosive atmosphere or where there are high temperatures or pressures. For example the design of systems able to conform to the ATEX directive.

4.6.5. Key Barriers

The main barriers to manipulation ability vary with application and scale. Fundamentally they relate to the focusing of other abilities to support manipulation and to mechanical design, actuation and tactile sensing. In miniaturised systems, the key barrier is uncertain environmental forces impairing the manipulation performances. Manipulation ability specifically requires the integration of Perception and Motion abilities.

The provision of realistic generic benchmarks for manipulation ability, so that results can be transferred to real-world tasks, is also a potential barrier to the assessment of progress.

4.7 Perception Ability

4.7.1. Description

The ability of the robot to perceive its environment. At the simplest level this is about specifying the probability of accurately detecting objects, spaces, locations or items of interest in the vicinity of the system. It includes the ability to detect the ego motion of a robot arm and the ability to interpret information and to make informed and accurate deductions about the environment based on sensory data.

4.7.2. Technology Drivers

The following technology areas impact on the perception ability of a system;

- Sensing
- Perception
- Cognition

The word “object” in the following level descriptions does not imply a physical or well defined object but does imply a distinct object with respect to sense data, so for example the “object” may refer to the thermal image of a fire, or the sound made by a saw cutting wood as well as a segmented image. These level descriptions use the phrase “sense data” to cover all types of sense data from chemical, visual, acoustic, thermal etc.

4.7.3. Ability Levels

Perception is a key part of the ability of any robot system. It is composed of several different types of ability each of which require the integration of different technologies:

- Perception ability
- Tracking ability
- Data fusion ability
- Recognition ability
- Scene perception
- Location perception

4.7.3.1 Levels of perception ability

The following levels refer to the generic ability of a system to perceive which are generally speaking categorised by abstracting sensor data in each level:

Level 0 - No external perception

Some robots do not sense their environment but simply carry out sets of pre-programmed moves triggered by a starting event. Although there may be safety systems that cause the robot to fail-safe these do not alter the operating cycle behaviour.

Level 1 – Direct Single and Multi-parameter sensing

A robot uses sensors that provide a single, or multiple parameter output directly., for example a distance sensor, or a contact sensor. The robot utilises these outputs to directly alter behaviour within an operating cycle.

Level 2 – Low Level processing parameter sensing

A robot system may use fixed and known markers in the environment to indicate objects or waypoints (e.g. Barcodes, reflective strips etc). The detection of these markers provide triggers to alter or switch between behaviours or sequences of behaviours.

Level 3 - Multi-Parameter Perception

A robot uses multiple single parameter sensors to create a unified model of the environment. Sense data can be collected from multiple types of sensor as well as multiple sensors of the same type. Each sensor contributes information to the model. The model us used to alter the behaviour of the system.

Level 4 - Feature based perception

Sense data is gathered from a region of the environment such that the sense data has a spatial mapping. The richness of the sense data information content is such that it is possible to apply feature extraction to the sense data and thereby interpret the content of the sense data as a set or sets of features. The system performs a data reduction with an assumption about the expected features. The presence of features is used to alter behaviour.

Level 5 - Grouped feature detection

The sense data gathered from the environment can be processed such that features can be aggregated to capture linkages between features. A group of features may relate to the same real object in the environment, but where the object has not been identified. The characteristics of the feature group can be used to alter the behaviour of the system. For example a set of features of the same colour that move in the same way may relate to a pink ball.

Level 6 - Object identification

The system can identify objects or coherent entities that it has detected in the scene through sets of grouped features and can use this identification to alter the system behaviour. The importance in this level is that a data source or a priori object model is required.

Level 7 - Property identification

The system is able to deduce the properties of objects in the scene or scene itself and utilise those properties within system behaviour.

Level 8 - Hidden state identification

The system is able to infer properties of an object, person or scene that are not directly observable. The scene and objects are not fully available in data sources ahead of time and scene interpretation and classification is required.

4.7.3.2 Levels of Tracking Ability

Because robots move within the environment the sense data for a distinct object will alter as the robot moves. It is important that the robot is able to track and maintain its sense of a distinct object during motion.

Level 0 - No tracking

Some robots will be able to carry out their tasks without any tracking ability.

Level 1 - Tracked Feature Perception

Features detected in the sense data are tracked over time. The tracking of features is used to build internal models of the environment. The tracking of markers in the environment is equivalent to tracking derived features.

Level 2 - Static Object tracking

It is possible to track a detected object. The detected location of the object can be maintained with a reliability and accuracy that is compatible with the task.

Level 3 - Dynamic object tracking

It is possible to identify an object and track it using sense data. As the object moves the system is able to disambiguate the motion of the robot from the motion of the object.

Level 4 – Tracking object shape

It is possible to track an object as it changes shape during the execution of a task. This may represent changes due to processes being applied to the object, or because it can be articulated.

Level 5 - Flexible object tracking

It is possible to identify a flexible or deformable object and track it.

Level 6 - Animate objects

It is possible to identify and track an animate object and extract the pose of the object.

4.7.3.3 Object Recognition Levels

Many robot applications require the robot to recognise objects in the environment. This ability may range from being able to recognise instances of a single object, to being able to distinguish between many different objects or even identify objects that fit a generic pattern.

Level 0 - No Recognition

The robot system does not need to detect or recognise objects in the environment in order to carry out its task.

Level 1 - Feature detection

Sense data is gathered from a region of the environment such that the data has a spatial component and can be mapped to a model of that region. The richness of the sense data is such that it is possible to apply a feature detection process to create a set or sets of features that persist.

Level 2 - Object detection

Multiple persistent features can be grouped to build models of distinct objects allowing objects to be differentiated from each other and from the environment.

Level 3 - Object recognition - single instance

Object models created from sense data can be matched to specific known instances of an object with a reliability that is appropriate to the task.

Level 4 - Object recognition - one of many

Object models created from sense data can be matched to one of a number of specific instances of known objects with a reliability that is appropriate to the task.

Level 5 - Parameterised object recognition

Object models created from sense data can be matched to a number of known, parameterised object types. The settings for the parameters (e.g. size ratio, curvature, joint position etc) can be deduced from the sensed object model. Note that in conjunction with single instance recognition ability this implies the ability to recognise a known (possibly learned) instance of a generic object, for example a particular brand of canned drink based on the generic recognition of a drinks can shape.

Level 6 - Context based recognition

The system is able to use its knowledge of context or location to improve its ability to recognise objects by reducing ambiguities through expectations based on location or context.

Level 7 – Object variable recognition

The system is able to recognise objects where there is a degree of variability in the object that approaches the scale of the object. For example many generic objects such as coffee mugs vary in shape size and colour.

Level 8 - Novelty recognition

The system is able to recognise novelty in a known object, or parameterised object type. For example a known mug where the handle is missing or broken.

Level 9 - Unknown object categorisation (Rigid)

The system is able to assess an unknown rigid object based on sense data and deduce properties that are relevant to the task.

Level 10 - Object property detection

It is possible to use sense data and the derived object model to deduce the properties of an object. For example analysis of the sense data may provide surface texture information, knowledge about deformability, or the content of an object.

Level 11 - Flexible object detection

The system is able to detect the shape and form of objects that are deformable and generate parameterised models of flexible objects. This includes articulated objects and objects with flexible and rigid components.

Level 12 - Flexible object classification

The system is able to classify flexible objects by their properties and parameters. It is able to recognise specific known objects relevant to the task with an appropriate level of reliability.

Level 13 - Animate objects

The system is able to detect animate objects and provide a classification appropriate to the task.

Level 14 - Pose estimation of animate objects

The system is able to estimate the pose of an animate object moving within the environment.

{Note Level 13 & 14 require a review at the next MAR edit cycle as it may be necessary to develop a specific animate object recognition ability level}

Recognition parameters

The recognition of features and objects is parameterised by different parameters of the objects. These parameters alter the difficulty of achieving the above levels in any particular task. The settings for these parameters are task dependent. In describing the level needed for a particular task it is important to state the requirements for these parameters:

- *Object orientation:* Some tasks may only present objects within a limited range of orientations, in other tasks there may be considerable variability in orientation. The difficulty of recognising objects increases with the number of presented orientations.
- *Object composition:* Object surface variation, texture, reflectivity, transparency, patterning etc. All affect the difficult of performing object recognition. Reflections and patterns are an integral part of everyday objects and can present significant difficulty.
- *Scale and range*: Some objects may be visible within a single field of view larger objects may require a sequence of views to enable recognition. The identification of scale and range in relation to sense data is also a key component in recognition performance.

- *Resolution and detail*: In fine grained tasks the level of registration between sensing and motion will be critical this will be impacted by the resolution of sensors and the ability to pick out fine detail within sense data.
- *Object types:* Recognition ability will depend on the number of different object types that must be disambiguated and the sensitivity of the recognition process to similarities between the objects.
- *Environment:* Nearly all sensors are affected by environmental factors, either directly (e.g. the use of vision systems in bright sunlight) or indirectly (e.g. the sound of rain hitting a window in acoustic recognition).

4.7.3.4 Levels of Scene perception

In many applications robots will need to be able to interpret the context of a wider scene, identifying static elements in the scene such as walls doors ceilings floor etc. as well as the delineation of objects. This scene interpretation is not related to the recognition of specific objects but to the wider identification of spaces and objects within a working environment.

Level 0 - No scene perception

The robot does not need to be able to interpret the environment in order to carry out its task.

Level 1 - Basic feature detection

The robot is able to detect features in the environment that relate to static structures in that environment.

Level 2 - Static Structures

The robot is able to identify static structures in the environment in a way that is appropriate to the task.

Level 3 - Combined Structures

The system is able to provide a consistent interpretation of the static structures in the environment over time. For example, it is able to identify the floor, walls and ceiling of a room and apply these as physical constraints to a model.

Level 4 - Multiple object detection

The system is able to delineate multiple objects from the static environment where there may be partially occluded with respect to the sense data gathered. For example it is able to delineate objects on the floor of a room.

Level 5 - Object arrangement detection

The system is able to detect arrangements of objects, for example objects in a stack or mixed in a receptacle and identify the relationships between objects with a success appropriate to the task. For example, a chair with books on it and a wine glass on top of the books.

Level 6 - Dynamic object detection

The system is able to detect an object that is moving within a static environment.

4.7.3.5 Levels of self location perception

In addition to the ability to locate and recognise objects and spaces and perform tracking robots also need to be able to identify their own location within their environment. This may be an absolute location, or a relative location.

Level 0 - No perception of location

The robot has no perception of its own location either in terms of its position relative to its environment or with respect to the relative position of its own structure.

Level 1 - Actuator position

The robot knows where its own mechanical structures are because of an assessment of the position of each of its actuators. For example a platform can assess its own position based on the amount its wheels have turned.

Level 2 - External beacons

The robot knows its own location as a result of information derived from the inspection of external beacons. Beacons may be active or passive and include global beacons eg GNSS..

Level 3 – Relative Location

The system is able to calculate its own location relative to its previous location within a degree of accuracy that is sufficient for the task.

Level 4 - Feature based Location

The system calculates its position within an environment based on the motion of fixed features in the environment. For example by using SLAM to build and maintain a local map.

Level 5 - Mapped location

The robot is able to relate its own position to a map that it has been given or that it has acquired. This may be a location within a task relevant space.

Level 6 – Spatial Occupancy

The system calculates the position of its own mechanical structures based on indirectly gathered sense data (i.e. Sense data gathered other than from the motion control system). This provides a spatial notion of occupancy.

Level 7 - Object coupled location

The system is able to calculate the position of its own mechanical structures in conjunction with objects it is connected to. For example an object that is being gripped by the robot, or the position of the user in an assistive task.

4.7.4. Ability Targets

The wide range of different types of a perception ability provides significant opportunity for R&D&I activity to raise ability levels and extend the range of ability parameters both in terms of generic systems development and in terms of specific application areas. In addition to this general goal the following tasks have also been identified:

- *Object property perception:* The use of perception to create or confirm generic property information about known and unknown objects (semantic property grounding). For example the ability to perceive qualities of an object such as will it break if dropped, or is it too slippery to hold. Such information can be used to inform planning and control tasks.
- *Scene attention strategies:* The development of strategies for analysing large scenes and identifying the elements of the scene that are task relevant within the current stage of an on-going task. This involves the development of improved methods for object segmentation and classification.
- *Immunity to natural variations:* The development of perception strategies that can overcome the impact on perception ability of natural environmental variations. For example different times of year, different weather conditions, different lighting conditions etc.

4.7.5. Key Barriers

The most important barrier is the limitation of the sensor technology for accurate measurement of specific materials (reflective, absorbing or transparent) using off the shelf, affordable and eye-safe sensors. Fusing these different modalities together into a common representation is also not generally solved. Currently, common sense knowledge is integrated only at higher level systems, but methods are missing to select which information to use at the sensor fusion level. Furthermore, the use of shape similarities in order to cover large variety of object types remains an open question. Biological systems are still not fully understood in particular on higher perception levels.

4.8 Decisional Autonomy

4.8.1. Description

The ability of the robot to act autonomously. Nearly all systems have a degree of autonomy. It ranges from the simple motion of an assembly stopped by a sensor reading, to the ability to be self sufficient in a complex environment.

4.8.2. Technology Drivers

The following technology areas impact on the decisional autonomy of a system;

- Perception
- Cognition

It is important to distinguish between the actions of a system that are the result of Decisional Autonomy and those that are caused by long term adaptation.

4.8.3. Current Ability Levels

4.8.3.1 Decisional Autonomy Levels

The following are a set of ability levels for decisional autonomy:

Level 0 - No autonomy

All robots exhibit a degree of autonomy. This level remains for consistency with other abilities.

Level 1 - Basic action

A robot that executes a sequence of actions that are unaffected by the environment and makes decisions based on the locations of actuators to proceed to the next action step.

Level 2 - Basic decisional autonomy

The robot makes decisions based on basic perceptions and user input and chooses its behaviour from predefined alternatives.

Level 3 - Continuous basic decisional autonomy

The system alters the parameters of a behaviour in response to continuous input from perceptions, or based on input control from a user interacting continuously with the system. The system may be able to override or ignore user input when certain criteria are encountered.

Level 4 - Simple autonomy without environment model

The system uses perception to make moment to moment decisions about the environment and so controls interaction with the environment in order to achieve a predefined task.

Level 5 - Simple autonomy with environment model

The system uses perception to make moment to moment decisions about the environment and so controls interaction with the environment in order to achieve a predefined task. The decisions made take into account an internal model of the environment.

Level 6 - Task autonomy

The system utilises its perception of the environment to sequence different sub-tasks to achieve a higher level task. For example cleaning a room based on a self-constructed room map where it returns to areas that have been missed and to a recharging station when the battery runs low. The events that cause behavioural changes are external and often unpredictable.

Level 7 - Constrained task autonomy

The system adapts its behaviour to accommodate task constraints. These might be negative impacts in terms of failed sensors, or the need to optimise power utilisation or other physical resources the process depends on, (water, chemical agents, etc.). Alternatively these might be constraints imposed by sensing ability, the environment or the user.

Level 8 - Multiple task autonomy

The system chooses between multiple high level tasks and can alter its strategy as it gathers new knowledge about the environment. Will also take into account resource limitations and attempt to overcome them.

Level 9 Dynamic autonomy

The system is able to alter its decisions about actions (sub-tasks) within the time frame of dynamic events that occur in the environment so that the execution of the task remains optimal to some degree.

Level 10 - Mission oriented autonomy

The system is able to dynamically alter its tasking both within and between several high level tasks in response to dynamic real time events in the environment.

Level 11 - Distributed autonomy

The source for task and mission decisions can originate from outside of the system. The system is able to balance requests for action with its own tasking and mission priorities and can similarly communicate requests for action.

Autonomy parameters

There are a number of task based parameters that will affect the achievability of individual levels of autonomy on a task by task basis.

- *Environmental factors:* The operating environment will significantly affect the ability to achieve any particular level of decisional autonomy. In particular cluttered, dynamic environments are more likely to affect perception and thus decision making. Such environments will also require more complex models if these are to provide high quality of information to the decision making process. Extreme environments will similarly cause a reduction in the ability to make decisions.
- *Decision cost:* Higher levels of decisional risk and reduced recovery options will decrease the confidence required to raise autonomy levels. In healthcare or in space where decisions have high cost implications the confidence levels required in the interpretation of sense data are significantly higher.
- *Time scale:* The longer a system must maintain autonomous decision making the harder it will become to rise through the ability levels.
- *Decision range:* A system that is only required to make a small range of decisions will be more likely to have a high level of decisional autonomy.

4.8.4. Ability Targets

In addition to R&D&I activity that focuses on the raising of decisional autonomy levels the following priorities have also been identified:

- *Decision validation mechanisms:* The development of systems and methods able to provide validation of decisions made within a task context. Where high risk decisions must be made such systems should be able to rate the risk level of the decision in the task context and provide corroborating evidence for the bounding of the decision.

- *User driven decisions:* In many complex tasks it may be necessary to confirm decisions with a human operator during the task. These confirmation decisions or requests for direction need to be framed so that the user understands the context of the decision and can provide added value in the decision making process.
- *Certification of decisions:* In safety critical systems it will be important for the decision mechanism to be certified. Design and implementation methods that allow certification and validation processes need to be developed to create high levels of confidence in decision mechanisms. In turn decision audit trails will be required to post-analyse failures of decision making.
- *Decisions based on uncertain data*: In many real applications there will be a task balance between the capture of new knowledge about an environment and the execution of the task at hand with incomplete or uncertain data. The development of decision support mechanisms that are able to manage this balance will be critical to a number of application domains.
- *Decision layering*: In complex missions there will be multiple layers of decision making from moment to moment decisions to high level mission decisions. These layers will need a decision support environment so that the relative priorities of decisions are handled in a task appropriate way.

4.8.5. Key Barriers

Complex decision making in uncertain environments will push the boundaries of current technical capability. Progress to application and deployment is likely to be delayed until the decision making technology is developed. This progress will also depend on advances in perception, adaptability and cognitive ability.

4.9 Cognitive Ability

4.9.1. Description

The ability to interpret the task and environment such that tasks can be effectively and efficiently executed even where there exists environmental and/or task uncertainty. The ability to interpret human commands delivered in natural language or gestures. The ability to interpret the function and interrelationships between different objects in the environment and understand how to use or manipulate them. The ability to plan and execute tasks in response to high level commands. The ability to work interactively with people as if like a person.

Currently, different aspects and faculties of the Cognitive Ability as a whole have different degrees of maturity and pose different challenges. Attempting to combine these differences into a single rating or overarching targets are likely to lead to invalid or misleading conclusions.

The assessment of cognitive ability is therefore divided into several components, or faculties. The assumption being that the cognitive ability of a system can be assembled and described more accurately by referring to a mixture of component abilities.

4.9.2. Technology Drivers

The following technology areas impact on cognitive ability.

- Systems Design
- Perception
- Human Robot Interaction

4.9.3. Ability Levels

Cognitive ability grows out of the framework built by the other abilities, particularly perception, interaction and decisional autonomy and is composed from a number of underlying components:

- Action ability
- Interpretive ability
- Envisioning ability
- Learning Ability
- Reasoning Ability

Individual sets of ability levels can be described for each of these component abilities.

There is also a close relationship between Interaction Ability and Cognitive Ability. This closeness derives from the essentially interactive nature of robotics and its physical embodiment in the real world. There is a distinction between levels of interaction that do not involve a cognitive element and those that do. The following Cognitive ability components characterise the levels of cognitive interaction with objects and people and are closely related to the Interaction Ability levels.

- Object interaction ability
- Human interaction ability

Ultimately it is the integration of these abilities which will create robots able to interact meaningfully in their environment. This integrated cognitive ability of a robot can be summarised as its ability to acquire knowledge about its environment, adapt its plans to fit the dynamics of that environment, including the user and their actions, and to be able to envision its own actions on the environment and reason about goals and interactions such that it can effectively carry out its tasks.

4.9.3.1 Action ability levels

Action ability concerns the ability of the robot system to act purposefully within its environment and the degree to which it is able to carry out actions and plan those actions. These abilities build on perception and decisional autonomy abilities. Action ability also co-depends on the other cognitive abilities.

Level 0 - No Action Ability

Robots are defined by having some level of action on the environment. This level remains for compatibility.

Level 1 - Defined action

The robot executes fully pre-defined actions as a sequence of sub-actions. This sequence can repeat until stopped by an operator or other system event.

Level 2 - Decision based action

The robot is able to alter its course of action based on perceptions or system events. It is able to select between a set of pre-defined actions based on its decisional autonomy ability.

Level 3 - Sense driven action

The robot is able to modulate its action in proportion to parameters derived from its perceptions. The perceptions are used to drive the selection of pre-defined actions or the parameters of pre-defined actions.

Level 4 - Optimised action

The robot is able to alter the sub-task sequence it applies to the execution of a task in response to perceptions or a need to optimise a defined task parameter.

Level 5 - Knowledge driven action

The system is able to utilise knowledge gained, from perceptions of the environment including objects within it, to inform actions or sequences of action. Knowledge is gained either by accumulation over time or through the embedding of knowledge from external sources, including user input that associate properties with perceptions.

Level 6 - Plan driven actions

The system is able to use accumulated information about tasks to inform its plans for action.

Level 7 - Dynamic planning

The system is able to monitor its actions and alter its plans in response to its assessment of success.

Level 8 - Task action suggestions

The system is able to suggest tasks that contribute to the goals of a specific mission.

Level 9 - Mission proposals

The system is able to propose missions that align with high level objectives.

4.9.3.2 Interpretive ability levels

The interpretation of sense data is key to the ability to identify, recognise, classify and parameterise objects in the environment. It particularly refers to the ability to amalgamate multi-modal data into unified high level object descriptions that create knowledge for tasks to draw on. The ability to interpret also engages knowledge sources to build increasingly complex interpretations of the environment and human interaction, in particular building frameworks of relationships between the environment and objects and between objects.

Level 0 - No interpretive ability

The robot does not need to interpret the environment or user interface actions.

Level 1 - Fixed sensory interpretation

The robot has a fixed interpretation of the perceptions that occur because they are pre-categorised. For example all sensed objects are applied to an occupancy grid and assumed to represent actual objects in the environment.

Level 2 - Basic environment interpretation

The robot uses sense data to interpret the environment into fixed notions of environmental space that are pre-categorised. For example it will search for floor and wall segments in the sense data as these are relevant to its task even if the environment it is sensing has neither.

Level 3 - Object delineation

The robot is able to disambiguate objects from an interpretation of its static environment. The disambiguation of objects is based on built in notions of object and environment. These notions may only be valid within a narrow operating context.

Level 4 - Object category interpretation

The robot is able to interpret the shapes and forms of objects based on categories of objects that are task relevant. It is able to interpret sense data to identify coherent instances of an object over a time scale appropriate to the task. Note that this ability level is particularly affected by the Cognition Ability Parameters.

Level 5 - Structural interpretation

The robot is able to interpret perceptions so as to extract structural information from the environment. It is able to identify the structural relationships between objects in the environment.

Level 6 - Basic semantic interpretation

The robot is able to apply semantic tags to locations and objects allowing it to plan actions based on functional objectives that depend on the semantics of objects and locations.

Level 7 - Property interpretation

The robot is able to interpret perceptions to determine the properties of objects or locations in the environment.

Level 8 - Novelty interpretation

The robot is able to interpret perceptions to identify novelty in objects or locations.

Level 9 - Environmental affordance

The robot is able to interpret the environment in terms of what it affords. For example it is able to interpret the ground conditions in a muddy field as being too unstable for the load it is carrying.

4.9.3.3 Envisioning ability levels.

Envisioning refers to the ability of the robot system to assess the impact of actions in the future. This may reduce to prediction but in the higher levels involves an assessment of the impact of observed external events.

Level 0 - No envisioning ability

The robot is not able to predict subsequent states.

Level 1 - Motion prediction

The robot is able to project the effect of its motion to predict short term local interactions with detected objects in the environment. The robot only has the ability to predict its motion with respect to static objects.

Level 2 - Dynamic motion prediction

The robot is able to project the effect of its motion to predict short term interactions with both static and dynamic objects in the environment that the system can detect.

Level 3 - Function projection

The system is able to project the effect of its function onto the local environment in order to be able to assess its effectiveness. For example a robot may assess the coverage of a room it has cleaned in order to identify areas it has missed.

Level 4 - Rigid interaction prediction

The system is able to envision the effect of its planned actions on rigid objects and structures that it has identified. For example it is able to predict how an object will behave when grasped in a particular way.

Level 5 - Flexible object interaction

The system is able to envision the effect its planned actions will have on flexible objects that it has parameterised.

Level 6 - Basic environment envisioning

The system is able to observe events in the environment that relate to the task and envision their impact on the actions of the robot.

Level 7 - Envisioning safety

The system is able to assess the safety implications on users of observed events occurring in the working environment.

Level 8 - Envisioning user responses

The system is able to envision the actions of a user responding to events in the environment.

4.9.3.4 Acquired Knowledge Levels

Operating environments will always contain a number of unknowns. In many proposed application areas robots will encounter unknown objects and environments as a normal part of task execution. The acquisition of knowledge about both environments and objects is fundamental to the success of these new application areas.

Level 0 - No Acquired Knowledge

The robot does not acquire knowledge during its operation. Required knowledge is embedded in the system.

Level 1 - Sense data knowledge

The system is able to acquire knowledge about its environment based on sense data gathered moment to moment.

Level 2 - Persistent sense data knowledge

The system is able to accumulate knowledge about its environment based on sense data that persists during the execution of the current task.

Level 3 - Property knowledge

The system is able to acquire knowledge about the properties of objects in the environment by observation.

Level 4 - Deliberate acquisition

The system is able to acquire knowledge about the composition of its operating environment by executing actions that are deliberately designed to increase knowledge through exploration. For example to determine if a cup is full of liquid.

Level 5 - Place knowledge

The system is able to accumulate knowledge about the location and types of objects and environmental features in terms of matching objects to pre-defined and known types.

Level 6 - Knowledge scaffolding

The system has the ability to integrate embedded knowledge of objects and places with related knowledge gained from the environment.

Level 7 - Requested knowledge

The system is able to recognise that it has insufficient knowledge about an object or place relevant to the task and can formulate a question to gain that knowledge either from a person, or an external data source such as the internet or another robot.

Level 8 - Distributed knowledge

The system is able to communicate its gained knowledge to other robots or systems and can receive and integrate knowledge from other robots or systems.

Level 9 - Interaction acquisition

The system is able to acquire knowledge about its environment and objects within it through planned interactions with the environment and objects. For example the robot deliberately selects an object of interest and picks it up to examine it more closely, putting it back where it picked it from.

Level 10 - Object function

The system is able to acquire knowledge about the function of objects in the environment. This knowledge may be acquired directly or indirectly through observation.

Level 11 - User knowledge

The system is able to acquire knowledge about the user by observation.

Level 12 - Critical feedback

The system is able to acquire knowledge about its actions by analysis of critical feedback that follows completion of the action.

Level 13 - Long term observation

The system is able to distinguish between long term and short term changes in the environment and the objects within it.

Level 14 - Patterns of behaviour

The system is able to acquire knowledge about the patterns of behaviour of the user that relate to the task. For example learning how to carry out an assembly process by observation.

Level 15 - Observation learning

The system is able to acquiring knowledge indirectly from observing other robots or people carrying out tasks.

4.9.3.5 Reasoning levels

Reasoning ability is the glue that holds the cognitive structures together. Perception, knowledge acquisition, interpretation and envisioning all rely to a certain extent on the ability to reason from uncertain data. As application tasks become more complex the need to provide task and mission level reasoning increases.

Level 0 - No Reasoning

There are numerous simple robots that do not carry out any form of reasoning but simply execute a pre-determined pattern of activity.

Level 1 - Reasoning from sense data

The robot is able to make basic judgements of sense data sufficient to allow actions to be controlled.

Level 2 - Pre-defined reasoning

The robot is able to use basic predefined knowledge about structures and objects in the environment to guide action and interaction.

Level 3 - Basic environment reasoning

The robot is able to use knowledge of the environment gained from perception in conjunction with stored knowledge to reason about the environment. For example it can build a map of the environment and plot a path to a goal.

Level 4 - Reasoning with conflicts

The system is able to reason about the environment and objects when there is conflicting or incomplete information. For example missing sections of a map, or competing classifications for an object.

Level 5 - Dynamic reasoning

The system is able to reason about the perceived dynamics in the environment.

Level 6 - Safety reasoning

The system is able to reason about safety in the environment.

Level 7 - Task reasoning

The system is able to reason about the appropriate courses of action to achieve a task where there are alternative actions that can be undertaken. Typically the system will be able to identify the course of action which matches the desired task parameters, typically these involve time to completion, resource usage, or a desired performance level.

Level 8 - Task hypothesis

The system is able to reason about the priorities of different tasks within a mission and propose priorities based on its knowledge of the mission and the tasks. The system will be able to fix on a task that must be achieved but make decisions about how tasks will sequence to achieve mission objectives.

4.9.3.6 Object interaction levels

Cognitive ability plays a vital role in the interaction with objects in the environment. The application of cognitive knowledge to the manipulation and interpretation of objects through interaction provides a significant step change in the ability of a system to interact.

These ability levels are modulated by the complexity and number of objects within a given task as detailed by the cognitive ability parameters.

Level 0 - No cognition based interaction with objects

Many applications will not need to use any kind of cognitive interpretation or knowledge in their interaction with objects.

Level 1- Environmental context utilisation

The system is able to use context information about the environment to guide interaction with a specific object. This relates to the transfer of knowledge from the environment to the manipulation of a specific object. For example knowledge about a surface onto which an object is to be placed altering the placement strategy, or knowledge about the relationship between objects.

Level 2 - Property Identification

The robot is able to pick up an object that belongs to one of a number of known object types and determine properties of the object from its holding and manipulation of it. It is able to use these determined properties to control how the object is manipulated and placed. For example a robot may pick up a cup and determine that it is full of liquid.

Level 3 - Object placement

The system is able to manipulate and place an object in a way that is compatible with its state and context. For example property knowledge is used when orienting and object.

Level 4 - Composite object manipulation

The system is able to identify that an object is composed of multiple different objects that are connected but which may be separable. Within the context of the task the system may be able to separate the parts, or exploit the union between them.

Level 5 - Generalised object manipulation

The system is able to interact with an unknown object and as a result of the interaction categorise the object in terms of its categorical relationship to other known or discovered objects. This includes generic categorisations such as “it is a container for liquid”.

Level 6 - Novel object manipulation

Based on contextual and historical knowledge the system is able to establish that an identified object is novel as district from being unknown. Novelty may result from the object being broken or incomplete. For example a known mug is missing a handle, or a bottle its cap. The system is then able to manipulate the object taking into account its altered state.

Level 7 - Use of affordances

The system is able to deduce that an object affords an action. The robot is able to grasp an object that has desired affordances within the context of the task or mission and manipulate the object in order to gain use of the afforded action.

4.9.3.7 Human interaction ability levels

The following set of levels relate to different levels of human interaction with a robot that have a cognitive element. They specifically relate to the interaction between a human and a single robot. Where multiple robots are involved a corresponding set of levels applies.

Level 0 - No Cognitive Human Interaction

Many robot systems will be able to operate successfully without cognitive interaction with the user.

Level 1 - Fixed interaction

Interaction between the user and the robot follows a fixed pattern. Typically this takes place via a user interface with well defined inputs and outputs. Typical of this type of interaction are domestic vacuum cleaning robots which offer simple button interfaces and display a minimum amount of status information. Fixed interaction also includes interaction via a computer based user interface where interactions directly control the robot according to pre-defined sets of commands with specific meaning. The connection between the user and the robot may involve a wireless link. Any interpretation of commands is fixed and embedded.

Level 2 - Task context interaction

The system is able to interpret commands from the user that utilise task context semantics within a domain specific communication framework appropriate to the range of the task.

The system is able to relay task status to the user using task context semantics suitable for the task.

Level 3 - Object and location interaction

The system is able to interpret user interactions that refer to objects, locations or actions in as is appropriate to the task. This includes the ability to interpret user interactions that identify objects locations and actions as well as processing commands that reference locations, objects and actions relevant to the task. Dialogues are initiated by the user.

Level 4 - Robot triggered interaction

The system is able to start a dialogue with the user in a socially appropriate manner relevant to its task or mission. The robot has a basic understanding of the social interaction appropriate to the task/mission domain. Interaction may continue throughout the operating cycle for each task as is appropriate to the task/mission.

Level 5 - Social interaction

The system is able to maintain dialogues that cover more than one type of social interaction, or domain task. The robot is able to manage the interaction provided it remains within the defined context of the task or mission.

Level 6 - Complex social interaction

Dialogues cover multiple social interactions and tasks, where the robot is able to instruct the user to carry out tasks, or enter into a negotiation about how a task is specified. The interaction is typified by a bi-directional exchange of commands.

Level 7 - Intuitive Interaction

The robot is able to intuit the needs of a user with or without explicit command or dialogue. The user may communicate to the robot without issuing explicit commands. The robot will intuit from the current context and historical information the implied command.

Cognitive parameters

The difficulty in achieving the above levels in each component ability depends on a number of characteristics of the task and environment:

- *Environment:* If the environment is unstructured and contains a wide variety of objects this will increase the difficult in achieving cognitive ability levels. If the environment contains dynamic elements or complex relationships between objects then this will also increase the difficult in achieving higher levels of cognitive ability.
- *Object Density:* The object density of an environment refers to the number of different objects that a system will encounter simultaneously. Where there are many objects within the perception range of the system their number will make cognition harder, the more objects there are the harder it will be to envision, learn, interact and interpret. This parameter is orthogonal to the complexity of each object and the variety.
- *Prior Knowledge:* The ability to achieve cognitive abilities with respect to environments, objects and interactions is strongly influenced by the level of prior knowledge about each element. Prior knowledge may range from knowledge about specific instances of an object or room, to no prior knowledge. It will always be harder to achieve a cognitive ability level where there is no prior knowledge of the elements that will be encountered.
- *User expectation:* The level of user expectation and experience will impact on the perceived attainment of cognitive ability levels. Users with realistic bounded expectation, or experience, will reduce the difficulty of achieving a particular level of ability.

- *Time scale:* If the time span of operation is longer then the difficulty of achieving higher levels of cognitive ability increases. Similarly if the time scales for observation and knowledge acquisition are longer there will be an increase in difficulty levels.
- *Task risk:* The difficulty in guaranteeing outcomes and the potential need for the certification of decision making mechanisms in tasks with high levels of risk will make the attainment of high levels of ability more difficult.

4.9.4. Ability Targets

The broad impact of cognitive ability on a wide range of robotics applications puts the main emphasis on the improvement of the different components of cognitive ability in a wider range of tasks. Each application will have different requirements for cognitive ability and this has an impact on the development of generic cognitive abilities.

The following R&D&I activities can be identified in addition to the above:

- *Cognitive integration:* Integration of the different types of cognitive ability in terms of formalisms and control. Focus should be placed on developing the interoperability of multiple, hybrid representation and reasoning frameworks and on the principles of designing flexible and scalable control architectures that can change with the robot morphology and with the multiplicity and distribution of processing units.
- *Robot centric AI tools*: The development of tools for knowledge representation and reasoning that account for the specifics of the robot environment that can be applied across all the cognitive abilities will have a significant enabling impact. Handling aspects of user, object and environment interaction within a common framework able to handle uncertainty and failure modes will enable a more integrated approach to the development of cognitive systems. It is important that such systems are demonstrated within real robot contexts to encourage early experimentation and real world deployment.

4.9.5. Key Barriers

The main barrier is the problem of integrating into a complete robot control system state-of-the-art modules that locally realise abilities in isolation. Formalisms and algorithms over different modules (perception, planning, learning, envisioning etc.) are typically incompatible. The top-performing state-of-the-art modules are often the hardest to integrate, because they use sophisticated and incompatible representations and algorithms that must first be adapted to the needs of robot control.

Designing a suitable robot control architecture that includes a number of abilities as part of the integration process remains a key goal. Currently there is no dominant solution. There will be considerable benefit in making it possible to transfer a cognitive architecture from one robot system to another. This will enable cross architecture comparisons to be made which in turn will contribute to developing deployable cross platform systems.

These issues currently represent significant barriers to the wide scale deployment of cognitive abilities in robot tasks.

5. Technologies

One of the primary outputs from investment in research and innovation are new technologies and improvements in existing technology. It is the purpose of the innovation pipeline to push these technologies to market while generating expertise and creating the skill base is needed to deploy and develop technologies and applications.

A fundamental part of this strategy is the desire to identify technologies that are mature enough to be pushed to market coupled to the identification of technologies that are critical to multiple application domains allowing a maximisation of impact.

Critical to this process is the identification of “step changes” in the capability of each technology. In particular the identification of generic step changes that will impact across multiple types of application and domain.

This strategy requires the ability to measure the current “state of the art” of each technology and to characterise its potential impact on applications and domains by establishing a progression for that technology. Both of these tasks carry significant difficulties. The measurement of maturity is compounded by the differing needs of market domains, and establishing a progression of capability is often dependant on the synergetic function of multiple technologies.

Technologies and Definitions

The roadmap uses a set of high level technology clusters to organise the underlying technologies. Within each technology methods and techniques to achieve capability are only outlined. The progression in each technology is identified by capability targets rather than through descriptions of method and technique.

5.1.1. Technology Clusters

The following major technology clusters are used within the roadmap:

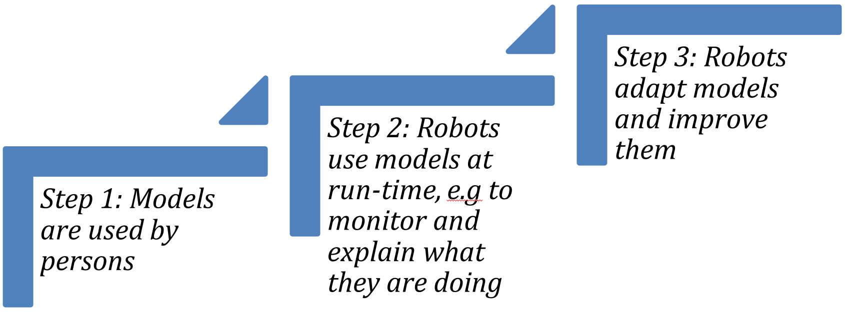
- Systems Development: Better systems and tools.
- Human Robot Interaction: Better interaction
- Mechatronics: Making better machines
- Perception, Navigation and Cognition: Better action and awareness

5.2 Systems Development

“Better Tools and Processes for Better Systems”

To create robotic systems for real-world applications, the need for a systems engineering approach has been identified which goes well beyond the current state-of-the-art regarding systematic processes, methods and models, and tools:

- Software and system design methodology and capabilities are seen as the “make or break” factor in the development of complex robot systems.
- Development needs to concentrate on "total lifetime (software) support" - from the initial product idea, to the end of the run-/use-time … and beyond.
- Openness and standardization are seen as important attributes for the further spread of robotics technology and for creating a business ecosystem for robotics
- Model based methods are needed at the core of all complex robot systems and through the lifecycle. To address increasing complexity, a shift from human-oriented document-driven approaches to computer-assisted tools and a computer processable model-driven approach is needed in order to gain from design support processes. Models can be used in different ways, which are reflected by the envisioned step changes illustrated below.
- On contrast to general, standard (software) engineering and algorithm development, in robotics application development additional constraints that have to date been abstracted away, must be taken into consideration. This requires a shift in viewpoint, focus, paradigm, and methodologies related to the development process and the semantic description of the building blocks and processes.



Step 1: Models are used by persons

Step 2: Robots use models at run-time, e.g to monitor and explain what they are doing

Step 3: Robots adapt models and improve them

Step changes in the robotics (software) development and life-cycle support. Models are abstract representations of the real system. Models capture sufficient characteristics to be valuable for a for a specific purpose such as system design, development etc.

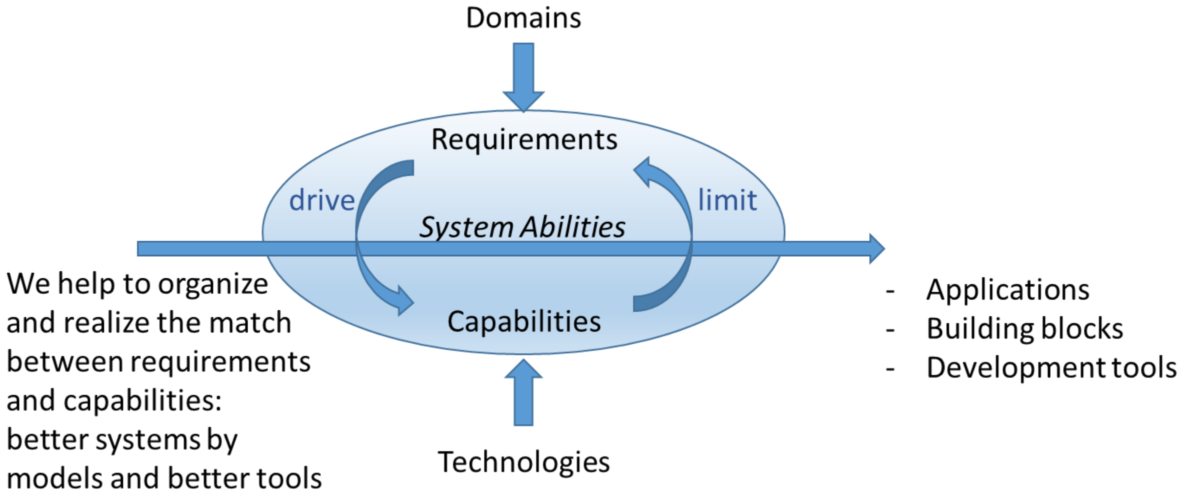
In developing the processes to design robots the analysis of those processes becomes critical to improving them. This cluster of technologies relate to the design process of robots and robot systems. It is well understood that saving time and cost during the development of a new product is most easily done during the early parts of the development phase. Tools, models, standards, processes, and workflows for system design can all help to streamline development. Investment in these technologies is critical to the timely development of products and services and a key enabling factor in the stimulation of a viable robot industry.

5.2.1. Technology Description

The technologies underlying Systems Development focus on the methodological and software aspects used in system development and integration process. This combination of technologies aims to deliver the underlying engineering methods and software tools for robot developers and manufacturers to use during the design, development and integration phases.

Robots are the result of integrating a wide range of technologies. With sophisticated software components and complete subsystems becoming more and more available as commodity products from other sectors (mobile devices, communications, automobile driver assistance systems), the success of robotics crucially depends on the ability to manage the integration of these complex systems into powerful and cheap robots.

As shown in the EFFIROB study,[17] "the development of software leads to significant costs for both manufacturers and integrators of service robots". This situation arises from the current lack of sufficient technologies and methods regarding system integration necessary to deal with the broad scope of heterogeneous robotic systems. Software-framework and robotic middleware development projects focus on sub-domains (e.g. real-time sensor-actuator networks, sensor data fusion, sub-system integration, cognition). This has led to greatly refined capabilities regarding sub-system design as well as horizontal integration. Smooth vertical integration (systems of systems) has yet to be properly addressed.



Bringing together technologies and domains

There is a demand for systematic and scientifically backed approaches for creating re-usable robot building blocks for system integration in the form of well defined modules with clearly explained and well defined properties. Such a system of modular integration, which supports hand-over between different roles, will stimulate component supply chains and significantly alter the robotics market place. For these reasons Systems Design is a key cluster of technologies that require R&D&I focus.

Current state of the functional landscape:

Usually there are no system development processes (highlighted by a lack of overall architectural models and methods). This results in the need for craftsmanship in building robotic systems instead of following established engineering processes.

Available integration frameworks and middleware are diverse in character and scope and are driven by different objectives. To date these efforts have not achieved the status of robotics commodities. Typically there is tension between different design approaches: *freedom of choice* is preferred by academia and mainly suits explorative research (ROS, YARP, OROCOS)

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[17] http://www.ipa.fraunhofer.de/Wirtschaftlichkeitsanalysen_neuartiger_Servicerobotik-Anwendungen_und_ihre_Bedeutung_fuer_die_Roboti.1643.0.html

whereas *freedom from choice* introduces structure for separation of roles and separation of concerns as is the prerequisite for a business ecosystem (OpenRTM, SmartSoft).

Freedom of choice means the support of many different schemes. The user (domain experts, customers, system engineers, system designer, system deployer, end-users, non-expert users) is left to decide which one best fits their needs. This requires considerable expertise, and discipline by the user in order to avoid mixing non-interoperable schemes. Typically, academia tends towards preferring this approach since it seems to be as open and flexible as is possible. However, there is a high price to pay since there is no guidance with respect to ensuring composability and system level conformance. In contrast, *freedom from choice* gives clear guidance with respect to selected structures. However, there is a high level of responsibility for the tool designer to coming up with the appropriate structures such that they do not block progress and future designs.

Freedom from choice needs to be based on open structures, however, some global players (such as Google) could potentially push to create "lock-in" to their proprietary business ecosystem.

Up to now, explicated resource-awareness and Quality-of-Service attributes are missing. As a consequence it is not possible to configure or provide robotic systems with resources just adequate and sufficient for an application. This is in contrast to other technology domains like automotive, aerospace and microelectronics.

Safety and complex systems (autonomous/cognitive) are not naturally compatible. The reason being that the presence of inherently unsafe components, the rigidity of safety requirements/validation and the complexity of functional safety relationships to be checked within a complex system.

There is a lack of decision support for package/module choice. It should be supported by providing a semantic description (machine interpretable) including additional information such as performance parameters, component level certification or standards met.

Formal models, theoretical approaches, and composition and verification tools usually focus solely on mathematical models and methods while neglecting capabilities and limitations of both current computer systems and dependent higher-level software. While other domains like mechatronics deal with these aspects foremost for closed systems, these need to be extended to all parts of robotics systems. They are missing in robotics due to the openness of robotic systems and the openness of their operational environment.

5.2.2. Key Techniques and Methods

The focus lies on the following lines of attention and design drivers:

- Quality-of-service (performance levels, system building blocks with semantically annotated model parts)
- Resource-Awareness
- Robustness
- Safety
- Standardization of models

These aspects come in at different points in time (stepwise refinement), depending on the application area. They require a substantial extension of original Systems Engineering approaches according to the specific needs of robotics applications. Bringing in the above listed aspects too late in the lifecycle may lead to inappropriate solutions or applications.

Generic approach

Systematic approach to the core areas of the development processes, including advanced requirements engineering. Specification of the overall system architecture and its automated design includes issues such as communication topology, reference architecture, open architecture and modular service architecture. A major goal is the high degree of re-usability of components.

Modelling in terms of levels of abstractions separating technical issues of implementation from conceptual issues of functionality is a first step. Modelling includes usability and reliability, scalability and evolvability, usage (human-machine interaction, user acceptance, and ergonomics).

Separation of roles is a key property to be supported in the overall life-cycle of robotics software (development, system integration, deployment, run-time) in order to allow for innovation along structures as typical and established in other high-tech industries. Main roles are component developers, system integrators, application domain experts, framework developers, tool developers, professional user or consumer. This enables the collaboration at the level of meta-models, models, standards etc. Especially, free and open standards, maintained in a dialogue between academia and industry, can act as a structuring element to facilitate a robotics business ecosystem. The focus in the context of innovation is on importing *freedom from choice* while still being open for *freedom of choice*.

Key techniques/methods:

Model-driven engineering: core technology which has reached mature level in other domains, but not in robotics. Model-driven software development (MDSD) and DSL (domain specific languages) are core technologies required in order to achieve a separation of roles in the robotics domain while also improving compose-ability, system integration and also addressing non-functional properties.

Use of semantic technologies, e.g. by semantic description of functionality and the interfaces, which allows to search for "off-the-shelf components" with explicated properties and rely on conformance for compose-ability during design space exploration. This increases the re-usability and will enable to offer black-box (protect intellectual property) or white box (open source) components.

Use of patterns on all levels (architectural, for model-driven design …)

Stepwise refinement: support for partial H/W bindings even in the very first design steps/phases and not only as the last step like in the OMG approach. Late/early binding needs to be modelled such that different aspects come in at different points in time.

Architectures and design methods which allow integration of cross-sectional requirements, e.g. safety, fault-tolerance, uncertainty etc. in different parts of the system, but ensure overall system properties regarding these aspects. The architectures should allow for hard, firm, and soft real-time as a system level property supported by Hardware/Software platforms both in processing and communication (mixed-real-time).

Hardware/Software co-design

Formal methods in software/system engineering are techniques and tools based on mathematics and formal logic used to describe the high-level behaviour and properties of a system without constraining the implementation. The tools can check automatically if the system behaviour and properties satisfy system requirements, such as real-time guarantees, dependability, reliability, robustness. Even if most techniques are domain-independent, research is needed to effectively use them in robotics, which is more challenging than other domains, such as avionics and automotive. The main difference between advanced robotic systems and other software-intensive domains is the need to take autonomous decisions in order to adequately face open-ended environments and respond with only limited resources.

Middleware and Virtualisation are technologies used to improve computer system performance, customisation, resource control, and reliability by decoupling the behaviour of hardware and software resources from their physical implementation.

5.2.3. Expected Step Changes

Total Life Time Support

- Definition of developer roles (component developers, system integrators, application experts, framework/ tool developers etc.)
- Generic process model for cross-market robot software development, providing dependable, safe, configurable, adaptable and reusable applications
- Software Product Lines: automatic selection of components - Automated testing and verification for components, systems and applications, methods and tools for implementing multiple instances of a system and adapting it to slight changes in specification
- Preventive maintenance, in-time detection of imminent failures
- Dependency aware update and maintenance of components and applications (updateability/ maintainability)
- Easy monitoring and diagnosis of system - runtime inspection
- Design for run-time adaptability

Tooling and availability of reference implementations

- Unified tools supporting the separation of roles, composability of (software) building blocks, and QoS for robotics. This includes requirements engineering, graphical design, design verification, component compatibility verification ("integration simulator"), model-based verification, and code generation.
- Develop strong open source support structures within Europe to enable the development of an open business ecosystem and to lower the entrance barriers for new players (SMEs, start-ups).
- Instantiation and tool support for reference architectures (including verification, versioning etc.), support for distributed computing and control (cloud)
- Task-oriented programming, i.e. specification instead of functional text-based programming, (e.g. graphical programming environments, programming by demonstration techniques). Advanced configuration (from programming to task specification) by user.
- Seamless migration between simulation and real robot - Hardware in the loop, software in the loop techniques available. Seamless migration between robot / computing platforms during runtime (e.g. virtual machines on clouds)
- Functional integration of complex systems and simulation of overall system behaviour including HW/SW-in-the-loop techniques.
- To develop Systems Engineering tools specific to the design of autonomous and semi-autonomous robots, in particular addressing the integration and deployment of whole systems composed of multiple robots, and the interaction between system and environment.
- Generic tools which can be tailored to application domains: Making it possible for experts to model/introduce their DSLs

Reusable and composable building blocks

- The import of best practice in Systems Design technologies from other market domains (e.g. automotive, aerospace etc.). To ensure best practice in the wider systems engineering community is rapidly absorbed into the robotics community through collaboration and to act as a driver for system engineering tool development. [Step 1]
- Development of design patterns and the creation of reference architectures. [Step 2]
- New processes for integration instead of adding components as long-term goal ("Science of integration") [Step 3]

- To establish widely used standard interfaces that enable the modular construction of systems.
- Development of modular (cross domain) system architectures with well-defined interfaces able to allow system modification and the provision of additional capability.
- New techniques for adding software-intensive components, for plug-and-play component systems, smart physical subsystems, and smart devices (self-identifying modules and self-configuring systems).
- Reference architectures for several domains that work across multiple operating environments and robot configurations. They consider mixed-real time aspects, resource awareness, dynamic deployment, communication topology, open architecture, and service modularity.

Quality of Service Everywhere

- Architectures, reusable software components and model-based design components that meet requirements for industrial applications (safety, security, reliability, timing, throughput, response time, fault tolerance, deployment, scalability, maintainability, evolvability, human- machine interaction, user acceptance, ergonomics)
- Safety by design, robustness by design, QoS by design, explicated resource-awareness and Quality-of-Service attributes
- Fully automatic recovery of the system – self repair through changes in production operations or physical system structure, self-healing. Self-configuring, modular systems capable of autonomously re-arranging the structure in compliance with safety or other non-functional requirements. Real time reconfiguration intelligence using design-time models to guarantee an appropriate quality-of-service given only sparse resources in open-ended environments [Step 3]
- Model-based verification (automatic transition from system design to deployed run-time system)
- Off-the-shelf components with open interfaces verified on the field or with a significant TRL to base robotics applications upon. Standardised metrics for robotic component quality
- Resource level autonomy – Selecting and implementing among pre-defined reaction scenarios [Step 1]
- Resource level autonomy – Generating and implementing new reaction scenarios based on previous knowledge [Step 2]
- Resources capable of autonomously assigning themselves with the tasks to execute [Step 3]
- First linkage of software models with decision mechanisms: software models used at design-time explicate purposefully left-open variability for run-time decisions and run-time configurations of the robot in order to better match non-functional requirements. [Step 2]
- Seamless interaction of software models and cognitive architectures: robots make use of their software models for resource awareness and quality-of-service decisions and configurations in order to achieve appropriate robustness with scarce resources in open-ended environments. [Step 3]

Models, knowledge representation, and standards

- Standardised component meta model to allow for interoperability between different middleware, separation of roles, and separation of concerns.
- Models and domain specific languages for the entire life-cycle of a robot (for example task models, resource models, platform models, etc.)
- Models for dealing with information and knowledge processing that are fused with models of physical world, involving concepts of time and space. Standardised semantic

description of multi-modal representation of environmental information, robotic resources (ontologies) and production processes
- Abstract (black-box) modelling of resource requirements, capabilities and variation points. Enhanced system synthesis methods for ensuring smooth system level composition. Semantic modelling of building blocks and for re-use of software components.
- Standardisation (plug and produce as candidate for standardisation, programmability, etc.), standardisation and integration of physical parts (hardware and mechanics), standardization for data and protocols.
- Complete description of mechatronic behaviour by merging mechanical and electrical modelling methods with computer science modelling methods - 100% virtual validation of the system
- Generalised, neutral task and resource modelling- Resource programming automatically achieved based on resource and task characteristics
- Robots integrated into internet of things and making use of big data methods and semantic web technology (Industry 4.0)
- Multi physics modelling of robot components (fluid, current etc.) - integration in real time control

Non-technical step changes:

- Provide added-value to the European robotics community by proactively disseminating the scientific outcomes to research and innovation projects in order to avoid duplication of efforts and to accelerate industrial innovation and exploitation cycles (e.g., by improving their software development activities).
- Establishing Robotics Software Systems Engineering as a science in itself enables innovation and would result in a robotics business ecosystem relying on a balance of effective collaboration and competition.
- Development of business ecosystem based on emerging standardisation and modularisation of components
- Development of certification and qualification systems for standard modules and components.
- Reaching acceptance and familiarity with model-centric approaches (terminology and related techniques) e.g. by training/dissemination activities (including a particular focus on industry).

5.2.4. Benchmarks and Metrics

Technical metrics:

- Standardised tests, time-to-failure, and other known metrics
- Time needed to design and commission a new production system

Non-technical metrics (or assessment criteria):

- Assessment by industry, success indicated by investment in methodology or tool set.
- Measured re-use of project results, define degree of reusability
- the same set of meta-models (they are independent from a specific programming language, operating systems, middleware, robot platforms, tool chains) is being used in 5 to 10 robotics projects (academic, industrial)
- Budget of project dedicated to system integration (currently management, research and demo costs are delineated, can system integration costs/efforts be identified during planning process?)

Benchmarks

- Pilot installations (with solid documentation, accessibility) to compare different approaches, e.g. mobile manipulation for individual commissioning in food processing. These installations could help to analyse the current approaches for integration and to extract detailed requirements for integration processes and the tools.
- Project implementing the same system with different approaches to assess the pros and cons in a vertical way (from the model to the physical installation) instead of a horizontal way.

5.2.5. Impact on Domains and Products

The management of complexity in design is critical to every domain.

The envisioned processes and tools are applicable to all application domains. However it is likely that no single process model or tool chain will apply to all domains. Generic process covering several related application domains will be developed, tailored to the individual requirements of those domains.

Systems Design technologies will provide the following key benefits:

- To reduce risks and effort during system development
- To reduce costs, development time, and time-to-market
- To increase robustness and the quality of products and services.

More specifically, the expected impact includes:

- Systems with well-defined properties (safety, robustness, modularity, resource-awareness, quality-of-service)
- Make development simpler and more manageable increasing the take up of robotics technology
- Lower barriers to entry for small companies
- Commercial use of new safety and cognitive functionalities, e.g. dynamic, self-defined safety zones around a robot, decision-making functionalities that are "safe" for use in defined settings

5.2.6. Impact on System Abilities

System abilities in the context of systems engineering and systems integration are twofold: On the one hand, the development tools and methods will have specific abilities while the application of these tools will allow the resulting systems to have specific properties and abilities resulting from a systematic development processes.

The impact of these activities will be to move from craftsmanship in building robotic systems towards established and computer-supported engineering processes for systems of systems. These will allow for business models in a robotics business ecosystem (including a competitive market for robotic software at all levels – from device drivers to applications and software frameworks and tools) which also supports a structured tech transfer for free exploration of robotics technology. Higher technology readiness levels of systems of systems can be targeted in a more focused and systematic way.

5.2.7. Impact on other Technologies

Because of the wide impact of Systems Development technologies across all aspects of Robotics Technology there are strong cross links between Systems Development and the other technology clusters. This addresses all technologies related to interaction with unstructured environment and humans, including cognitive and AI techniques, perception, learning, but also to HW related technologies such as sensors and (advanced) actuators, as they are the building blocks of the systems and need to be considered during the design process.

5.3 Human Robot Interaction

"Better Interaction"

The new robot applications currently being explored are in many cases characterised by greater levels of human robot interaction. The development of intuitive and natural interfaces allowing the operation of complex robotic systems with less training and lower fatigue levels is a key driver of this cluster of technologies. Interaction will take many different forms from immersive virtual worlds to direct and precise physical interaction. In all application domains improved human robot interaction will enable new applications and new markets.

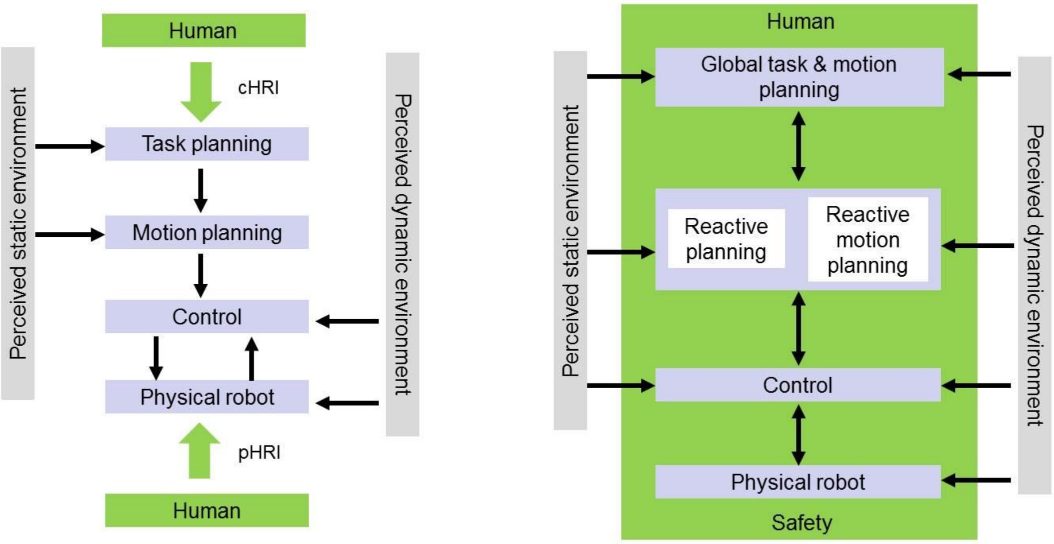
5.3.1. Technology Description

Robotics is currently undergoing a fundamental paradigm shift, both in research and real-world applications. Having been dominated for the last decades by position-controlled, rigid robots for typical automation tasks such as positioning and path tracking in various applications, a new generation of mechatronic robots has appeared on the landscape. These include novel directions in general robot design within the soft-robotics context (intrinsically elastic robots equipped with embodied intelligence), as well as new sensors and software methods for the seamless integration of these new sensors with robots. Together these advances bring robot systems closer to the long-term goal of safe, seamless physical human-robot interaction in the real world.

Recent advances in physical Human-Robot Interaction (pHRI) have shown the potential and feasibility of robot systems for active and safe human and robot workspace sharing and collaboration. Fundamental breakthroughs include the human-centred design of robot mechanics and control (soft-robotics), which also induced the novel research stream of intrinsically elastic robots (Series Elastic Actuation (SEA) or its generalisation Variable Impedance Actuation (VIA)) as well as advances in sensing and computer processing power to process and fuse complex sensor data. By considering the physical contact of the human and the robot in the design phase, possible injuries due to unintentional contacts can be considerably mitigated. Furthermore, taking into account the human's intention and preferences will ultimately lead to human-compatible motions and interaction behaviour.

Europe has pioneered in this field both technologically and scientifically. In this line of development, some of the most advanced systems were developed that are now entering industrial markets. In the development of the next generation safe robots, Europe is clearly leading innovations to embody intelligence in the mechanical design of robots and integrating new sensing technology with existing robots to make them safe for pHRI. Technologies developed hereby serve the purpose of industrial as well as service-oriented domains.

There is a broad range of potential application from industrial co-workers, the professional service sector, and assistive devices for rehabilitation. In the longer term pHRI will apply to service robots for support of the elderly. Common to all these applications is *the close, safe and dependable physical interaction between human and robot in a shared workspace*. Therefore, such robots need to be carefully designed for human-compatibility and in the long term they will have to be able to safely sense, reason, learn, and act in a partially unknown world in close contact with humans. In turn, this set of requirements necessitates the design of novel solutions in various theoretical and technological developments. In contrast to the classical modular view on robotics technology and the role humans play in this (Fig. 3 (left)), a fundamental paradigm shift in robot development has to be pursued. For this, the human needs to be placed at the centre of the entire design and all essential aspects of safety, intuitive physical interaction between humans and robotic systems need to be addressed in an interconnected manner, see Fig. 3 (right), leading to complex, human like robotic systems.



The fundamental paradigm shift from a strictly separated view on pHRI (left) to placing the human into the centre of robot design and development (right).

Safety issues based on biomechanical human injury analysis as well as on the mechanics of human movements will be addressed through human-compatible hardware design and innovative software and control strategies for tighter integration of sensors and robotic hardware. Furthermore, new techniques for improved sensing, learning, perceptive and cognitive functionalities need to be developed with safe pHRI in mind and validated in user-driven applications. These need to enable robots to track, and interpret human motions in mixed real-time in a weakly structured, dynamic environment. Biomechanical knowledge, neuro-mechanical insights, and biologically motivated variable compliance actuators can be used to design manipulation/interaction systems of varying complexity compatible with human properties and performance. Further fundamental insights in novel designs of VIAs for improved torque/mass ratio and energy efficiency with novel control methods to exploit the stiffness and damping properties are required.

Planning and adapting motions and tasks of such complex systems in mixed real-time requires new concepts, including tight coupling of control, planning, and learning, which will lead to reactive action generating behaviours capable of self-improvement. Moreover, self-explanatory interaction and communication frameworks need to be developed to enhance the system usability and interpretability for humans. These should communicate with humans using not only verbal, but also non-verbal communication cues such as gestures, sounds, and visual cues. Finally, the dependability of all system components and algorithms is a major issue, which systematic treatment is of particular importance for subsequent commercialization of the technology by the European industry and also for the commercial domestic use of robots in everyday environments.

Barriers

The identified barriers to market can be clustered into the following ones:

- Missing high-performance dependable low-cost technology, i.e. robot hardware, safe sensing, etc.
- Lack of systematic bridging technology for system integration, control, learning, and autonomy.
- Lack of safety technology and very precise standardisation procedures (coordinated standardisation efforts needed, as up to now this has only little connection to safety research)
- Lack of methods and tools for verification, validation and test of safety in robots, and lack of awareness in the community regarding industrial standards

5.3.2. Key Techniques and Methods

Key techniques and methods used in the development of pHRI systems are required in order to deliver systems able to meet the requirement to develop safe pHRI systems that are human compatible. This requires the system to model and control the interaction and learn interaction skills.

The development of pHRI technologies and systems requires numerous core technical competencies that can be clustered into the following capabilities:

- The Real-time dynamic modelling of external environment and planning or modifying the system's actions accordingly.
- The design of highly dependable systems utilising a variety of different design technics across the design lifecycle including: Multi-concern architecture design; Dependability of system components and interrelations; Numerical precision assessment of algorithms implementation; Formal methods application to produce safety proof ; Model-based testing and validation of user-driven applications
- The development of systems for motion and trajectory planning for pHRI including the need for human aware motion planning that accounts for safety and ergonomics aspects. Biomechanically safe motion planning and dynamic motion planning for online collision avoidance. The use of a risk-metric approach to motion planning and the trading-off of productivity with safety through multi-objective motion/trajectory planning
- The development of action and interaction planning systems for pHRI including; reflex planning and behaviours for physical contacts; monitoring of interaction plans and behaviours; interaction planning for human-robot joint actions/tasks and according role

In order to create a component based supply chain and disseminate best practice the development of system architecture, programming paradigms, and integration frameworks are needed. In particular fault tolerance and mixed real-time capability as well as programming models for interaction are required.

The design of pHRI systems must take account of robot safety standardisation and design systems able to meet international safety requirements. In many areas of application the novelty of close coupled human robot systems has not been addressed by standards and there is significant work to be done to re-align standards.

In order to complete the development lifecycle it is important to evaluate and benchmarking complete systems. This requires the definition of benchmarking scenarios and systematic studies.

5.3.3. Expected Step Changes

Scientific step changes

- Novel actuators and model based control principles for soft-robots, sophisticated interaction control
- Basic interaction planning and learning skills (e.g. human-robot joint assembly, joint object manipulation)
- More systematic understanding of human injury in robotics with particular focus on representing the results in a robot centric view
- Basic motion planners for pHRI tested in rather complex lab environments
- Basic pHRI architecture for complex robotic devices
- Concepts for systematic dependability analysis in the pHRI domain
- New perception techniques to understand dynamic environments with humans
- Adaptive interaction control and tight interrelation with interaction learning

- Online workspace surveillance techniques
- Programming models for interaction
- Significant scientific contributions integrated into international safety standards
- Real-Time motion planning for safe pHRI
- Systematic analysis of motor, sensor, and sensorimotor performance in humans based on robotics perspective
- Interaction planning and learning solutions for rather complex and dynamic human-robot interaction scenarios
- New VIA actuators with human-like performances in weight, torque, stiffness, power and efficiency
- Unified control, planning, and learning framework for complex pHRI systems
- Dependability analysis frameworks for distributed robots in the pHRI domain
- Systematic frameworks improving the unification of perception, planning, and control for pHRI
- Advanced cognitive architectures able to estimate intention and social intelligent behaviour based on pHRI frameworks
- Autonomous interaction capabilities for complex robots in complex partially unknown environments

Commercial step changes

- metrics to assess safety of robotic technology, in particular human injury can be assessed
- new system integration methods and programming paradigms for interaction become available
- Certified close collaboration between human and robot in industrial settings
- Widespread and longitudinal tests of physical HRI in order to have best practices.
- Mature, cost effective and certifiable workspace surveillance
- Real-Time algorithms for workspace surveillance are available
- Safe human-robot collaboration in real industrial and professional service settings is a commodity technology
- Intuitive augmentation devices available

Barriers

- Lack if standard platforms.
- Industrial take-up of new technology requires clear analysis of benefit and technical validity.
- production cost of technology needs to be reduced
- Standardisation of technology needed
- Legal framework in member states for close coupled and shared space collaborative working.
- Step changes in performance in workspace surveillance sensors and algorithms
- Certification of the technology against safety standards.
- Stimulation of SMEs to pioneer new technologies.

5.3.4. Benchmarks and Metrics

VIA actuation technology/Soft-robotics

- VIA datasheet with standardized performance tests and characteristics
- Performance increase capabilities

- Safety characteristics
- Development of actuators with human comparable performance in torque, efficiency, and power.
- A set of standard controllers and performance problems (e.g. maximum peak velocity achieved by energy storage and release) should be defined, tested, and validated
- Safety characteristics of the joints need to be evaluated and quantified.

Human-Robot Collision Analysis and safe motion

- Standard protocols for on-site testing of robots
- Set of injury indices that describe potential injuries (soft-tissue injury, fractures, ...)
- Robot centric representation of safety data in order to make it applicable to robotics (very different from automobile, biomechanics, forensics, and accident research)
- International injury database for collecting injury data from experiments all over the world and making this available to the community
- Making use of the injury knowledge to enable robots to move in a bio-mechanically safe manner
- Performance of collision detection and reaction

The following specific activities are needed to progress the development of benchmarks and metrics:

- on-site test experiments can be used to assess the level of injury that the robot might cause to a human during different types of collisions.
- Large scale soft-tissue injury experiments that capture the inherent collision characteristics
- Classification of injury in robotics based on medically accepted descriptions
- Make use of existing literature/knowledge in biomechanics, accident research,...
- Quantify the safety performance of collision detection and reaction by suitable experimental setups that are able to predict human injury/prevention during accidental collisions
- The set of concrete benchmark tests is to be developed as is the safety database, which is still preliminary and incomplete as of today.
- These benchmarks should find their way into international industrial and domestic robot standardization

Haptics (force, position and tactile feedback devices)

Generally, benchmarks in haptics can be divided into physical evaluation and psychophysical evaluation. Physical evaluation is related to kinematics, elastostatics, dynamics, actuation and sensing capabilities, impedance range and control bandwidth. Psychophysical performance metrics is more related to human perception of quantities (forces, velocities, vibrations) generated by technology.

Robotic devices that work in physical contact with a human also convey information through the established physical connection. In this regard a number of parameters are critical for efficient human-robot interaction. These parameters can be quantified purely based on physical measurements, or through subjective assessments of subjects interacting with robotic devices. In the latter case various questionnaires can be used.

Human perception and intention detection

Human perception and state estimation is still at a rather early stage and needs further research to be suitable for benchmarking. It is, however, extremely important to define according benchmarks timely, so that the required information needed can be used to prioritize research.

Intention detection is a relatively new field of robotics research, thus no standardized benchmarks exist. Guidelines and benchmarks for evaluation of robot based intention detection will have to be proposed and evaluated.

Future robots will have to cooperate with humans and therefore they will need to predict human actions based on the context of the cooperation and real time observations of human activities. Different types of cooperation might require different levels of robot intelligence. In certain cases the robot will have to be as close to 100% reliability as possible (for example in the case of exoskeleton based power augmentation). In other cases the robot will be allowed certain amount of erroneous decisions. Therefore, metrics are required for the assessment of a robot's decision making competence.

Interaction control, action and interaction planning

- User studies rating the intuitiveness, complexity of the robot's interaction capabilities
- Benchmarking by a set of basic interaction problems that are to be solved

The set of benchmarks still needs to be developed, as is the case for the user studies. This will need more experience with real-world pHRI, so that one can elaborate a clear set of suitable benchmarks that reflect also the needs from reality.

Robustness and fault tolerance

pHRI systems need high robustness and fault tolerance capabilities. The overall system performance could be validated in a set of benchmark scenarios, where standardised errors of varying nature are tested (e.g. sensor signal errors caused by the sensor itself in a standardised situation, and time-errors caused by non-deterministic processing algorithms).

A set of benchmark “arenas” could e.g. be initiated, where the overall system behaviour and fault tolerance could be rated in a set of problems/scenarios in different applications. A full set of problems would have to be solved, while during execution several errors are induced into the scenario that the robot would have to cope with.

5.3.5. Dependent Domains

All shared space applications can potentially benefit from step changes in human robot interaction technology. Physical interaction within partially unknown environments, and in particular with humans, will be the key ability of next generation robots. The potential impact of the technology is expected to be significant. For example, rehabilitation and prosthetics are based on the concept of highly dependable close coupled interaction.

Automation of processes currently carried out manually by combining the advantages of humans and robots has enormous unexplored potential that can contribute to bringing manufacturing (e.g. small batch) back to Europe. Furthermore, the technology addresses very promising application domains such as the professional service sector (e.g. hospital support systems) and in the logistics domain (food logistics and quality inspection). In the long term, systems capable of pHRI will feature in the domestic sector as home assistants, elderly care assistants, and assistive devices for disabled people. Clearly, the vast range of application domains already indicates that basically all next generation robots, regardless their particular structure, will depend on the technology described in this document. Depending on the application and the corresponding business case:

- single arm manipulators
- Force and reachability augmentation devices such as exoskeletons and cobots. (These can reduce workers' physical stress and Work related musculoskeletal disorder, promote healthy aging and late retirement)
- mobile robots and mobile manipulators,
- humanoids,

- robot assistants, and
- human augmentation devices, wearable robotics and prostheses will be designed according to human-compatible paradigms and equipped with the respective software technology to enable them for pHRI.

In order to ensure the European leadership in the field of pHRI also for the years to come, efforts in all the aforementioned scientific disciplines are to be significantly intensified to be able to solve the awaiting complex real-world problems within a suitable time-frame. This will be the key enabler to making robots part of everyday life, with Europe being the main supplier a well as beneficiary of such robotic systems. European SMEs and global market companies in manufacturing are currently pursuing strategies to make active use of the aforementioned technologies.

5.3.6. Impact on Domains and Products

The application of advanced human robot interaction technologies to manufacturing will be highly disruptive. It has the potential to impact industrial competitiveness and enable new forms of manufacturing in high value economies such as Europe. In particular it has the potential to remove complexity from the application of robotics technology in small scale manufacturing allowing SME’s to benefit from higher levels of productivity.

In healthcare dependable human robot interaction is one of the main core technologies that are essential for applying robotics to helping the ageing society and thus impacting one of Europe’s main societal challenges.

Safety certification will become an important aspect of the development and deployment of close coupled human robot interaction systems especially when these systems are deployed in everyday environments and in systems that are reconfigurable.

Achieving safe and dependable human robot interaction is likely to become one of the most significant technical step changes in robotics.

5.4 Mechatronics

“Better Machines”

Mechanical systems moving under control form the basis of all robotic devices. The development of “Better Machines” has always been at the heart of R&D&I activity in robotics. The success of future applications depends on making step changes in capability within this technology cluster and in particular the development of certifiably safe mechanical systems is paramount to the closer interaction between humans and machines.

5.4.1. Description

Mechatronics, as close coupling of mechanism, sensors, actuation and control, has always been a cornerstone of robotics. This group of technologies is critical and fundamental to the functioning of every robot. A high proportion of the core innovation in robotics lies therefore within the mechatronics developments.

Mechatronics includes some of the most mature technologies associated with robots. The importance of these technologies means that any significant developments or improvements in capability will have a wide impact across all sectors of the community. Step changes in capability are likely to result in observable product steps and impact across markets and enhance competitiveness.

It is expected that the results in mechatronics research will significantly step forward the body capabilities of the state of the art robotic machines by concurrently advancing the fundamental body design and associated manufacturing methodology. Mechatronics technologies will focus on one hand on developing current prototypes towards commercial products through technology transfer between research and industry.

On the other hand, the research will focus on a new generation of robots which are safer when working close to humans, are highly adaptive to interaction constraints both in pre-programmed or in unplanned and accidental scenarios and demonstrate improved efficiency and physical robustness.

The topic group aims at developing new principles of sensing, actuation, and control which are closer to the biological archetype by their dynamic range, scalability, adaptability, intrinsic compliance, damping, flexibility. They will lead to robots that are robust against mechanical stress and store mechanical energy for highly dynamical motions, close to human athletic performance. They will integrate a multitude of sensors in a fault-tolerant and synergistic way.

5.4.2. Key Techniques and Methods

Mechatronics actually subsumes a large range of individual technologies, each of which will be addressed within dedicated sub-topic groups. The main contributions are expected in:

Mechanical System Design

The current large interest in mechanically elastic actuation clearly illustrates the advantages of mechanical design at system level instead of component level. Functionalities originally achieved by dedicated system components (including control and software) can be embodied at system level with superior performance and integration degree. This holistic approach demands for new design methods, new multidisciplinary simulation techniques, and a more general understanding of materials and manufacturing technologies. The resulting “Smart

Mechanics" will have a tremendous impact on the possible morphologies and functionalities of future robots.

Sensors

New measurement concepts, materials and tighter integration are expected to highly impact sensor developments. A substantial breakthrough is expected in increasing the performance of heterogeneous sensor networks through self-diagnoses and sensor fusion approaches.

Actuators

Along with the sensors and the mechanical system, actuators themselves are key components for the robot performance. Current actuators provide high efficiency and power density. Nevertheless, e.g. electric motors are optimized for applications that largely differ from the requirements of robotic systems. Consequently, they demand heavy and energetically inefficient gearboxes to adapt the actuators to the intended field of use. Robotics needs new actuator concepts that provide the specific characteristics of a robot drive such as high forces/torques at low speed, overload protection capabilities, back-driveability or ideal torque source behaviour. These properties are needed in the micro- as well as in macro scale. Such characteristics can e.g. be achieved by energy storage and release concepts, functionally adapted designs, new materials and clever usage of the micro-macro scaling properties. Furthermore, variable impedance and serial elastic actuation might provide enhanced robustness and dynamics to robots in industrial applications and environments and enable a new era of automation.

Power Supply and Management

Power Supply and Power Management is a major issue especially in mobile robotics. Dedicated basic research in this area is largely outside the scope of robotics. Therefore one should investigate alternative power sources and track these trends in other industrial sectors, such as electro-mobility.

Communications

Robots will need to communicate with each other, with internet based services in the "cloud" and to the "internet of things" around them. Hard real-time communication between different sensors and actuators within one robotic system needs to be automatized and standardized. In view of the increasing complexity of robotics systems, communication protocols and code generation tools are needed, which allow to easily design flexible topologies of sensors and actuators and to automatically generate and configure the code for their communication.

Materials

New developments in materials and their fabrication, although hard to plan and predict, might have a disruptive effect especially for the design of sensors and actuators, but also for smart structures. Trends and developments in related areas need to be closely monitored.

Control

The new trends in mechatronic developments towards compliant, kinematically complex robots interacting with humans and unstructured environments rise new and very challenging control problems. To address them, dynamic simulation and control design needs to be pursued simultaneously with the mechatronic design and to influence the latter in an early stage. Robust and adaptive control methods, optimally exploiting the intrinsic mechanical properties of robots are attractive alternatives to already advanced nonlinear, model based design approaches.

5.4.3. Expected Step Changes

The major challenges to be addressed in mid-term are:

New actuator concepts

State of the art: Actuators designed for common purposes are used for robotics applications. They are not designed to the particular demands of robotics. *Expected step change:* Actuators that are designed to provide the robotics or even ability/domain specific needs.

Smart mechatronic design

State of the art: Components of robotic systems are chosen according to their availability at first. Out of those available components the ones fitting the robotic system best are selected. By this, robots are composed of rather limited sets of subcomponents *Expected step change:* Robots are designed to provide the abilities needed. Modularization is done where it intentionally reduces system complexity. Integration is done where the performance can be improved by removing subsystem boundaries.

Sensors

State of the Art: Controllers as well as planning algorithms use single sensors as input. Sensors do not provide the necessary information to fusion sensory input without affecting the overall quality of sensory information.

Expected step change: Sensors are capable of evaluating the quality of the sensor signal. This information is available in real-time. All sensor information is clearly designated to a dedicated time stamp. Even in case of sensor failure the robotic system receives information of the sensor status in real-time.

Mechanical and control design concepts

State of the art: Failure of a single component of a robotic system leads to system failure.

Expected step change: Robotic systems are capable of self diagnosis. In case of failure of single components up to multiple joints control and planning algorithms are capable of compensating those failures using e.g. the kinematic redundancies of the systems and can successfully complete the task.

Development of robust and adaptable control methods

State of the art: The control of a majority robots is performed using state of the art control methods without adaption of the method to the specific requirements and intrinsic properties of the robot or the task.

Expected step change: Control methods are designed to largely exploit or even to be adaptable to the intrinsic physical properties of the robot and the task.

I-PIA (industrial passive impedance actuation)

State of the art: Current industrial robots either have to be protected from impact situations or to be bulky and strong to be able to cope with the extremely large forces caused by impact situations. This affects the field of use of the robots as well as their applicability for safe human robot interaction.

Expected step change: Industrial robots are capable of coping with impact situations and finishing the task even in case of collision without being bulky and dangerous for the human being.

Next generation “ideal torque source”

Actuator prototypes that provide high torques/forces at low speed without transmissions, are overload proof and can provide energy storage or release capabilities available in macroscopic scale.

State of the art: Robots in most cases are built using drives that are optimized for non robotics specific requirements. E.g. most electric motors are optimized to provide maximum efficiency at high turning speeds. In robotics turning speeds are typically low and poor efficiency leads to thermal problems in particular at low speeds and high loads of the robot. Typical drive trains also have a fixed transmission ratio and are not overload proof or even releasable.

Expected step change: Drives for robots are built for the specific needs of robots. They in particular provide maximum efficiency during typical robotic operation. Drives also offer overload protection and/or release capabilities for applications and robots that demand for these functionalities

Smart Mechanical System Design

State of the art: Mechanical design is done on component or even subcomponent level using as simple as possible interface descriptions that allow for modularisation of the system and by this division of the design task to several subtasks that can be performed by single persons and small teams.

Expected step change: Design and simulation approaches allow for a holistic system design that embodies functionalities using multiple components of the system including software and control.

Standardized and modular mechatronic components

State of the art: Mechatronic components in many cases are developed for specific domains or applications. By this they are often very specific in terms of the their interfaces and possible use cases. Furthermore they are rather expensive.

Expected step change: Mechatronic components are designed to address the demands of several domains and applications but still allow for a high level of integration. Due to the large scale production processes they are available at low cost.

Soft robotics approach

State of the art: The majority of robots consists of rigid structures connected to actuators as well as sensors.

Expected step change: The boundaries between structure, sensors and actuator are dissolved and allow for integrated compliance and/or damping on one hand and intrinsic sensors on the other.

Bio-compatible robotic components

State of the art: Robotics technology assists the human being as surgical robots, or external rehabilitation devices.

Expected step change: Bio- compatible robotic components allow for the seamless integration of robotic components and the human in medicine, surgical robotics, rehabilitation. Minimal invasive interfaces allow for integration of robotics technologies in the human control loop as well as intra-corporal robot operation.

5.4.4. Benchmarks and Metrics

According to the two main directions of development, namely the commercialization of current research results and the development of the next generation of robots, benchmarks and metrics can be subdivided into two categories:

Product Oriented Metrics

- Cost
- Reliability
- Resilience
- Robustness
- Repeatability
- Safety

Research oriented metrics

- Energy efficiency
- Performance increase compared to equivalent conventional robots (velocity, force, power density)
- Robustness in unknown environments
- Bio-compatibility (for medical, rehabilitation and prosthetic applications)

The primary benchmark for a number of mechatronic systems is comparison to human performance in an equivalent task. For more industrial tasks benchmarks are set by performance comparison to existing systems. Mechatronic systems will also need to be benchmarked for safety and bio-compatibility both in terms of human impact and in healthcare applications.

5.4.5. Impact on Domains and Products

Mechatronics represents a baseline technology for robotics, all other domains and nearly all embodied robotics development depends on mechatronic systems for its success. Advances in mechatronics will impact on all domains and markets in particular lower costs for a given mechatronic performance level will enable new markets and expand existing ones. The ubiquitous nature of mechatronics within robotics means that well focused and targeted R&D&I investment has the potential to yield significant gains if major step changes can be achieved.

Advances in mechatronics will make on the one hand current research prototypes like torque controlled robots, mobile manipulators, humanoids, rehabilitation devices, UAVs more robust and low cost, preparing the way to mass market on service and assisting robotics.

On the other hand, the mechatronics research roadmap will pave the way towards a new robot generation that has richer and more robust motion capabilities, are safer for human-robot interaction, and more energy-efficient than current robots in all robotic domains and their products.

5.4.6. Unknowns

There is a risk that some of the newly developed actuator or sensor concepts will not have the expected performance characteristics in terms of efficiency, accuracy, maximal force, velocity, power characteristics or sensor accuracy. This is especially valid for the novel actuators based on electro-active polymers and carbon nanotubes, as well as on the new structural materials which constitute a very new research field with many open questions.

This risk can be addressed by development of different actuator and sensor prototypes in parallel, based on various design principles. The risk for actuators based on more conventional technology and on variable impedance principles is relatively low, such that these actuators are expected to be available for integration into systems and application without substantial delay. This constitutes a low risk alternative to more ambitious novel actuators based, e.g. on electro-active polymers and nanotubes.

5.4.7. Mechanical Systems

5.4.7.1 Description

Many different types of robot depend on complex mechanical structures to perform their tasks. Walking machines able to traverse rough or icy ground, micro-manipulators used in surgical robots, or robots able to respond to an elderly person falling all require specially designed mechanical systems. The wide variety of different types of mechanical system mean that there are different perspectives on key development themes which range from design methods to manufacturing techniques and standardisation.

Key areas of interest for R&D&I funding are the design of miniaturised systems for healthcare and manufacturing, the design of large scale systems for civil domain applications and the development of systems and mechanisms inspired by the impressive efficiency of the natural world.

5.4.7.2 Key Techniques and Methods

Key techniques and methods centre around the development of improved mechanical design tools and the use of novel structures and materials. The integration inherent within mechatronics means that the mechanical system of a robot is rarely considered in isolation from the other technologies within mechatronics and the focus of R&D&I activity is on “mechatronic design” rather than “mechanical design”.

Bio-inspired design also has a part to play in replicating many of the advantages exhibited by natural systems by inspiring novel approaches to problems.

5.4.7.3 Expected Step Changes

Step changes in mechanical systems relate to either cost vs performance criteria, typically on the basis of multiples of previous performance, or on achieving higher metric performance levels than previous designs. It is expected that even a doubling of performance can have a significant impact in some market areas.

Step changes in miniaturisation relate to a scaling of magnitudes of size and performance, for example moving from centimetre to millimetre scale mechanisms will open new market opportunities.

The following have been identified as generic domain needs for mechanical structures:

- Low cost multiple DOF systems
- Light weight mechanical systems
- Large scale structures
- Standardised mechanical interfaces enabling plug and play for mechanical systems
- High mobility structures
- Mechanical structures for grasping and manipulation, especially of soft objects.
- Smart materials, including self healing.
- Miniaturisation of mechanisms particularly for grasping and manipulation (e.g. Medical and manufacturing)
- Bio-compatible mechanisms, both for exoskeleton use and use in-vivo.
- Mechanical systems design compatible with extreme environments
- Energy efficient and energy conserving structures.
- Deformable structures able to absorb impacts and reform.
- Intrinsically safe structures.
- Bio-inspired mechanisms and properties such as adhesion.

5.4.7.4 Benchmarks and Metrics

Mechanical system metrics can be characterised as follows:

- Number of Degrees of Freedom
- Limiting forces both exerted by and applied to the structure.
- Torque and force related to mechanism size and cost.
- Overall physical properties such as density and mass of structures with given properties.
- Energy efficiency.
- Strouhal number (a dimensionless measure of thrust optimality).
- Froude number (a measure of manoeuvrability), used as metrics for benchmarking the bio-inspired robots against their natural counterparts.

Mechanical system benchmarks can be established based on combinations of metrics relevant to specific tasks and to scalability. For bio-compatible structures comparison to human equivalent performance is a useful benchmark.

5.4.7.5 Impact on Domains and Visions

All embodied systems depend on mechanical structures for their operation, therefore each domain application can be impacted on by advances in the design of mechanical systems, either in terms of design process and modelling or in terms of mechanism design and manufacturing processes.

The development of standardised systems, large and small scale systems, energy efficient mechanisms and smart mechanical structures have the potential to enable markets in all domains.

The development of miniaturised robotics assembly systems for manufacturing will in itself impact on the assembly and cost reduction of miniaturised robotic assemblies.

The development of robust mechanical systems for use in hazardous environments, particularly in marine, space and industrial environments will help to expand these markets.

The development of bio-compatible systems both in terms of human interaction and in terms of human embedding will be a significant enabler for numerous healthcare applications.

The standardisation of mechanical interfaces will lead to cost reductions and system flexibility that will enable many different applications and allow a modular approach to system construction.

5.4.8. Sensors

5.4.8.1 Description

What sets robots apart from other types of machine is the ability to sense their environment. Sensing in 3D, sensing fine movements in a mechanical joint, or providing a sense of taste and smell all require sensors.

Sensor technology is one of the most mature technologies within robotics. Sensors are used in many products outside of robotics. The majority of recent advances in sensor technology have come from the automotive, mobile phone and games industries. Many novel types of sensor are also being developed for bio-medical applications. Robotics stands to benefit from all of these developments. Most of the sensors currently used in robotics are commodity parts readily available from suppliers.

Sensors can be used to sense almost any measurable physical property. In robotics sensors are typically used to measure motion, position, objects both in contact and at a distance, light, both infra-red and visible, and sound, both audible and ultrasonic. Sensors for heat, magnetism, specific chemical elements, pressure, colour, texture and other physical properties are also used in specific applications.

All robots rely on the signals produced by sensors, for moment to moment decision making, for interpretation of the environment and for control functions. Sensors are used to detect the motion and position of mechanical links and joints, to detect the physical environment around a robot, typically using sensors that operate at a distance, and to detect direct contact between the mechanical elements of the robot and objects in the environment. Sensors also play an important role in the user interface allowing users to interact with the robot, either through touch screens, buttons or by physically moving the robot.

Many different types of sensor are now produced with a wide range of parameters (size, cost, power consumption etc.). This is a direct result of the increased use of sensors in mass produced products in non-robotic applications.

The most recent advances critical to robotics have been in the development of direct 3D sensors able to deliver moment to moment depth information within a field of view. These 3D sensors now beginning to be manufactured in small sizes at mass market costs.

5.4.8.2 Key Techniques and Methods

There are numerous different techniques and methods in use across the different types of sensor.

These can be categorised as follows:

- Direct sensing of a physical quantity with an individual sensor element, typically delivering an electronic signal.
- Sensing of a physical quantity with an array of sensor elements.
- The emission of energy, light, sound etc. and the detection of a reflection to measure distance by time of flight, phase difference or some other distance related parameter.
- The use of physical effects to influence an electrical circuit, for example resonance, proximity or motion used to alter a circuit's electrical character (capacitance, resistance etc.).
- The use of chemical interactions to create an electrical signal or pattern from specific elements for example in gas detectors.

5.4.8.3 Expected Step Changes

The following are seen as important changes that will take place in sensor technology:

- The integration of robot specific sensor processing within commonly used sensors as commodity parts.
- Establishment of standard sensor interfaces.
- An increase in the resolution, range and signal to noise ratios of 3D sensors.
- The development of improved mechanical force and torque sensing and their miniaturisation.
- Development of improved bio material sensing.
- Development of improved chemical sensing.
- The exploitation novel sensing mechanisms and materials, and the development of multi-modal sensors.
- The development of broad spectrum sensing technologies that increase the dynamic range of sensors.
- The extension of working ranges to different natural environments (e.g. all-weather, temperature, light, etc.).
- The development of low power sensors for use in distributed sensor networks.
- The development of self diagnosing sensors and embedded signal quality monitors.

- Multiple DOF tactile sensing

The maturity of sensor technology means that the step changes that will result in the greatest impact are those which impact on extended sensing ranges, miniaturisation and reduced cost per part.

5.4.8.4 Benchmarks and Metrics

The primary metrics for sensing are;

- sensitivity,
- dynamic range,
- speed of response,
- signal to noise ratio,
- environmental operating limits (temperature range, supply voltage etc.),
- reliability.

With optical sensors the following metrics are also relevant;

- resolution,
- depth of field,
- field of view.

All sensors are also governed by physical parameters that affect their utilisation in robotics applications;

- size,
- weight,
- power consumption.

5.4.8.5 Dependent Domains

All robotics domains depend on sensing. Some domains have a safety critical dependence on sensing include medical and healthcare applications where sensing failure may result in system failure and injury to users.

In many consumer applications optimising cost vs function is critical and designs often require miniaturisation or low power consumption in order to be product viable.

5.4.8.6 Impact on Domains and Products

Sensors are expected to undergo incremental improvements in in terms of cost vs function, as defined by the above parameters, over the coming decade. There will be critical cost points where a factor of ten improvement in cost vs function has been achieved. These points are likely to enable new markets by providing significantly better sensing for the same cost. These steps will result in an increment in system dependability/functionality creating a significant improvement in end user experience and therefore market.

In specialist applications the enhancement of response times, sensitivities and signal to noise ratios may allow faster control loop times to be achieved in mechanical systems, or faster sensing of the environment.

The miniaturisation and integration of force and displacement sensing into mechanical joints will enhance control resulting in the development of more complex multiple degree of freedom mechanical systems. These developments will have to be matched by developments in actuation technology in order to achieve a broad impact.

5.4.9. Actuators

5.4.9.1 Description

A principle function of robots is to interact with the physical world. Actuators provide this motive force. The rage of robot operation means that actuators must be individually designed to meet a wide range of electro-mechanical requirements. From large manipulators able to lift a car, to the high precision actuation used in surgical robots, actuators must be able to meet the demands of continuous dynamic use.

Robotics needs new actuator concepts that directly provide the specific characteristics required by robot mechanisms such as high forces/torques at low speed, overload protection capabilities, back-driveability or ideal torque source behaviour. These properties are needed at the micro- as well as in macro scale. Such characteristics can be achieved by energy storage and release concepts, functionally adapted designs, new materials and clever usage of micro-macro scaling properties.

5.4.9.2 Key Techniques and Methods

Actuator development is relatively mature as a core element in every robot. Electrical motors provide the motive force in the majority of actuators. Hydraulic and pneumatic and piezoelectric actuation are well understood. Novel actuators based on electro-active polymers and on bio materials are at an experimental stage.

The design of bio-compatible actuators for mechatronic devices that will cooperate with humans and that have similar size and mass as humans; also require comparable efficiency, power, strength, velocity and interaction compliance.

5.4.9.3 Expected Step Changes

- Incremental improvement in power to weight ratios and energy efficiency are to be expected. Novel actuation technology and the employment of new materials are expected to yield new opportunities.
- Fine scale high resolution actuation, particularly in surgical applications is likely to be a major growth area.
- Next generation “ideal torque source”: Actuator prototypes that provide high torques/forces at low speed without transmissions, are overload proof and can provide energy storage or release capabilities available at the macroscopic scale
- I-PIA (industrial passive impedance actuation): Variable impedance and serial elastic actuation will provide enhanced robustness and dynamics to robots in industrial applications and environments and enable a new era of automation.
- Bio-compatible actuation and the development of actuation systems that are intrinsically safe will be critical to applications where there is close coupled human interaction.
- High power to volume ratio actuation.
- Actuators exploiting novel materials and advances in power generation and energy storage.

5.4.9.4 Benchmarks and Metrics

Metrics for assessing performances are:

- Force
- Strain
- Tensile stress
- Weight
- Power consumption.

5.4.9.5 Impact on Domains and Visions

New developments in actuators will impact on all robotics domains. Improved bio-compatible actuation will specifically impact in Healthcare and Manufacturing, where robots operate in close and even physical cooperation with humans.

- Rehabilitation robotics: compliant and controllable stiffness actuators for improved safety and more flexible exercise programming
- Exoskeletons: safe actuation due to compliance of the actuators
- Bio-mimetic robots

5.4.10. Power Supply and Management

5.4.10.1 Description

Robots will need to be able to operate for long periods without access to a source of power. Managing their stored energy, designing systems that have low energy requirements and managing the use of energy are key to extending the working time of each robot.

This is an area of technology development where incremental improvement and step changes come from outside of the robot R&D&I activity.

5.4.10.2 Key Techniques and Methods

Systems design increasingly employs multiple power domains and allows for their management. Energy storage typically relies on conventional battery systems, or in rare cases on on-board electrical generation. Experimentation with electrical generation from bio-mass is being carried out.

5.4.10.3 Expected Step Changes

- To increase system level efficiencies to reduce power requirements through improved design and systems engineering.
- To utilise alternative energy sources for long term operation. (Solar, thermal, wind).
- To improve the storage and recovery of power from mechanical systems including human operators.
- To investigate alternative power sources and track these trends in other industrial sectors.

5.4.10.4 Benchmarks and Metrics

The following metrics are typically used to characterise power systems:

- Power consumption
- Leakage under no load
- Standby time
- Energy mass density (Watts per kilogram).

5.4.10.5 Dependent Domains

All robots require an energy source to operate. In many applications the operation of mobile robots are constrained by the availability of energy supply and behaviours are included to either recharge or stop before the available energy becomes too low to operate.

5.4.10.6 Impact on Domains and Visions

The lack of long term energy solutions will significantly impact on many long time scale applications and alternative sources of energy for on-board electrical generation will need to be considered, (bio-mass combustion, fuel cells and chemical energy).

5.4.11. Communications

5.4.11.1 Description

Robots need to communicate with each other, with internet based services in the “cloud” and to the “internet of things” around them. Internally different modules need to communicate and the development or adoption of existing of internal communication protocols are a vital part of standardised module construction.

Wireless communication protocols, particularly ad-hoc protocols and mobile to mobile systems will be of importance to robot communication.

5.4.11.2 Key Techniques and Methods

Robots use a wide variety of existing communication protocols and methods, both wired and wireless. Some specific industrial protocols are used in factory automation.

To date robots have been able to make use of generic protocols established for mobile wireless communication and local area network communication these protocols. In the future it may be necessary to define higher layer protocols specifically for communication with robots, in particular the latency requirements of tele-operation, the need for remote haptic feedback and the processing of high level cognitive functions in the cloud may all require alternative network protocols.

Communication security is also a of critical importance in many personal applications of robotics particularly where the users are elderly or vulnerable. The future ubiquity of robots will mean that the data they gather as a natural part of their daily operation will be of great value. Secondly the threat of robot “hacking” will be heightened by poor security in control systems both in industrial and domestic settings.

In transport the current proposals for car to car and car to road systems will need to be integrated into autonomous transport systems and in the limit these new communications protocols may need to be augmented with autonomy specific layers and security mechanisms.

The use of robots in the setting up of local communication infrastructures has a number of applications:

In disaster scenarios where existing communication systems may be overloaded or out of operation mobile robots can establish a communication network by positioning themselves around the disaster site, placing themselves on existing structures or by providing an airborne communication umbrella. Such a system can provide whole site visibility and can be deployed rapidly using small vehicles. In the limit it can dynamically reconfigure to adapt to changing demands and circumstances. Such a network also allows other autonomous systems to communicate efficiently without absorbing bandwidth on existing networks.

In agriculture multiple autonomous machines need to communicate to complete tasks and missions, however the remoteness of farms and fields means that it is likely that there is no existing communication network available. Systems are then needed to establish a communication network across the fields and possibly into the internet. Since autonomous machines may enter and leave the process it is necessary to set up these networks independently of these machines and the use of small autonomous systems to create a network is one solution.

Similar issues arise in other application scenarios involving teams of robots that will need to establish ad-hoc networks at the operating site when this may be remote from existing systems or where high bandwidth low latency communication is essential to the team.

5.4.11.3 Expected Step Changes

- Ad-hoc networks built by and into autonomous teams.
- Sub-sea network technology and protocols.

- Robot specific protocols for low latency networks.
- Low energy communication systems.
- In-vivo communication.
- Communication systems for micro and nano robots.

5.4.11.4 Benchmarks and Metrics

Communication metrics are well known and understood and fully apply to robotics technology:

- Bandwidth/Data rate
- Channel capacity
- Latency
- Accessibility
- Contention
- Error rate.
- Signal power

5.4.11.5 Dependent Domains

Communication capability will be particularly important in team operation, and therefore in many Civil domain applications. High reliability communication will be required in some Healthcare applications.

Various operating environments present specific communication issues. Notably communication between aerial robots without access to a ground based network. Underwater marine robots where conventional wireless communications cannot be used can use either optical communication or low bandwidth acoustic communication.

5.4.11.6 Impact on Domains and Visions

In a number of application domains communication either between robots or to the internet is a critical part of the application. In most cases existing networks will be able to provide appropriate capacity. In some particular applications ground based capacity will either not exist or have insufficient capability to allow tasks to progress. In these cases the autonomous system must establish its own communication network.

5.4.12. Materials

5.4.12.1 Description

Mechanical structure, sensors, and energy sources form the core of every robot. Materials provide the engineered mechanical and physical properties of these core elements. Advances in materials have the potential to have a disruptive effect on the impacted technologies.

As a result advances in Materials technology often underpin new developments in robotics, from the creation of novel sensors, and more advanced mechanical structures to more efficient drive mechanisms and active structures. In time the use of active materials and nanotechnology will enable mechanical structures that can mimic natural systems and thereby create a new generation of robotic systems.

Advances in materials technology used in robotics are expected to have the greatest impact in the following areas:

- Materials for bodies and structures
- Actuation
- Energy and power sources.
- The development of novel sensing devices.

A primary challenge is to replace the current metallic mechanical structures with polymeric or nano-composite materials having engineered physical and chemical properties. The possibility to modify at nano-scale the physical properties of fibres and to control the polymer properties enables the synthesis of nano-composite materials with controlled stiffness and elasticity, light weight, electrically-active and at a lower cost than the standard metal-based production.

Materials with such characteristics will allow in the future the design of “soft robots”, with passive and active compliance and lower weight in comparison to today’s machines. In addition, nano-composites such as carbon fibre materials, offer the possibility to introduce conductive fibres or optical fibres as well as sensing arrays that serve as an embedded nervous system in the scaffold of the robot.

Highly integrated sensing networks in the robot structure are crucial to accomplish distributed sensing capabilities (such as touch and force sensing) which in turn are crucial to develop the cognitive capabilities of the robots. Noteworthy embedded sensing networks require new mechanical energy harvesting materials, exploiting piezoelectric, tribo-electric, or electromagnetic effect to convert motion and vibration into electrical energy. To this aim flexible, new soft functional materials, such as hybrid piezoelectric (e.g. III-V Nitrides grown on flexible Kapton substrates), polymeric piezoelectric, soft magnetic and piezoelectric nano-composites, and tribo-electric composites, represent promising and emerging approaches.

This opens up the development of self-powered sensors and sensing networks and, possibly, their wireless operation leading to a substantial simplification of the robot design. The optimisation of materials in terms of weight and elastic compliance, together with the architectural simplification given by the distributed sensing/harvesting network will considerably reduce power consumption, which is conversely another main challenge of future robotics. Robots will be required to operate for many hours (>10), autonomously, in human and natural environments. As such hybrid battery/super-capacitor as well as fuel cell technologies with power density approaching the value of 400 Wh/kg have to be developed in conjunction with flexible harvesting devices distributed throughout the body of the robot, providing a few tens of watts during normal movements.

5.4.12.2 Key Techniques and Methods

Typically robots use conventional materials and processes for forming and shaping components. Additive manufacturing is used extensively in the development of robots. Research is being carried out to exploit the properties of novel materials in a number of robotic domains.

Materials for bodies and structures:

The structural materials for future robots must be robust enough to sustain the weight of motors, batteries, and other parts without undue deformation due to bending or flexing. At the same time they have to be lightweight in order to avoid high energy consumption during the robot’s activities; they also need to efficiently absorb energy of vibrations and impacts without damage. In this perspective, for the short to mid-term (e.g. next 5 years) the materials of choice to be developed for robots will be polymeric-based for the entire endoskeleton (or exoskeleton) structure. Polymer nano-composites, such as Carbon fibre materials, will substantially reduce weight compared to metallic structures, also enabling the possibility to embed sensing networks in the fibre matrix and to design the elasticity and mechanical characteristics of the materials by a proper choice of the fibre chemistry and texture. In the long-term structural materials will embed more life-like features, which in turn will be similar to a wide range of natural structural materials like wood or bones. They will be easily employed both as structural elements and for energy storage. Examples of material classes to be investigated are metal foams and soft polymer composites.

Actuation:

Actuation represents the bottleneck in many robotic applications, especially in biomimetic ones. The available actuators are mainly electromagnetic and their performance is far from natural muscles. The main limitations are in the relatively large inertia and lack of back-drivability, stiffness control and power consumption. Nevertheless, new and promising technologies are emerging, thus offering new possibilities to fill the gap between natural muscles and their artificial counterparts. Ideally, these novel technologies will be able to match, or even outperform, natural muscle in terms of key robotic actuation metrics such as active stress, active strain, power density, inherent compliance and stiffness control.

Energy and power sources for robots:

A future goal is to develop energetically autonomous machines possibly equipped with an on-board supply system, which would be able to power the robot for the duration of a mission or task. The power requirement depends on the embodiment/size of the robot. For example, for human-size, service robots, power consumption is estimated in the 800W-1kW range. It is expected that materials technology will play a significant role in energy harvesting, energy conversion and storage.

Novel materials for sensing devices:

Improving the capability and properties of sensors is an on-going challenge; smaller size, lower power consumption, better performance. In addition closer human robot interaction requires highly distributed sensing. Tactile sensors are one typical example. Copying nature in this case would require as much as 1700 sensing point in one finger with four categories of sensors detecting stimulus frequency and the direction of forces and adapting over time to the external stimulation. Measurement of the contact location, the direction of force, its distribution, incipient slip, texture, temperature and moisture may all be required for dexterous object manipulation. New materials through nano and micro-fabrication technologies (NEMS, MEMS) are likely to be the only way to provide these types of step change in sensing.

5.4.12.3 Expected Step Changes

- To exploit new materials that can enhance the design of robots, though improved sensing, mechanical systems or manufacturing processes.
- To engage the materials science community in seeing robotics, particularly medical robotics, as a new growth area in need of new materials to meet complex sensing and mechanical design requirements.
- The development of robot body structures using soft polymeric materials.
- The use of polymeric nano-composites in the development of integrated sensing and actuation.
- The use of soft polymers for actuation; particularly Liquid Crystal Elastomers, Dielectric Elastomers, Conducting & Ionic Polymers and Carbon Nanotube Actuators.
- The development of novel and integrated multi-process fabrication techniques based on new materials.
- The use of metal foams as structural elements in robot mechanisms.
- Development of multi-technology power systems based on new materials; Including super capacitors, fuel cells, and energy harvesting.
- The application of novel materials to the construction of Smart sensors including the use of electro-mechanical and electro-magnetic properties

5.4.12.4 Benchmarks and Metrics

Benchmarks and metrics in materials is an established discipline owing to the consolidated physics and formalisation of the measurements of materials.

5.4.12.5 Dependent Domains

The availability of new robot-specific materials has theoretically a wide impact on our capacity to develop more efficient machines. Since material science research is a long-term endeavour, we do not expect here to see progress in all possible areas and especially with the more wild research ideas. It is likely that progress will be made in some areas within a 3 to 5 years time frame. Particularly in providing new composite materials for body structures – to e.g. provide weight saving and/or controlled stiffness as well as embed some simple wiring in the robot structure.

Combined tactile sensing built on flexible materials (e.g. capacitive and piezoelectric) is almost ready to be used at high TRL levels for applications and able to impacting the ability of a robot to interact with people in real time.

It is expected that the impact of new materials will be most effective in advancing the following robot abilities:

- *Motion Capability: the possibility of designing bodies with intrinsic controlled stiffness improves adaptability to different environments, as e.g. adaptation to rough terrains, to unexpected impacts with the environment, etc. Energy autonomy is also important for adapting the robot to different operating conditions.*
- *Interaction Capability: a full body skin system is crucial for human-robot interaction.*
- *Manipulation Ability: new materials in the design of the hand (e.g. with intrinsic compliance) can improve manipulation simplifying control considerably.*
- *Perception Ability: a skin system can give robots a new level of perception about the environment, objects, and their contact with the world (e.g. measure forces at various points of contact while moving).*

Integration and innovation of existing and new smart soft materials and composites into micro- and macro-scale robot designs will adequately address sustainability of future robots in terms of their maintenance, longevity and recycling. Particular impact is expected in: sensing (e.g. soft skin to touch; deformable tissue; pressure, heat and humidity sensing); movement (e.g., elastic and compliant materials for muscles, tendons; variable compliant actuators; less energy needed for movement due to lighter-weight materials); interaction (e.g., soft movements, social and cognitive skills).

5.4.12.6 Impact on Domains and Visions

Materials being a determinant of the shape of the robot have a comprehensive impact into the final products as well as into their time to market. Materials will be a key enabling technology of future robotics. It is expected that existing new materials can be utilised to build better robots, sensors and actuators within a relatively short time frame provided appropriate R&D&I investment is made. The following list some the initial areas where this impact can be expected:

- Apply newly engineered composites to the construction of the robot body;
- Design robust sensor networks for advanced measurement of mechanical interaction of the robot in various environments (being these marine, industrial, harsh, air);
- Design appropriate “energy” packs to make the robot autonomous and rechargeable with reasonable down time;
- Develop flexible and stretchable circuits to conform to the robot shape and motion;
- Use existing known fabrication techniques.

In the longer term the following areas will be impacted by materials R&D&I:

- High-performance artificial muscles;
- Functionalised exo- or endoskeletons (body structures);
- Mixed mode energy packs (combining various forms of generators);

- Self-healing materials;

Impact is to be expected in all domains albeit possibly to arrive first in micro or nano-robotics and partially in larger robots. For example, we can expect to see skin systems and energy packs available in the short term on service or personal robots and new body/actuation structures to reach first the micro or nano world of robotics. Clearly, self-healing materials, fully stretchable electronics are for the longer term. Although examples and prototypes are already available, turning them into production is still a future goal.

5.4.13. Control

5.4.13.1 Description

Control is one of the core technologies required in all robotic systems. It is relevant for all domains.

Position, velocity, and force control for serial manipulator arms are well known and available in industrial products. Vision based control is applicable in well controlled environments. Control algorithms for floating base robot systems, like space robots, aerial robots, and legged robots including humanoids are at a lower TRL. Additional resources in these fields are needed to bring these algorithms closer to the market.

The new trends in mechatronic developments towards compliant, kinematically complex robots interacting with humans and unstructured environments gives rise to new and very challenging control problems. To address them, dynamic simulation and control design needs to be pursued simultaneously with the mechatronic design and to influence this in an early stage. Robust and adaptive control methods, optimally exploiting the intrinsic mechanical properties of robots are attractive alternatives to already advanced nonlinear, model based design approaches.

Safety issues in controlled robot systems interacting with humans have seen a major progress in the last decade and are progressing towards application in commercial products.

Active compliant control is mature in the research environment with first products emerging on the market.

Novel and efficient actuators connected to complex mechanical structures require a coevolution of sensory feedback control methods to ensure that motion is fast, accurate, stable, robust to environmental changes and repeatable. Controllers that limit the impact of contact with the environment and cause the robot to react with a compliant behaviour are critical for safe operation in collaboration with people. To optimise the final robot performance hardware design and controller design need to be closely interconnected from the very early design stage in concurrent engineering and simulation processes.

Advanced nonlinear control approaches require precise models and sensory data of high quality. In current industrial scenarios this leads to cost intensive solutions and robust methods which can work at a high performance level under noisy, uncertain, and incomplete sensory data are desired.

5.4.13.2 Key Techniques and Methods

In the automatic control community exist a large variety of advanced control methods which were adapted or specially developed for robotic systems. An exhaustive overview of these techniques is beyond the scope of this document. The following overview clarifies the terminology in the state-of-the art and highlights the most common methods which were successfully applied to robotic applications. Depending on the type of plant model it is useful to distinguish between:

Kinematic control that is based on a plant model which refers to the kinematics rather than the dynamics. Kinematic control is often used in the context of redundant robots and in mobile robotics.

Dynamic control refers to control approaches, where the plant model contains dynamics effects like inertia. Depending on the type of actuator used and the level of abstraction in the model, the control input can be a generalised position, velocity, or force. Control problems for multi-physics system models with dynamic actuator models (electric, hydraulic, pneumatic, etc…) also belong to this class.

Position, Velocity and Force control of serial manipulators on a fixed base are well known and available in industrial products. Active compliance and impedance control are mature in a research environment with first products emerging on the market.

Control problems for time delayed systems arise from several perspectives. In tele-presence applications, the combined master and slave dynamics is considered. In visual servoing applications, the time delay is mainly related to the processing time of the vision sensors and algorithms.

Among the industrial and research developments, several key techniques can be identified:

- PID control is widely seen in industrial applications. Tuning procedures are based on a multitude of approaches including heuristic guidelines, formal robustness analysis, and H_inf analysis.
- A major breakthrough in position control of serial manipulators has been achieved by the concept of inverse dynamics, which is also known under the term “computed torque control” in robotics. The key idea of inverse dynamics lies in an active compensation of the nonlinear dynamics by control.
- Operational space control can be seen as a variant of inverse dynamics, which utilises a model description based on task coordinates. Extensions to prioritised control of multiple tasks have been proposed and are currently under experimental evaluation on real systems.
- Energy based approaches based on passivity generalise more simple concepts like PD control. These methods often show stronger robustness than control approaches, which aim at a compensation of nonlinear dynamics.
- Interaction control based on force or joint torque sensing is well understood. Control of passively compliant mechanical systems is at a high interest in research laboratories around the world. Despite its lower TRL, first products based on compliant actuation are appearing on the market.
- Nonlinear model based control approaches like Back-stepping, Lyapunov based control, etc. are established in the research community.
- Adaptive control in robotics benefits from the linearity of the dynamics parameters in the model.
- Model predictive control is popular in mobile robotics and in walking control where simplified template models are used for computationally intensive predictions.
- Optimal control is used in both industrial and research context for offline trajectory planning. The use of novel actuators with compliant elements has renewed the interest in optimal control as a method for exploiting the full capabilities of the intrinsic system dynamics.
- Iterative learning control (ILC) is dedicated to precise control of repetitive tasks, where the control action along a periodic task is iteratively refined based on the control error during the previous iteration.
- Flatness properties can be utilised in systems which allow for static or dynamic feedback linearisation. Typical examples are mobile robots and under-actuated systems.
- Neural and Fuzzy control are model-free approaches used mainly in lab environments.

5.4.13.3 Expected Step Changes

Development of robust and adaptable control methods for the increasing diversity and complexity of robot morphologies and tasks. Controllers will optimally exploit intrinsic mechanical properties and provide safe interaction with humans, stable locomotion and dexterous mobile manipulation in unknown environments. Comparison with biological body control will give new impulses to robotics control and provide a new perspective to biomechanics and neuroscience.

The steady progress in hardware developments including novel actuators and materials as well as the realisation of more and more advanced robot systems for demanding applications requires a co-evolution of appropriate control methods. Expected step changes include the following challenges:

- To devise adaptive, self-calibrating controllers: Controllers which do not apply pre-set controller gains and control topologies but allow for self-organisation and adaptive systems.
- To achieve a closer integration of the reactive (feedback) and deliberative (planning) parts in the control architecture. Therefore, the capabilities of modern reactive control approaches have to be represented in an appropriate form at the planning levels.
- To develop fault-tolerant and resilient control methods: In complex robotic systems, the operability of the whole system should not critically depend on the operation of a single component (e.g. joint),
- To control highly redundant and under-actuated robots.
- To operate robots under hybrid (i.e. switching) contact situations with strong dynamic constraints, e.g. in legged locomotion or humanoid multi-contact scenarios.
- To develop robust control methods able to work in noisy and uncertain environments with incomplete sensory information.
- To allow tele-operation of robots everywhere on Earth: Tele-operation is at a mature development level from a research point of view, ready to be transferred to industrial scenarios.
- To develop controllers which are energy-efficient and optimally exploit the dynamic properties of the system.
- To develop bio-inspired control approaches.
- To devise safe control strategies allowing for physical interaction between human and robot, including wearable exoskeletons.

5.4.13.4 Benchmarks and Metrics

Stability properties (of different types) for regulation and tracking tasks are seen as a basic requirement in closed loop control. In the context of physical interaction with humans or the environment, passivity plays a prominent role. Stability definitions related to legged locomotion are less well established.

Quantitative measures on absolute accuracy and repeatability are common use in industrial robotics.

Qualitative metrics and evaluation criteria of control systems are:

- the complexity of the control law (for implementation),
- the robustness with respect to parametric model uncertainties, as well as
- the robustness with respect to structural model uncertainties (unknown dynamics).

Specific benchmarks on generic control questions are not intended. Instead, domain and application specific benchmarking plays a stronger role than benchmarking of different control strategies.

5.4.13.5 Dependent Domains

All robotic domains depend on control. Human robot interaction, healthcare, and space applications have increased safety requirements and therefore critically depend on reliable and safe control approaches.

5.4.13.6 Impact on Domains and Visions

While control, in a mechatronic context, is necessary for nearly all applications of robots in most domains the types of control are well understood and successfully applied.

In many proposed applications for robotics technology it is the implementation of novel control paradigms that are critical to safe and effective mechatronic systems. In rehabilitation, in physical human robot interaction and in bio-compatible mechatronic control methods play a critical functional role in providing safe and appropriate motion.

5.5 Perception

5.5.1. Description

Perception technology provides a robot with the means to measure and interpret its environment. In order to enable intelligent behaviour, perception technologies process raw sensor measurements to infer additional information and represent sensor data in a useful way, for example, compacting sensor data, filtering irrelevant or erroneous data, inferring relations between sets of data, or learning patterns from data collected over time or from different settings.

Perception techniques can be categorised roughly into Sensing and Interpretation. The goal of Sensing is to distil useful information from the stream of data produced by a robot's sensors. Interpretation aims to produce a higher level understanding of the environment based on the stream of data produced by the sensing processes.

Perception technologies are fundamental to all robot domains.

Perception technologies are also influenced by fields beyond robotics, especially by the consumer and gaming industry. Many current sensors used in robotics have been developed for consumer and games industry applications, such as many of the current 3D sensors.

This has also spawned a number of non-robotics applications that impact on human robot interaction and robot sensor interpretation. Much of this work has found its way into the robotics domain through open source adaptation.

Perception technologies also integrate multi-modal sensor data to build a coherent picture of the environment, allowing the recognition of both objects and their properties and arrangements. Combining non-visual sensing, such as chemical signatures, heat, or tactile sensing helps to provide a rich perceptual dataset for higher level robot control systems.

5.5.2. Key Techniques and Methods

Key techniques within Sensing include

- 2-D visual sensing and processing (using, for example, colour or thermal cameras)
- 3-D sensing and processing (using, for example, laser range finders or stereo imaging systems)
- Tactile and force sensing and processing
- Fusion of measurements from several sources
- Imaging of glossy/reflective objects such as: Mirrors, reflectors, bathroom accessories, etc.
- Imaging of high curvature and reflective objects: Bearings, artificial joints, aeroplane parts, engine and automotive parts
- Imaging of micro parts and components.

Key techniques within Interpretation include:

- Detection, recognition, localisation, tracking and modelling of objects and active agents based on 2D or 3D data
- Recognition, localisation and modelling (e.g. shape, stiffness, surface material) of objects based on tactile and/or force data
- Interpreting scenes semantically (e.g., determining which parts of a scene correspond to vegetation or buildings, or determining which areas are drivable and estimating the cost of driving there)

- Learning patterns over time (e.g., learning traffic rules by observing how vehicles drive, learning common motion patterns in order to avoid disturbing or interrupting humans in the environment)

5.5.3. Expected Step Changes

The perception technologies have a high level of maturity and have already achieved wide spread application in mobile communication devices, digital cameras and in the games market. Technologies such as gesture recognition, object recognition, and location awareness all have wide application outside of robotics and many of the recent developments are "in-flowing" to robotics.

To these wider applications Robotics adds specific requirements, most specifically in tactile sensing, and the self localisation of multiple degree of freedom and articulating structures. Robotics also utilises of multi-modal sensing and in some applications requires the fusion of multiple sources of data some of which may be mobile.

Step changes are likely to arise in the following areas:

- Improvements in real world object recognition and segmentation under variable environmental conditions; sunlight, different weather conditions, seasonal changes etc.
- To develop the ability to recognise characteristics and properties of objects.

5.5.4. Benchmarks and Metrics

The following are generic metrics for sensing:

- Sample rate
- Dynamic range
- Resolution

Metrics for interpretation are difficult to define, although specific aspects of interpretation can be characterised. Metrics for the recognition of objects are typically based on statistical rates of success and failure.

There are numerous benchmarks for visual recognition performance although these may not always be relevant to robotics, further robotics benchmarks can be included in competitions, such as RoboCup, ELROB, or RoCKIn. A similar effort for perception systems in isolation has been the Visual Object Classes Challenge and the ICRA 2012 Perception Challenge.

There are also some benchmarks for SLAM and localisation defined within the Rawseeds Project (http://www.rawseeds.org/home/).

5.5.5. Dependent Domains

Many advanced applications depend on perception to provide information about the operating environment.

5.5.6. Impact on Domains and Products

Improved sensing and perception impacts on nearly all domains in robotics that rely on interpretation of the environment. The ability to better extract information from multiple sensor streams can impact on the placement and type of sensors, and improvements in the speed of processing and recognition rates can significantly affect the viability of applications.

There is a strong link between perception technologies and cognitive technologies. Many cognitive technologies rely on high quality perception output and any enhancement in the perception technologies is likely to have an impact on cognitive ability.

5.5.7. Sensing

5.5.7.1 Description

If a robot is to correctly interpret its environment it must be able to distil useful information from the stream of data produced by its sensors. Transforming and merging this data so that salient information is extracted is a critical step in the process of interpretation.

5.5.7.2 Key Techniques and Methods

Raw sensor data processing involves scaling, noise filtering and integrity and consistency checking. In more advanced applications data is fused from multiple sensors to provide a broader range of information over time. The time taken to carry out sensor processing operations can limit the minimum loop time in dynamic control applications.

Key techniques within Sensing include

- 2-D visual sensing and processing including segmentation and texture recognition.
- Feature extraction and object identification and recognition.
- 3-D sensing and processing including the generation and filtering of depth information.
- Processing and interpretation of tactile and force sensing
- Fusion of sense data from several sources with different modalities.
- Conversion of sense data to measurements.
- Sensor calibration.

5.5.7.3 Expected Step Changes

- To increase the distribution of basic sensor processing closer to the sensors, through increased integration of sensing and processing.
- To develop techniques to enhance sensor fusion in both non-distributed and distributed systems,
- To develop methods for sharing sense knowledge between cooperating robots.
- To standardise sensor interfaces to enable a component market place to develop.
- To perform all-weather sensing in the natural environment.
- To improve the visual recognition of glossy/reflective objects such as: Mirrors, reflectors, plated object etc.
- To improve the imaging of high curvature reflective objects that apparently distort the visual image: Bearings, artificial joints, aeroplane parts, engine and automotive parts
- To develop techniques applicable to the imaging of micro parts and components.

5.5.7.4 Benchmarks and Metrics

Metrics for sensing vary with different types of sense data stream (Samples, frames, sequences etc.). In general metrics concentrate on the speed of processing, the volumes of data being processed, the efficiency of data abstraction and the error rates associated with the processes being applied.

5.5.7.5 Dependent Domains

All domains depend on sensing and most applications require some processing of raw sense data prior to it being used in decision making.

5.5.7.6 Impact on Domains and Products

Improvements in sensing will impact on dependability since better sensing leads to better decision making. Advances in fusing sense data from multiple sensors has the potential to reduce the cost of sensor systems and this may have an impact in cost sensitive applications.

In certain domains, notably Healthcare, Manufacturing and Agriculture the development of novel sensing techniques may have a significant impact on applications.

5.5.8. Interpretation

5.5.8.1 Description

Robots need to interpret and perceive the objects and features in their environment based on the information extracted from their sensors. Recognising objects, knowing where to grasp an object, or where to place it. Noticing that something important has happened against a background of other events. These skills are essential for a robot to carry out tasks where it must operate in an everyday environment in conjunction with people. A critical stage in achieving these abilities is the interpretation of sense data streams.

5.5.8.2 Key Techniques and Methods

Recognising a handful of objects in constrained circumstances is well known and applied in commercial systems. The recognition of faces, hands and body pose is well understood and widely used in commercial products. The recognition of gestures and to a lesser extent facial expressions is beginning to be exploited both in user interfaces but also in video analysis for example in the advertising industry. The interpretation of 3D and visual sensory data is well known for the identification and recognition of salient features in an environment. The extraction of shape and 3D reconstruction from vision sensing is well understood particularly in relation to body pose estimation, and is exploited in a limited number of commercial products.

Key techniques within Interpretation include:

- Detection, recognition, localisation, tracking and modelling of objects and active agents based on 2D or 3D data
- Recognition, localisation and modelling (e.g. shape, stiffness, surface material) of objects based on tactile and/or force data
- Interpreting scenes (e.g. determining which parts of a scene correspond to vegetation or buildings, or determining which areas are drivable and estimating the cost of driving there)
- Detecting patterns over time (e.g., learning traffic rules by observing how vehicles drive, learning common motion patterns in order to avoid disturbing or interrupting humans in the environment)
- Interpreting the arrangement of objects in a scene.
- The tracking of objects and features in the environment.

5.5.8.3 Expected Step Changes

- To improve recognition rates for robot task related object detection.
- Development of standard perception engines for sense data types and sense data fusion.
- To be able to reliably recognise a wide range of known objects in everyday environments.
- To be able to reconstruct 3D object shapes from sensor data to allow fast and efficient grasp planning and visual servoing.
- To be able to recognise object properties form both tactile and visual data.
- To be able to recognise novel objects or novel properties and configurations of known objects
- To be able to recognise dynamic relationships between objects and features.
- To exploit the potential for facial expression recognition.

- To be able to recognise and interpret complex gestures.
- To provide reliable salient point and situation recognition over wide scale ranges.
- To be able to track dynamic objects in real world environments.
- To be able to track and estimate the pose of animates.

5.5.8.4 Benchmarks and Metrics

The field of perception for robotics is quite diverse, and so it is difficult to enumerate commonly used benchmarks. Competitions provide snapshots of perception ability though the specification of specific tasks.

5.5.8.5 Dependent Domains

Nearly all advanced applications involve sense data interpretation in order to properly interpret the workspace. Many applications have limited environments where specific techniques can be honed to deliver high levels of dependability. In more open environments where systems may regularly encounter unknown objects or where objects may be encountered in widely different conditions improvements in interpretation will significantly affect the viability of applications.

5.5.8.6 Impact on Domains and Visions

The interpretation of data is needed in all advanced applications of robotics where sensors are used to detect real world environments.

The provision of standard perception engines will help to create greater performance reliability and in turn will increase dependability levels. As techniques and methods are developed to interpret both physical and visual data with greater reliability new applications will become viable in almost all domains. This is a key area where R&D&I investment can have a broad impact on domains and the realisation of product visions.

5.6 Navigation

5.6.1. Description

Purposeful motion in robots requires the ability to navigate. Navigation technologies are required to successfully move through the operating environment. In advanced applications robots need to perform in unstructured and dynamic environments without continuous human guidance. In the future applications may require extended periods of continuous operation in which case the provision of task appropriate levels of autonomous navigation performance may become a critical barrier to market uptake.

Navigation can be defined as the combination of the three fundamental technologies:

- Self-localisation
- Map-building and map interpretation
- Path and motion planning and execution

Typically the two first competences are enablers of the third. Not being able to localise in a known or unknown environment in a reliable way inhibits the generation of successful path/motion plans. For this reason, it is a priority is to increase localisation and mapping reliability and dependability at high TRL levels.

The autonomy of a robot is realised by its ability to navigate independently in the environment and in cooperation with other elements involved in its function such as humans or other robots.

5.6.2. Key Techniques and Methods

Robots mainly rely on on-board sensors to localise and create reliable maps of the environment so as to establish where to move autonomously. Robots can also make use of intrinsic environmental information to establish position, or rely on beacon based systems in order to increase robustness.

There are different self location mechanisms that can be used according to the scale and nature of the operating environment. These can be categorised as:

- Satellite and network-based,
- Sensor-based (including vision-based),
- Beacon-based.

Satellite and network-based technologies are mainly used for global navigation and absolute positioning outdoors, namely global satellite positioning systems and cellular networks, whereas sensor (inertial systems, odometry, range based systems, visual sensing and 3D depth sensors) and beacon-based (WiFi, RFID, NFC etc) approaches are mostly used for an indoor navigation and local/relative positioning. In practical cases, in outdoor scenarios, a mixed approach is used in order to fully exploit both global and local information coming from different sources. For instance, light aerial vehicles perform self-localisation by fusing global positioning data, inertial sensor and on-board camera data.

Mapping generates an absolute or relative reference frame for navigation. Map-building concerns world representation and closely relies on the localisation process. The most common technique involves Simultaneous Localisation and Mapping (SLAM) where mapping and localisation occur moment to moment as a robot explores its environment.

Global positioning

Most of global positioning technologies and techniques are well understood and commercially mature. Satellite-based technologies use the following techniques:

Multi-lateration is the basic technique used for global positioning receivers. Here the distances from the receiver to the satellites are calculated and used to compute the receiver's position. The number of satellites, its geometry and the obstacles surrounding the receiver significantly affects the accuracy achieved. Accuracy of about 10 to 20m can be easily expected.

The other most common techniques used for satellite-based positioning are assisted, differential and augmented global positioning. These techniques use additional information such as orbital data, correction from a reference station or source errors (clock drifts, ionospheric delays...) to improve the algorithms used in the position computation. These techniques easily achieve accuracies between 1 and 5 meters, some centimetre accuracies and the more sophisticated methods such Real-Time Kinematics millimetre accuracies.

Alternative techniques used by network-based technologies for localisation are based on the estimation of signal parameters such as the received strength and time or angle of arrival, and are mainly the following: cell identification, radio-mapping or multi-lateration. Since in most of these cases the networks are not designed for positioning, the nodes and the signal are not optimised for localisation and that directly impacts on the accuracies that can be achieved.

Localisation and mapping

Sensor and visual-based technologies are the most commonly used for on-board localisation. In most of cases they are combined using SLAM techniques. Most of these techniques are well understood at research level and tested in real environments.

The most common techniques used for these technologies are the following:

- *Dead reckoning* (from motion sensors such as wheel encoders or internal sensors such as accelerometers and gyros)
- *Data association* (These methods aim at correlating data segments which represent the same part of the environment. These allow local data registration and loop closure detections)
- *Bayesian Filtering*, also known as online SLAM e.g., Kalman Filter, Information Filter, Particle Filter): on-line state estimation where the state of the system represents the current position and the map. The state estimate is incrementally refined by incorporating new sensor measurements as they become available.
- *Smoothing* (Graph-SLAM), also known as off-line SLAM: the full robot trajectory and the final map are estimated from the full history of sensor measurements typically relying on the solution of a large error minimisation problem. This error represents the consistency of the built model with the collected measurements and extrapolations.

For vision-based methods the most common techniques are:

- Fixed arrays of external cameras monitoring the work space, typically from the outer edges.
- Landmark-Based Positioning (Artificial Landmarks/Markers)
- Model-Based Approaches (Three-Dimensional Geometric Model-Based Positioning and Digital Elevation Map-Based Positioning)
- Feature-Based Visual Map Building (Natural Landmarks)

Appearance-based Localisation (These class of methods aim at identifying revisited places on the basis of sensor similarity and are mainly used as visual SLAM re-localisers. Each observed scene is represented by an appearance model constituted by a set of visual attributes (e.g. Tree-based classifiers and Bag-of-Words-based methods)

Localisation by using geo-referenced information. For example aerial vehicle localisation can be performed by registering the currently acquired ground image with an available geo-referenced map.

Assisted teleoperation

Although fully autonomous robots are often considered the ultimate goal in navigation, there are scenarios where it is desired to have a human in the loop. The decision making capabilities of humans are often superior, and need not be traded just for the sake of autonomy. Autonomy is not necessarily a goal in itself.

There are various levels of autonomy for mobile robots. For motion planning of mobile robots, the level of autonomy can be considered to be spanned by the two extremes; Fully autonomous motion planning and direct manual control. For fully autonomous control, the operator only specifies the target location, while in direct manual control, the operator specifies for instance the velocity reference to the robot, typically by a joystick. However, the operator might want to control the overall direction, where safety systems, such as collision avoidance, can be required to override the operators control in certain circumstances. This is often denoted as switched or traded control. The control of many multi-rotor drones can be considered a shared control system; Because of the instability in their design, automatic control is needed to maintain stable flight. The operator then provides the reference for the automated controller, responsible for achieving the desired motion. Without the automated controller the user would not be able to operate the aircraft safely.

Assisted teleoperation refers to a shared control mode, where a remote operator controls a mobile robot, but some tasks are handed over to the robot. For instance, in a search and rescue mission in an unknown environment, a robot might be controlled by an operator with a video link. As the video only provide a limited field of view, and maintaining spatial awareness can be problematic, it would be desirable with some kind of assistance to avoid collisions. The operator would then only provide desired control input, and the robot would possibly adjust the control input to avoid collisions. As an example, it can be difficult to judge the distance to some obstacle based on camera information, but the robot can use a laser to accurately measure the distance, allowing for collision avoidance.

Motion and Path planning

Trajectory planning and simple motion planning around obstacles is well understood. Complex motion planning for multiple degrees of freedom arms is well understood as an optimisation problem.

Model based coverage planning algorithms/Motion planning for 3D infrastructure inspection based on CAD model or similar:

- Approximation of model, complexity vs accuracy
- Optimize for minimum time or shortest path for full coverage of infrastructure
- Vehicle constraints, e.g. dynamics/kinematics
- Sensor constraints, e.g. sensor range, pan/tilt ability, sensor field-of-view and required overlap from view to view

Model independent coverage planning algorithms/Motion planning for 3D inspection of infrastructure without a priori access to CAD model or similar:

- Fast 3D model construction -surface based or volumetric modelling
- Exploration strategies, e.g. based on boundary exploration or information gain prediction. One-step or many steps strategy?
- Vehicle constraints, e.g. dynamics/kinematics
- Sensor constraints, e.g. sensor range, pan/tilt ability, sensor field-of-view and required overlap from view to view
- Selection of termination criterion

- Two-stage approach: Systematic, but fast preliminary run to build a quick and dirty model as an input to a more detailed plan that accounts for the missing part.

5.6.3. Expected Step Changes

- *Seamless indoor to outdoor navigation:* Development of methods to achieve seamless Indoor-Outdoor navigation and robust navigation through different positioning systems totally transparent at the application level. Resulting systems that fuse different localisation sources should be able to provide more accurate and robust navigation.
- *High accuracy low cost systems:* The development of new mapping techniques through the combination of existing algorithms with cheaper mass market sensors (such as 3D depth sensors, miniature cameras or similar) to generate improved navigation performance at a lower cost.
- *Deployment of map hierarchies:* hierarchical mapping, conditional independent mapping and tectonic mapping type techniques combined with distributed computing are expected to reduce the computational cost and increase the scalability of autonomous navigation ability.
- *Dynamic map building:* Development of map-building methods for dynamic and changing environments (e.g. crowded environments, human body mapping, mapping of flexible structures).
- *Cloud based localisation:* The integration of third party external cloud based services in the robots system design for localisation and mapping, both indoor and outdoor. This has the potential to reduce computational load and speed up map generation and localisation.
- *Localisation in dynamic environments:* Prediction methods for estimating localisation in crowded and dynamic environments. Including localisation in moving media such as under the sea or on unstable ground.
- *Efficient motion planning for multiple degree of freedom structures:* Including energy minimised planning and motion planning in flowing water.
- *Motion planning in dynamic environments:* Including high density environments and against changing environmental conditions.
- *Motion planning for teams:* Distributed cooperative motion planning for teams in air, water and on land
- *Collaborative navigation:* Development of collaborative map-building and interpretation strategies, collaborative positioning. Heterogeneous robots working as a fleet could help each member of the group by offering positioning or mapping information.
- *Improved localisation systems:* Development of advanced signal processing algorithms to achieve high accuracy positioning (RTK-like) with cheaper receivers such as single-frequency receivers.
- *Novel localisation techniques:* Ability to create localisations from non-visual clues, such as ambient sounds, tactile sensing, air flow etc. Including the integration of maps generated using different sense modalities.
- Virtualisation of base stations for absolute localisation in outdoors
- *Long term map correction:* The relevance of most maps decays over time and need repeat references, beacons or place detection strategies to enable map maintenance over long time spans.
- *Long term localisation*: For some applications it will be important to accurately return to known locations over long periods of time (several years). This is a challenge because the environment around the location can change significantly.

- *Semantic mapping:* Including semantic information in the world models is important in order to move towards navigation strategies where the robot can interpret, in human terms, where it is and where it has to move.
- *Social navigation:* A social navigation is needed so that robots can easily be accepted in environments and collaborate with people. Robots will need to follow commonly accepted human behaviours when navigating such as following the people flow when moving in the same direction. This type of navigation will be strongly linked with cognitive ability.
- *Human like motion:* The ability to interact and work in close collaboration with users will require motion planning that is compatible with human expectations.
- *Motion planning with flexible links and tools:* Motion planning while holding a flexible tool or object, or where links react flexibly to external forces in the environment.

5.6.4. Benchmarks and Metrics

The primary metrics for localisation are:

- *Accuracy*: Degree of conformance of the estimation or measurement against its truth value at a given time.
- *Integrity*: Ability to provide timely warning to the system when the solution should not be used for navigation.
- *Availability* (in terms of update frequency): Ability to remain usable within the intended area, defined as the portion of time during which the estimation is reliable for navigation.
- *Continuity*: Ability to perform without interruption in the intended application

The primary metrics for mapping are:

- *Accuracy*
- *Map entropy* (in case we are dealing with a probabilistic map)
- *Map convergence*
- *Correspondence to ground-truth*. The aforementioned metrics depend on the availability of a ground truth that is often provided by other measurement system, that in turn has its own accuracy.
- *Reliability*: confidence interval to cope with uncertainty measurements. For instance, if the system does not find a landmark for a long time, it may consider its position is not reliable any more.
- *Repeatability*: ability to provide the same result from a given same observation or realisation.

Although many robotic datasets are available on the web which constitute a reliable mean for benchmarking algorithms at research level, the definition of standard metrics and tests, such as in automotive or aeronautics sectors, is needed. This will allow system integrators to compare among different systems and platforms.

5.6.5. Dependent Domains

In some applications the failure of navigation capability can direct or indirectly put humans at risk. In some other applications or domains a failure in navigation can cause material losses. The following describe some applications where navigation is a critical ability:

Transportation of goods: Applications in logistics or supply chains such as in harbours or interchange of goods or in decommissioning and construction services

Transportation of people: Autonomous navigation becomes a safety critical ability when transporting people; For example in driverless cars and autonomous aerial vehicles. In these cases systems will need strong certification.

Aerial robotics (excluding transportation of people): Aerial robots will be able to fly in non-segregated airspace in the medium to long term. As such, they will have to operate in harmony with the other occupants of the airspace and inhabited overflown areas.

Agricultural robots, both indoor and outdoor: Farm environments are dynamic and alter with ground conditions, the weather and the seasons, maintaining localisation, long term maps and motion paths is critical to many farm applications.

Search and rescue: Unstructured non-anthropic outdoor environments, possibly severe weather conditions, speed constraints, interaction with dynamic environments and other human and robotic teams all contribute to a challenging application domain.

Manipulation and assembly in aerial and marine robotics: Precise pose are required for manipulation and assembly in aerial and marine robotic applications against environmental flows and turbulence.

5.6.6. Impact on Domains and Products

Many of the proposed application for robotics technology require high quality navigation solutions in both indoor and outdoor environments. Particular challenges exist for aerial and marine vehicles and in environments where satellite based positioning systems cannot be used.

High quality navigation, at task appropriate scales, will significantly affect the quality of may tasks and impact on long term deployability. Low cost modules and components for indoor navigation which provide high levels of dependability and accuracy will enable faster system integration and development.

5.7 Cognition

5.7.1. Description

Cognitive robots are able to express adaptive anticipatory behaviour in real time on the basis of the contingent situation, past experience, and inferred future conditions. Cognition is the system-wide process that provides an agent with the ability to understand, given only partial knowledge, how things might possibly be, not just now but at some point in the future, and to use this understanding to influence action. Predicting the future requires the robot to remember past, so learning is critical to all cognitive systems. Cognition breaks free of the present in a way that allows the system to act proactively, reliably, to adapt, and to improve.

Many of the other technologies exploit cognitive processes and techniques, and vice versa, including sensing, planning, navigation and human-robot interaction (HRI). All of these will benefit from further improvements in cognition and in turn cognition depends on them.

5.7.2. Key Techniques and Methods

5.7.2.1 Knowledge representation and reasoning (KR&R)

KR&R is a wide and mature field of AI, which is pivotal to high impact application domains like data mining, search engines and recommendation systems. The main assumption behind KR&R is that knowledge should be represented in the system in an explicit, machine-readable form, to provide the ability to reason from this knowledge and about this knowledge, and to prove formal properties about the knowledge and about the reasoning mechanisms. This concerns both descriptive —declarative— knowledge ("know-what") and prescriptive —procedural— knowledge ("know-how"), particularly important in robotics. More generally, knowledge can be of many different types, including ontological, causal, deontic, procedural, temporal, spatial, and still others. Accordingly, different KR&R formalisms have been developed, each one being typically geared toward one type of knowledge. Formalisms have also been developed to deal with the uncertainty that may affect knowledge, including those based on probability theory, Dempster-Shafer theory, and fuzzy logics. Reasoning in the above formalisms is often done by logic-based methods, and a great attention is put in the formal and computational properties of these methods, like soundness, completeness, decidability and complexity. A plethora of tools for KR&R are available, both commercially and in the open source community. Some languages produced in this community have become standard, like the OWL family.

KR&R in Robotics: Grounded Knowledge Representation and Reasoning

The issues addressed in the field of KR&R have started to be also addressed by the robotics community, as a means to endow robots with the ability to represent, use, exchange and reason about knowledge. Notable examples are:

- the representation of higher level concept in semantic maps, that integrate several types of knowledge, e.g. geometric, topological, functional, categorical, temporal, and so on;
- the use of ontologies to enable robots to elicit information from the web.

Ensuring a high level of communication and synergy between robotics and the field of KR&R is essential in order to leverage the large body of knowledge, experience and tools acquired in the former, and in order to make this knowledge and tools suitable to the needs of robotics systems. Two points are central in this context: (1) knowledge should be represented in an explicit way inside the robot, using a suitable representation formalism; and (2) the elements in this representation must be grounded in real physical objects, parameters, and events in the robot's operational environment.

How to demonstrate the added value of KR&R

- Less pre-programming in a given or new domain, since robot can leverage generic semantic knowledge;
- Robots can more easily learn new knowledge and skills using general semantic knowledge.

Current technological barriers

- Encoding and use common sense knowledge and contextual knowledge;
- Dealing with uncertainty, incompleteness and inconsistency in the knowledge, due, e.g., to conflicting sources, ambiguous interpretation, or incomplete information.

5.7.2.2 Action planning

Knowledge-based planning is an active and one of the oldest areas of research in the field of AI. The type of planning addressed in AI is task planning in its wider sense, which includes scheduling, dealing with resources, and observation planning. Many results are also available with respect to planning under uncertainty, planning for distributed systems, and distributed planning. Geometric or motion planning are usually not addressed in this area. Planning techniques in AI have a high degree of maturity, and the field has developed its own de-facto standard language (the PDDL family), benchmarks and competitions. Commercial and research planners are available.

Action planning in robotics

Planning in AI was originally developed for use on robots, namely on the SRI robot Shakey from the late 60's. Since that time, there has been an extensive development, and AI planning is now a mature field with applications to, e.g., logistics, production, and space exploration. Advanced AI planning capabilities in space have been notably demonstrated by NASA in the "remote agent experiment" on-board DeepSpace-1 back in 1999. However, only the most basic AI techniques for planning have been typically used until now in deployed robotic systems, due to the fact that tasks and domains were simple and predictable. In order to move to changing, more complex and less predictable application domains, especially those where robots and human co-exist, more sophisticated AI planning techniques will need to be incorporated into robotic systems.

If we want the generated plans to be physically executable, however, planning should take into account heterogeneous types of knowledge multiple levels of abstraction, observations and uncertainty. For example, task planning must be done in combination with motion planning in order to verify the geometrical and kinematic feasibility of a given sequence of abstract actions. Spatial, temporal and resource reasoning may also be needed to guarantee that plans can be executed. Decision-theoretic approaches can be used to take uncertainty and observations into account.

Techniques for plan execution and monitoring will also need to take into account multiple types of knowledge and multiple levels of abstraction. Robots may leverage knowledge to detect failures, diagnose their cause, and possibly recover. Cognition can therefore contribute to the dependability of the system.

How to demonstrate added value

- Empirical evaluation of the performance of task execution when they have been planned using a hybrid planner over using separate planners.

Current technological barriers

- Computational complexity of the combined hybrid planning problems.
- Computational complexity of planning when uncertainty is taken into account, e.g., in decision-theoretic approaches.

5.7.2.3 Learning Development and Adaptation

Machine learning techniques most often used in robotics can be roughly categorised to:

- supervised classification or regression;
- unsupervised clustering;
- reinforcement or policy learning.

Supervised recognition is widely used in robotics for skills such as speech recognition or visual recognition, in most cases with off-line training. Similarly, supervised regression methods are used for learning the robot's dynamics or other physical properties based on sensory data. On-line supervised learning using programming by demonstration (PbD) and learning from (direct and indirect) demonstration (LfD) is set to become increasingly important. Unsupervised clustering is mainly used for pre-processing of sensor data or more recently as part of semi-supervised methods. Policy learning is mainly performed by reinforcement learning approaches where advances have been made recently especially in the learning of individual motion skills (e.g. the PI2 method). The machine learning community is actively developing advanced methods but many of the general advances require being customized to robotics because they either rely on vast amounts of labelled training data, on off-line processing or often on unrealistic computational budgets. The long-term autonomy of robotic systems will be dependent on machine learning because the agent's environment will be dynamic and environment models then need to be updated during the life-time of the agent.

Learning Development and Adaptation in robotics

Machine learning methods are increasingly being used in robotic applications owing to the recent progress in the formalization of many of them and consequently the mathematical guarantees that they now provide. The advances of the past couple of decades enabled the mathematical characterization of the problem of generalization in high-dimensional data spaces: the use of the mathematics of reproducible kernel Hilbert spaces and associated kernel methods enabled the design of efficient classifiers and similarly of regressors since then successfully applied to the problem of image (and more in general sensory data) recognition. Regression methods (conceptually identical to classifiers) were employed for system identification – to acquire a model of the plant – to later use in model-based control methods. These led to the widespread use (in research but also in industrial application) of computed torque and the related force control methods. Methods for temporal data classification and modelling, as e.g. speech, have been also applied consistently driving the advances in speech recognition. The formalism of graphical models was employed together with probabilistic algorithms for both learning and later inferring solutions to specific problems of classification as well as regression. In many cases (e.g. Gaussian Processes), the same algorithm had different possible interpretations depending on the mathematical tools being employed. For problems when labelled data are not available, reinforcement learning techniques have been improved leading to learning from demonstration approaches for movement acquisition in robotics. The research of learning in robotics has been fruitful in characterizing and fine-tuning machine learning methods to specific robotic problems and tackling the issues of on-line learning as well as the computational efficiency of methods to be e.g. used in tight robot control loops. This last topic has long range connections to the problem of life-long learning in AI and robotics.

5.7.2.4 Natural interaction

Humans communicate via a large number of rich means, many if not all of which are now exploited by contemporary AI systems. This communication includes but is not limited to natural languages such as French or Mandarin, which have both spoken and written forms. But natural human interaction includes deliberate gestures such as pointing, and also incidental “backchannel” feedback that can take the form of grunts, shifting posture, or facial expression. Such feedback may not be explicitly noticed by either the sender or the receiver, yet serves to allow both participants to monitor each other’s interest and level of understanding. In addition, humans have evolved social emotions that help shape and motivate the extent and nature of their interactions, including turn taking and conflict resolution.

Natural interaction in robotics

Natural human-robot interaction is clearly needed for robots aimed at the service and domestic sectors, and it is highly desirable in the industrial sector as a way to instruct the robot and cooperate with the robot. Collaborating and interacting with humans and other co-workers requires a high level of cognitive compatibility between human and machine. Successful interaction depends on an understanding of a partner’s needs and intentions. These may be conveyed by a variety of cues, including words, gestures, and emotional expressions. While complete and perfect communication even between two humans from the same village is impossible, basic competencies of shared attention, turn taking, expressing understanding and agreement or disagreement are possible even across species. As much as possible interaction should be seamless, and certainly human users will expect interaction to improve rapidly with familiarity of the task.

How to demonstrate the added value

- End user asks robot to perform n tasks, evaluate with respect to end user.
- Users more likely to use the robots with good HRI (measure usage rates on robots with & without new traits.)
- Note that transparency is one of the ethics requirements identified by the UK EPSRC Principles of Robotics.

Current technological barriers

- Understanding non-verbal communication.
- Speech understanding in uncontrolled settings (see further "grounding" above).
- Transparency of the robot's intentions, self-assessed competences.

5.7.3. Expected Step Changes

To be sure of success in step development, candidate techniques and methods must satisfy the following three requirements: (1) they have a good degree of maturity, (2) they require focused investment in research to make them applicable in a robotic system, and (3) their application to robotics would enable critical new capabilities which are essential for some important domains.

These include the following:

Grounded Knowledge Representation and Reasoning

Increased use of predictive models and hybrid knowledge representations: planning has stressed and progressed extensively in search issues with shallow (abstract) descriptive models. Complex challenges remain for deliberate action (including planning, monitoring, etc.) with possibly much less search but deeper predictive models, combining declarative and procedural knowledge.

Hybrid KR&R: one key missing ingredient in current KR&R is the ability to integrate multiple types of knowledge (declarative – semantic and episodic – and procedural), and to reason across multiple types of knowledge. This is important in robotic systems, in which heterogeneous data must be considered, ranging from formalized knowledge from ontologies to the heterogeneous data coming from the different sensors.

Reasoning under uncertainty: existing KR&R techniques need to be extended to allow a realistic and tractable treatment of the uncertainty, incomplete knowledge and conflicting information which are inherent to the robotic domain.

Knowledge services: build, maintain, and use huge remote knowledge services for robots, together with the mechanisms that enable robots to translate the retrieved knowledge into interoperable, actionable knowledge.

Reason about robot data: most of the data in robot control systems are of numerical nature. We need methods for the effective integration of numeric representations and computation with logic-based knowledge representations.

Context management: the interpretation of the knowledge available to the robot is usually dependent on both the context of acquisition and the context of restitution. Explicit context management requires first context identification and then context representation.

Action Planning

Closed-loop planning: task planning and plan execution are usually loosely coupled; tight coupling of planning, plan execution, and learning will enable plans that are updated on-line based on observations but also planning how to learn about the attributes and dynamics of the environment, which will be necessary for long-term autonomy.

Hybrid planning: task planning and motion planning are usually done independently from each other: a more integrated approach is needed in robotic systems, in which task-level actions and geometric motions may have mutual dependencies. Planning for robotic systems should also take into account other aspects related to physical execution, like time, observability and resources.

Joint action planning, execution and monitoring: the formation, execution and monitoring of plans that take into account the presence of the humans. Humans may be considered as sources of constraints and goals for the robot, as resources, or as potential collaborators in the achievement of shared goals.

Formal specification and synthesis of control systems: the ability to prove formal properties on the behaviour of a cognitive robotic system, especially related to safety, is pivotal to their introduction in the market and society. Formal methods are needed to specify and synthesize robot control systems starting from rich models of the robot, of the environment and of the task. These methods should enable the formal verification of the system, the run-time monitoring of its performance, and the diagnosis in case of failures. Tools like temporal logics and description logics have reached a good degree of maturity, and are good candidate to create such methods.

Internal simulation: symbolic and non-symbolic associative knowledge representations for predicting the many possible outcomes of a robot's actions and their consequences for subsequent interaction are needed to deal with uncertainty. This will be realized in the form of internal simulation – effectively cognition without engaging the motor commands – through multiple causal chains of perception-action couplings. Action selection will be effected by internal attention winner-take-all processes, adjudicated according to a context-sensitive (possibly application dependent) value system.

Meta-cognition: in a similar vein, there is a need for cognitive robots to be able to reason about their own performance: their current state, their state of preparedness for upcoming actions, and the behaviours that satisfy ethical standards and provide for safe operation.

Such autonomic processing is necessary to support greater autonomy and promote user acceptance.

Learning Development and Adaptation

Symbol grounding and perceptual anchoring: connecting the discrete symbols used in a knowledge-based methods to the continuous signals linked to the sensors and actuators is a fundamental problem that is often solved in a ad-hoc way on a case-by-case basis; a principled, well-founded approach is still lacking. In particular, a principled approach that combines top-down and bottom-up representations would enable knowledge based sensor interpretation, reasoning and planning with limited knowledge.

Automatic categorization and generalization across categories: by generalizing learned knowledge and exploring innovative strategies for using that knowledge, cognitive systems can uncover innovative ways of addressing problems and dealing with unforeseen situations. This will involve the ability to improve existing world models (pre-programmed or learned), including plans, solution strategies, action repertoires, and affordance-based interaction.

Learning in unconventional data domains: learning for vector valued functions is a requirement in many domains and it is often treated as learning a collection of scalar functions, effectively missing the opportunity of learning the deeper structure of certain vector valued problems (e.g. the robot body dynamics). Similarly, there are situations where the data set is incomplete and techniques for semi-supervised learning have to be employed. For a robot it is often easier to acquire and store lots of data rather than waiting for a teacher to provide the labels (which are typically scarcer). These basic improvements are needed to move from the large databases required today to the robotic applications of ML techniques. In all cases, care must be taken, to guarantee bounded memory and time so that machine learning is applicable to reasonably sized robotic computational infrastructures.

Deep Learning methods: automatic extraction of semantics from experiential learning is required to allow robots to adapt to new situations, either on-the-fly or when being reconfigured for new applications. Deep Learning has recently surged to the state-of-the-art by demonstrating high quality performance both in training and testing time and accuracy. Restricted Boltzmann machines for example have been shown useful in the classical domains of image classification and more recently in continuous speech recognition. These methods are less understood mathematically than kernel methods. Curiously, multi-layer (deep) representations and methods are more brain-like and thus they are proving important both as a computational and as a modelling tool for certain brain architectures. Dictionary and feature learning are two other methods that fall to a certain extent in the category of deep learning as they act as data pre-processing before shallow learning methods are applied. These include “sparsification” principles which have shown exceptional performance increments.

Learning from Demonstration (LfD): building on established results in programming by demonstration, new techniques are required to allow robots to resolve ambiguities in non-expert supervised learning and exploit accelerated forms of reinforcement learning. Furthermore, there is a need for learned skills to be fine-tuned by implicit or explicit coaching by the end-user.

Integration of learning in knowledge-based technologies: cognitive robots need to learn to plan and plan to learn, especially when using knowledge-based techniques such as semantic maps and production systems.

Natural Interaction

Human affective and social behaviour detection. New algorithms and design principles for machines that can detect, interpret and recall complex human behaviours in everyday contexts such as the home, the office or in public places.

The investigation of "natural". Assess the essence and various means of natural interaction with robots, developed from a research-based understanding of human behaviours and needs, dignity and well-being.

Cognitive modelling of humans. Interaction requires to build a cognitive model of the human the robot interacts with, though this can be limited in scope. These models should represent not only (dynamic) physical features (location, posture, gestures…), but also mental features: cognitive capabilities, beliefs, desires. The correct interpretation of these cues requires building new modality-independent representations that support parallel and hybrid (continuous/symbolic) perspectives, including temporal and spatial models, models of the (grounded) beliefs of each of the agents, cultural/social contexts. Demonstrate this skill for example with perspective-taking and theory of mind building.

Robot soft communication skills. New mechanisms, control and scheduling techniques to realise socially aware robot responses that are physical as well as affective and social.

Verbal and non-verbal communication. For verbal communication, see discussion of "grounding" above. Non-verbal expression by the robots may require special actuators, and certainly requires a capacity to plan over and recognise time. Particularly important is pursuing a single goal at a time (at least, that might require communication or coordination) and providing and looking for temporal gaps that are species or possibly even culturally-specific. Note there is already a great deal of work on facial expressions for iCub, but gestures may also be useful for less expensive, more purpose-built robots.

Autonomous navigation and localisation in crowded environments. Precise localisation and mapping is needed for crowded scenarios where large numbers of features can correspond with mobile objects. Advanced models of peoples' and groups' motion patterns are needed as well as applying social constraints to navigation planning. Additionally, a guide robot may adapt its path planning to its user's road preferences.

Physical interaction. This includes handover, joint construction, tele-operated and collaborative tasks.

Adaptation and learning triggered by social interaction. Learning in this sense aims to achieve better performance in a social interaction, in contrast to other learning applied to robotics activities devoid of HRI. For instance, learning may aim to promote human-robot collaborative achievement of a task or to improve human-robot communication (such as the robot changing its behaviour to help the human better understand the robot's intent).

User personalisation. New machine learning approaches to learn and adapt to user preferences in a natural way, over multiple interactions.

The ethical and social implications of social robots. Autonomy and decision power of the robots oblige the researchers to think also about ethics and the respect of intimacy of subjects. Creating a robot that is indistinguishable in appearance from a human is subject to controversy for ethical point of view. Co-evolution between humans and robots has also social implications. We need a new interdisciplinary mix of computer, social/psychological sciences and engineering to understand the substantial impact of Robots in the society.

Finally, techniques which have a strong potential but are currently at the basic research stage, so their exploitation in robotic systems is on the long term scale.

Neuro-morphic engineering & learning: neuro-morphic engineering comprises a set of techniques that imitate brain architectures at the hardware level. Recently progress in hybrid neuro-morphic and digital architectures has enabled the implementation of learning methods based on neural principles (as for example LTP and LTD or spike-dependent synaptic plasticity techniques). Neuro-morphic engineering leads naturally to efficient encoding of either sensory or motor signals in terms of spikes and to a completely new class of data processing algorithms which rely on "sparse" event-based representations. Besides, hardware neuro-morphic neural network are now under investigation. One of the major advantages of the neuro-morphic hardware is the extremely low power consumption owing to the use of transistors in the sub-threshold regime. Albeit all these techniques are certainly experimental, they are worth exploring as a longer term endeavour for autonomous robots to operate on batteries or other portable energy sources.

Dynamical systems theory: dynamical systems theory has been successfully used to model the behaviour and learning of animals and humans in various sensorimotor tasks including rhythmic behaviours, locomotion, etc. In short, concepts of trajectory generation become attractors in the language of dynamical systems, learning becomes the modification of certain potential functions, etc. The same mathematics has been used in robot control and it found its application also in reinforcement learning (PI^2). Motion primitives based on dynamical systems have been very popular recently to encode the robot's tasks in a small and manageable number of parameters. This area of cognitive systems theory needs further development in order to transition from a mostly analysis tool into a proper engineering method, i.e. to develop methods that allow the design of generic dynamical systems given a set of behavioural goals of the robot.

5.7.4. Benchmarks and Metrics

Evaluation and benchmarking of cognitive robotic systems is a challenging area because cognition is a system-wide process that effectively integrates the sensorimotor capabilities in a manner that achieves the meta-functional requirements necessary for deploying in uncertain and poorly-specified application scenarios: dependability, reliability, usability & reusability, versatility, robustness, fault-tolerance, safety, security, and maintainability, among others.

We distinguish between evaluation of the individual components, and evaluation of the whole cognitive system. For the former, there are many standard methods already available. For the latter, we adopt the same approach that is used in software engineering for assessing the quality of software products. Since quality cannot be measured directly, we need to identify a set of indicators that correlate will with the degree to which the meta-functional (often referred to as non-functional) attributes are exhibited by the robot. Performance indicators will target environmental variability, task diversity, and range of interactions with human and other machines.

Regarding benchmarks, we make the same distinction between benchmarks aimed at assessing the performance of a specific cognitive component, and benchmarks aimed at assessing the performance of the full robotic system. For the former, several benchmarks exist for specific types of components, e.g., artificial vision (Pascal), planning (the International Planning Competition), knowledge contents (the QuerySet from the University of Bremen), etc. For the latter, the best established benchmarks that stress the cognitive abilities are RoboCup and the RoCKIn EU C.A.

Current work (e.g., in the RoCKIn EU FP7 CA, in the RAWSEEDS EU FP7 CSA) has set several directions that should be extended in HORIZON2020 upcoming calls, especially system benchmarks in unconstrained or partially-constrained test scenarios. It is important that benchmarks assess both functional and meta-functional performance.

both individual components/subsystems/abilities/subtasks and the integrated system/task should be separately evaluated and benchmarked - there are different ways in which abilities can be integrated, but abilities themselves should also be applicable to a wide variety of domains and perform well across them;

software tools should be developed to implement the measurement of performance based on (also to be developed and established) metrics of common use for different abilities (e.g., error with respect to a reference path during robot navigation, but also comfort index for a human being followed by a robot while traversing a given path; number of correctly classified gestures or recognized words, but also gesture naturalness index for the humans) and be used in benchmarking test beds specified to allow reproducibility and repeatability of tests.

5.7.5. Dependent Domains

Cognition is critical in all domains that cannot be modelled completely and accurately, e.g., because they exhibit variability over time, diversity of tasks and diversity of interactions. These domains include marine robotics, flexible manufacturing, health robotics, elderly assistive robotics, most service robotics, and in general all domains in which humans and robot share the same environment and possibly cooperate.

5.7.6. Impact on Domains and Products

Already today, commercial service robots meant to operate in previously unknown environments or in environments where humans are present already leverage some simple cognitive technology. These include domestic cleaning robots (e.g., Roomba floor cleaners), industrial service robots (e.g., Atlas Copco’s automatic mining vehicles), and marine robots (e.g., Seetrack by Seebyte.com).

6. Innovation

{This is section will be expanded in future versions of the MAR}

This section contains details for:

- Standardisation and Benchmarking
- TRL Levels

6.1 Standardisation, Benchmarking and Regulation

6.1.1. Overview

Standardisation and regulation play an important role in the development and deployment of systems. Standards are important in ensuring product and operational safety, providing a common basis of comparison and in setting interoperation parameters between modules and systems. Ideally standards should be harmonised on a global basis, however local variations are inevitable, especially in a fast moving field such as robotics. One goal in the development of standards is to work towards ensuring that both the regulatory processes and the standards they rely on are kept in step with the underlying technology developments they seek to shape.

It is also important to appreciate the distinction between de-facto standards and formal international standards especially safety standards. In many cases individual organisations that dominate particular domains or areas of application are able to enforce de-facto standards more rapidly than formal standards can be ratified. From a European perspective where *de facto* standards have often been driven by its competitors, it is important to regain the initiative, especially in areas of technology where Europe has a current advantage.

International Standards help to develop and maintain a global quality culture and set minimum requirement levels which are acceptable within international markets. These International Standards, where they exist, enable free movement of goods between regulatory regions. However, in reality local variations in testing and certification together with multiple similar but competing standards often create barriers to product introduction.

The introduction of new types of product into a market often involves a dialogue with regulatory bodies to interpret and shape the processes of certification and approval.

Quality based standards also act as a barrier against low quality or unsafe products by stipulating minimum standards for the sale of goods in a particular territory, for example CE certification in Europe or UL certification in the USA. Legislation is needed to establish an appropriate regulatory framework and to ensure that the market system conforms to the agreed rules and laws.

Standards are voluntary, regulations are normally backed by legislation and hence are mandatory even though compliance may be asserted either through self-certification or third-party testing. International standards, such as those produced by ISO (International Organisation for Standardization; www.iso.org) or the IEC (International Electrotechnical Commission; www.iec.ch), have the greatest weight because they have been developed by involving all stakeholders and involve an open consensus based approach.

6.1.2. European Status

Within the international framework, Europe has generally an important role in standardisation as well as in robot standardisation. Europe has formulated a number of EC Directives[18, 19] which are incorporated into national regulations in key areas such as safety. Some of the EC Directives relevant to the robotics domain are the following:

- Directive 2001/95/EC: General Product Safety Directive. This requires that no producer shall place a product on the market unless it is a safe product.

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[18] www.etsi.org/about/our-role-in-europe/public-policy/ec-directives

[19] http://ec.europa.eu/enterprise/index_en.htm

- Directive 2006/95/EC: Low Voltage Directive. This provides common broad objectives for safety regulations, so that electrical equipment will be acceptable for use in all EU countries.
- Directive 2004/108/EC: Electromagnetic Compatibility Directive. This sets the essential requirements for all electrical and electronic equipment that may interfere with other equipment or that may be interfered with by other equipment. The directive states that the result must be a device that cannot be disturbed by electromagnetic interference and that in itself limits the generation of interference in such a way that the other equipment is not disturbed by it.
- Directive 2006/42/EC: Machinery Directive. This is written to promote the design of machinery that is as safe as possible according with the current status of technological development. This directive applies to machines generally defined as devices with at least one moving part, containing actuators, control, and power circuits. Exceptions to the Machinery Directive exist and are normally covered by other regulations, as well as machines in which the main risk is of electrical origin (in which case only the Low Voltage Directive would apply). Machines with increased risk (due to high power, mass, speed, etc.) must be certified by a Notified Body. Most robots to date have been classified as machines and hence the robot safety standards are designed to give guidance for complying with this directive. One of the key issues is how the wide variety of human-robot interaction can be achieved with the appropriate level of safety measures in place.
- Directive 2001/104/EC: Medical Device Directive. This harmonises the laws relating to medical devices within the EU. The key issue to note here is the definition of a medical device, which is the following:
  - Any instrument, apparatus, appliance, software, material or other article, whether used alone or in combination, together with any accessories, including the software intended by its manufacturer to be used specifically for diagnostic and/or therapeutic purposes and necessary for its proper application, intended by the manufacturer to be used for human beings for the purpose of:
    - diagnosis, prevention, monitoring, treatment or alleviation of disease
    - diagnosis, monitoring, treatment, alleviation of or compensation for an injury or handicap, investigation, replacement or modification of the anatomy or of a physiological process
    - control of conception

    and which does not achieve its principal intended action in or on the human body by pharmacological, immunological or metabolic means, but which may be assisted in its function by such means."
- Directive 2009/48/EC: Toy Directive. This directive establishes the safety assessment that manufacturers need to carry from analysing the various hazards that a toy may present. This includes consideration of chemical, physical, mechanical, electrical, flammability, hygienic and radioactivity hazards, and an assessment of the potential exposure to them. Some toy robots exist and clearly need to be regulated under this directive.

The Medical Directive is particularly relevant to assistive and medical robotics development. Any robot designed to meet a medical need must be regulated as a medical device (under this Medical Device Directive) rather than as a machine (under the Machinery Directive). Plans have also been announced that would extend this directive in the future. The implication is that that future medical robots will also need to meet new and more stringent requirements.

These EC Directives form the legal basis of the national legislation needed to ensure the free market system conforms to the laws specified in the Directives. Conformance of a product to the applicable Directive(s) is indicated by CE-mark. Within this context EC standards for safety also undergo a process of "harmonisation" which means that there must be compatibility between the different safety standards that apply across Europe.

Until recently, the only international robot safety standard which existed was ISO 10218 (Parts 1 and 2) applying to industrial robots and robot systems; it is well known that industrial robots have been traditionally designed to operate in isolation from humans (in real or virtual cages) and human-robot collaboration has been prohibited because of safety concerns. Over recent years there has been an interest to develop collaborative modes, but the lack of a safety standard for close human-robot interaction has been a barrier. A similar issue arises for service robots which are fundamentally designed to allow humans and robots to co-exist in the same space at the same time, but the lack of international safety requirements is a significant barrier.

In February 2014, ISO 13482 was published as a harmonised safety standard for personal care robots aimed at applications involving close human-robot interaction as well as human-robot contact to provide a variety of services to humans for improving the quality of life. This is a new standard and manufacturers and certification bodies need to become familiar with it so as to allow new products to enter the market. To date it has been mainly adopted in Japan and a number of personal care robots have been certified to it by JQA. Takeup has been slower in the rest of the world and this is of some concern New standards need adoption and compliance testing and perhaps a European level approach is needed to adopt the new standards and consider their inclusion in EC Directives.

Besides safety standards, other types of standards are also important for ensuring quality and cost effectiveness in global markets. In this regard performance and interoperability standards are most important.

6.1.3. Europe's place and contributions to the development of international standards

Europe is active in the international Working Groups developing robot standards. Notably few EU countries are currently involved and the spread of representation across domains and organisational types is poor, in particular hardly any SMEs are involved. SMEs are often the most technically active organisations and are likely to benefit from clear well defined and relevant standards, particularly with respect to safety and module interfaces. The time constraints and cost of participation are likely to be the main factors prohibiting SME engagement in standardisation. It is important to find novel ways to address this shortfall.

Most recently the European contribution has been a key factor for the creation of the ISO WG on Modularity of service robots. However, this initiative requires support as it benefits the whole European community.

6.1.3.1 Barriers to development, market and use

The main barriers are:

- Lack of knowledge and of concern about standardisation issues (relevant also at the societal level) in the scientific and robotics community at large
- Lack of robotics specific political and regulatory drivers
- Lack of research and coordination actions to support industry, SMEs and research to include the environmental performance, the LCA, the 3Rs issues in their products, use cases and prototypes.
- Lack of coherent theoretical and functional framework of the domains, hence requirements and terminology are not consistent across stakeholders
- Large variety of robot architectures with different interaction capabilities
- Lack of reusability of the hardware and software modules across research/industrial organizations (lack or interoperability).

6.1.3.2 Main international robot standardisation issues

The following types of standards (in priority rank) form the current focus of international standardisation groups:

- Safety standards
- Vocabulary standards
- Performance standards (safety-related first and then non-safety-related)
- Inter-operability (or modularity) standards

As the deployment of robot increases and new markets are developed it will be important to increase the number of focus areas for standardisation. The following are considered as candidates for standardisation:

- Boundaries/classification between different robot domains as well as between robot and non-robot domains
- Standardisation of complex robot processes
- Human-robot interaction/collaboration standardisation
- Environmental impact certification.

With respect to three particular domains of robotics activity (Industrial Robotics, Healthcare and Assisted Living) it is likely that these additional areas of standardisation may become critical to addressing barriers to deployment.

Table 1: Keys issues of Standardisation for Robot Domains

Standardisation issue	Industrial	Assistive	Healthcare
1. Safety	Critically important	Critically important	Important
2. Vocabulary	Important	Important	Important
3. Performance	Well defined	Application specific	Application specific
4. Inter-operability	Mainly closed modularity exists	Could speed up market development especially based on SMEs	Could reduce costs
5. Boundaries	Industrial-service boundary important	Industrial-service Personal care-medical	Service-medical
6. Complex processes	Important for business customer reference settings	Important for private customer rights	Important for patient rights
7. Human-robot Interaction	Important	Critical to domain	Critical to domain
8.Environmental impact	Important for future	Important now	Important, but adopt sterilisation requirements

6.1.3.3 Europe and international cooperation

It is important to note the vital linkage of efforts in standardisation with those in research so that they can support and complement each other for maximum impact not only in Europe but also worldwide. In fact, cooperation with the key regions of the world active in robotics is needed for developing normative human safety related data as an enabler for advances in the new emerging service robotics sectors. For this, Europe needs to work closely with China, Japan, Korea and the United States of America to ensure that the results have global acceptance for inclusion in the new standards for safety and benchmarking. Actions aimed to encourage the involvement of emerging countries, such as India and Brazil, are also advisable (even if they are not eligible for EU funding).

6.1.4. Standardisation areas

The following sections provide some detail about each standardisation area with respect to the following issues:

- Current developments and opportunities
- Contributions to key technology readiness levels
- Future opportunities and why relevant
- Barriers to development
- Barriers to use
- Relationship to other topics and market domains
- Europe's position in the standardisation process and European contributions
- Key stakeholders

The discussions will be continued and elaborated in future updates of this document.

6.1.4.1 Robot safety

For industrial robots, the traditional approach has been to separate robots from humans using real cages or virtual cages, referred to as "safeguarded space". Non-contact sensing, referred to as "electro-sensitive protective equipment" (ESPE), is to be used to detect a person entering the safeguarded space of a robot in the general sense - although for fixed base robots contact-based sensing methods (such as safety mats and door switches) can also be used. If a person is detected a protective stop must be issued. The sensing R&D for this has focussed on removing physical safety barriers to facilitate robot-human interaction without physical barriers, and the use of more sophisticated ESPE (e.g., light curtains and light grids (IEC 61496-2), laser scanners (IEC 61496-3) and safety cameras (IEC 61496-4)) is mandatory for ensuring human safety. In the recent update to the industrial robot safety standard (ISO 10218-1 and ISO 10218-2), a collaborative mode has been introduced, in which collaboration operation is defined as the state in which purposely designed robots work in direct cooperation with a human within a defined workspace. The various minimum gap and distance requirements for ensuring safety are presented in ISO 13854, ISO 13855, and ISO 13857.

Biomechanical criteria for collaborative industrial robots according to the paradigm of "power and force limiting" (see ISO 10218-1, section 5.10.5) As a result the technical specification ISO/TS 15066 has been developed and published in 2016 to describe basic forms of collaborative operation for industrial robots. ISO/TS 15066 defines quasi-static and transient contacts for ensuring human safety and also presents force limits for adults based on pain sensitivity thresholds for 29 points on the body. The main technical committee for robot standardisation is ISO TC 299 "Robotics".

Standardising safety in wider human-centred environments is also important and there is a need for the standardization of physical safety requirements for such robot applications.

Standardising safety for physical human robot interaction (HRI) regards bi-directional physical contact between human and robot. This poses the challenge of ensuring those contacts are safe, and the robot is not causing any type of harm (electric shock, injury, etc.) to the human.

With regard to service robots, where robots and humans share the same workspace WG2 has produced the new standard ISO 13482, published in February 2014. This covers applications where the operational spaces for personal care robots facilitate closer human-robot interaction; these include the following: monitored space, safeguarded space, protective stop space and restrictive space. The problem of human sensing for safety remains a key topic.

For medical robots, new basic safety and essential performance standards are likely to be developed in the next 3-5 years, but at present existing standards for medical electrical equipment apply (IEC 60601 family of standards). Key standards being developed are the following:

- IEC TR 60601-4-1: Medical electrical equipment - Part 4-1: Guidance and interpretation - Medical electrical equipment and medical electrical systems employing a degree of autonomy was developed by IEC SC62A & ISO TC299/ JWG9. The technical report has recently been approved for publication subject to resolving the DTR comments submitted. Publication is expected in February 2017.
- IEC 80601-2-77 (ed. 1), Medical Electrical Equipment - Part 2-77: Particular requirements for the basic safety and essential performance of medical robots for surgery. This is being developed by IEC SC62D & ISO TC 299 JWG35.
- IEC 80601-2-78 (ed. 1), Medical Electrical Equipment - Part 2-78: Particular requirements for the basic safety and essential performance of medical robots for rehabilitation, compensation or alleviation of disease, injury or disability. his is being developed by IEC SC62D & ISO TC 299 JWG36.

A key difference between machine safety and medical device safety is that in medical devices it is possible to perform a risk-benefit balance with respect to individual patients whereas safety is always at an “absolute” level to prevent harm.

Pursuing the perspective that collaboration between humans and machinery (and possibly also medical devices) will grow beyond the confines of robotics, the ISO Technical Committee ISO/TC199 has initiated with the creation of a study group dedicated to develop generally applicable criteria for the physical interaction of humans and machinery. The group has concluded its work and has recommended the creation of a new group to develop a Type B standard to consider not only healthy adult workers as is the case in WG3’s work, but children, elderly persons, disabled people, pregnant women, etc. ISO TC299/WG12 (Human-machine interactions) has recently been set up to develop the new work item proposal ISO/NP 21260 “Safety of Machinery – Mechanical safety data for physical contacts between moving machinery and people”. It is important that research and standardisation activities in Europe support this work to develop the urgently needed normative human safety related data.

6.1.4.2 Vocabulary for robotics

Harmonising and agreeing a common vocabulary is most important when it comes to international standardisation. In this respect all standardisations activities focus on defining important terms which are needed for their domain. For the area of robotics, many terms have been agreed and already published in international standards, e.g., ISO 8373, ISO 10218-1, -2, ISO 12100, ISO 13482, ISO/TS 15066 as well as standards being developed such as IEC TR 60601-4-1, IEC 80601-2-77 and IEC 80601-2-78, etc.

IEEE Robotics and Automation Society published “Ontologies for Robotics and Automation” (http://standards.ieee.org/develop/project/1872.html) in 2015 to provide a core ontology that specifies the main, most general concepts, relations, and axioms of robotics and automation which is intended as a reference for knowledge representation and reasoning in robots, as well as a formal reference vocabulary for communicating knowledge about between robots and humans.

6.1.4.3 Benchmarking robot performances

In the "research - development - innovation" path, performance evaluation and technology assessment play a fundamental role. While experimental procedures and methodologies are well-developed within scientific and engineering disciplines, it is not possible to objectively evaluate most of the state-of-the-art of methods, technologies, and systems in the fields of robotics and cognition. Assessment is currently subjective and does not lend itself to comparison of research results produced by different labs and in different countries. Objective procedures to characterize and measure behaviours and behaviour combinations are needed as a scientific basis for standardization activities in robotics.

It is thus clear that the foundations, the methodologies, and the tools for benchmarking and integrated testing need to be developed further within the community, at all levels, from defining the key challenges to development of appropriate benchmarks. The results of some preliminary efforts (including the EURON Special Interest Group on Good Experimental Methodology and Benchmarking and FP7-funded benchmarking initiatives like Rawseeds, euRathlon, and RoCKIn) provide a solid starting point.

The methodologies and metrics for testing and benchmarking

Although the current RoCKIn and euRathlon competitions include benchmarking for their specific challenges, there are no widely shared procedures concerning research result replication. There is an urgent need to improve technical evaluation especially with regards to human involvement and other aspects of unstructured environments and to assess usability in its multiple dimensions. Concerning human factors, ergonomics is currently not adequately evaluated. Factors such as the "learning curve" for interaction or the how much of the biomechanical and psychological stress on the user depends on the robot's interaction design have no formal measurement process. Usability and user satisfaction, ease of use and objective measures of the interaction all require benchmarking procedures. There is also no metric to account for human variability in usage scenarios or any means of evaluating how much validation is required, nor are there complexity metrics. In terms of product function validation benchmarks are needed to examine the impact and effectiveness of autonomy.

In particular it is the addition of autonomy to a product that both provides the added value but in turn creates the need to validate and certify in ways that are not necessary for products operated by humans. This is particularly important in applications which have safety implications or where there might be legal or even ethical issues.

To a certain extent the development of standards and benchmarks will be incremental with respect to whole system evaluation, just as it has been with existing technical products. However, underlying this is a need to establish technical benchmarks for sensing, motion, autonomy, cognition etc., the core technologies that robot systems are composed of.

It is important that any benchmarks cut across the different domains, where this is practical, and that best practice for testing and certification is applied. The driver is to create universal benchmarks that enable companies to test a wide range of products using standard processes, both to provide design cycle validation of performance and end product conformance. Such a development will require the broad engagement of both end users and product and systems developers including SMEs and innovators.

Existing Benchmarking Activity

Existing benchmarking tends to result from competitions where targets are set for performance in a given scenario or set of scenarios. This has proved to be an effective process in driving systems integration and technical development but only within the confines of the tasks set.

Benchmarks are needed that exemplify standards, and standards are needed to codify the results of benchmarking, in turn these mutual activities must keep pace with technical development otherwise they run the risk of simply documenting what has already happened.

The most advanced benchmarking criteria can be found in industrial robots where specific attributes are used as metrics, for example “pose accuracy”, “position overshoot”, “cornering deviations” etc. ISO 9283 provides a supporting standard for these benchmark metrics.

Various technical benchmarks exist particularly with respect to perception and recognition tasks, grasping and motion based metrics such as the Froude number. Similarly a number of competitions define standard environments that must be traversed for example in the W-Prize.

6.1.4.4 Robot modularity

Activity to establish standards for modularity in robotics are largely top-down. The ISO technical sub-committee for robots and robotic systems (ISO TC 299) set up a working group (WG6) in this area. This is seen as an opportunity to create an open global market. IEC has established a strategic ACART committee (Advisory Committee on Applications of Robotic technology) to investigate the standardisation needs for products that incorporate robotic technology.

The Object Management Group (OMG) has been pushing for standards in robot middleware software since 2005. Its Domain Task Force meets regularly, and the work has a web presence at http://robotics.omg.org/.

Setting standards for modules is also important for the design of safe systems. The goal being to provide automatic checking of designs against safety criteria during the design process. Early assessment of conformance with safety standards will reduce product development costs and time to market. More research is needed to extend the scope of such tools, or to develop good practice for robot programs.

Boundary issues in robot standardisation

Boundary or classification issues are closely related to Vocabulary. Such standard vocabulary is highly relevant for exchange languages for robot to robot interactions it is of critical importance when defining standards that apply to particular domains or applications. For example, clear distinctions between medical and assistive robotics are required to ensure that standards that depend on these definitions minimise grey areas of application. Similarly, it may be important to distinguish between classes of machine, and in particular level of “degree of autonomy”.

Standardising complex robot processes

There are a number of advantages that will stem from being able to standardise the description of complex processes notably the ability to establish conformance across different products which may apply alternative techniques and methods, or to allow subsidiary standards to be defined that relate to common sub parts of common processes. For example a complex process that involves producing a particular surface finish on an item may need to include the standards appropriate to that surface finish, e.g. in a adhering to a particular surface hygiene standard.

Further opportunities exist in the following areas:

- Standard (languages) for describing complex processes (similar to BPMN for business processes)
- Classification of complex processes
- Setting of quality reference levels (maybe in combination with benchmarking studies or competitions)

6.1.4.5 Standardising Human-Robot Interaction

One of the most important areas where standardisation is needed in order to drive both regulation and certification is in physical human-robot interaction (pHRI). An important distinction in pHRI is between direct and indirect pHRI: in the former, the user and the robot are directly in contact (e.g. human hand touching robot's gripper), while in the latter the contact happens indirectly through an intermediate object (e.g. hand-over of a tool between human and robot). In order to execute such actions degrees of context awareness are required that will be application specific. In most cases robots will be required to maintain appropriate margins of safety while performing these types of interactive actions. Also of importance is that users must be able to understand the actions of the robot and interpret its next action correctly. Relevant standards in this context are for pHRI and include ISO 9241-920:2009 and ISO 9241-910:2011 for tactile and haptic interaction. In the limit a balance may need to be struck between overriding safety requirements and socially acceptable interaction. Humans may need to learn to interact with robots differently to the way they interact with people.

In case of Human Robot Safe Interaction (HRSI), spatial constraints such as human-robot distance, velocity, direction, etc. need to be taken into account, both for mobile platforms and static bases with movable extensions (e.g. robotic arms). In general, the use of spaces shared by the robot and the user should be regulated by a sets of expected motion behaviours that guarantee safety and effectiveness of the intended interaction. Other interaction modalities may also need to be standardised, particularly in high risk or hazardous environments, for example voice communication, lights and warning sounds, or particular gestures or graphical displays by the robot. Relevant standards that consider taxonomies of cultural and linguistic adaptability of user requirements (ISO/IEC TR 24785:2009), gesture-based interfaces (ISO/IEC 30113-1:2015 and ISO/IEC DIS 30113-11), as well as voice commands (ISO/IEC 30122-1:2016 and ISO/IEC 30122-4:2016) are important. Ergonomics standards related to dialogue principles (ISO 9241-110:20060) could also apply in design of the HRIs.

The presence of robots in human centred environment is challenging with regard to safety and mutually comfortable coexistence, particularly such that the latter does not compromise natural human behaviours. Some of the key aspects to take into account for standardization in HRI are the following:

- *Standardising robot's spatial behaviours in response to human presence:* Despite the large number of navigation algorithms available for mobile robots, in many social contexts they often exhibit inopportune motion behaviours near to people, often with very "unnatural" movements due to the execution of segmented trajectories or the sudden activation of safety mechanisms (e.g. for obstacle avoidance). Standardised methodologies and tools are necessary to formalise spatial interactions between robots and humans, and to design complex robot behaviours that balance both safety and the social acceptability of HRSI.
- *Standardising robot's noise level for robots in human environment:* The noise generated by the robot as a machine is part of the human-robot interaction and important in the long term acceptance of robots in various types of environments. For the industrial environment, the revision of ISO 10218-2 will include an annex on noise level limits.
- *Standardising perception for HRI:* For effective HRI, it is very important that the robot is able to perceive its environment and any interaction, within sufficient quality to execute the task. A standardization effort in this direction will improve and accelerate the development of HRI applications. Performance and benchmarking approaches are also pertinent to this issue.
- *Standardising generic and high-priority commands for HRI:* Defining a minimal set of generic commands recognizable by interacting robots, and a minimal set of commands that all robots must execute with higher priority is an important goal. For example, should there be a universally recognised shut-down command?

- *Standardising interfaces for HRI with respect to type of service and media:* While there may be standards for generic interactions standards for specific types of service or for specific user application domains will be required. It is important that these are unambiguous and that there is a consistency between different application domains.
- *Standardising gestures across different cultures:* HRI through gestures has the potential to become an effective form of communication in both directions. However, the use of gestures on human-human interaction can vary greatly across different cultures. It is therefore important to standardize conventions for HRI through gestures which are applicable or at least easily "translatable" between cultures.

6.1.4.6 Environmental impact and life cycle issues for robots and robotic devices

Commercial domestic robotics products (e.g. Roomba and similar household appliances) and future products for the general user and household use (like home assistance robots) will be considered under the WEEE (Waste Electrical and Electronic Equipment) requirements. WEEE products are regulated at EU level and through the implementation of national laws following EU Directives. Recently much attention has been paid to the 3Rs approach (Repair, Remanufacture, Recycle) for some mass products areas such as white household appliances and in the automotive sectors. The 3 Rs are the alternatives to waste disposal (such as landfill).

Given the complexity of robots and the wide range of different parts, a similar approach is likely to be adopted for robotic products. The environmental performance of a product can be evaluated using the Life Cycle Assessment (LCA) methodology. LCA is dealt with by the ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework standard. Also the European manual called ILCD provides guidance to the implementation of LCA studies.

6.1.5. Main international robot standardisation projects

The main active robot standardisation projects are presented in Table 3.

Table 3: Ongoing international projects on robot standardisation

Name of Work group (WG)
ISO TC299/WG1: Vocabulary and characteristics
ISO TC299/WG2 Personal care robot safety
ISO TC299/WG3 Industrial robot safety
ISO TC299/WG8 Service robots
ISO TC299/JWG9 Medical robot safety; this comprises: • Jointly with IEC TC62 SC62A: JWG9 Safety for medical electrical equipment and systems using robotic technology • Jointly with IEC TC62 SC62D: JWG35 Medical robots for surgery • Jointly with IEC TC62 SC62D: JWG36 Medical robots for rehabilitation
ISO TC299/WG6 Modularity for service robots
ISO TC199/WG12 Human-machine interactions

IEEE Standard ontology for robotics and automation
IEC TC59 SC59F/WG5: Surface cleaning robots

Relevant robot standards and documents

- ISO 8373:2012 Robots and robotic devices -- Vocabulary
- ISO 9283:1998 Manipulating industrial robots -Performance criteria and related test methods
- ISO 9409-1:2004 Manipulating industrial robots - Mechanical interfaces - Part 1: Plates
- ISO 9409-2:2002 Manipulating industrial robots - Mechanical interfaces - Part 2: Shafts
- ISO 9787:2013 Robots and robotic devices - Coordinate systems and motion nomenclatures
- ISO 9946:1999 Manipulating industrial robots - Presentation of characteristics
- ISO 10218-1:2011 Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots. Harmonised standard
- ISO 10218-2:2011 Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration. Harmonised standard
- ISO 11593:1996 Manipulating industrial robots - Automatic end effector exchange systems - Vocabulary/presentation of characteristics
- ISO 12100:2010, Safety of machinery - General principles for design - Risk assessment and risk reduction
- ISO/TR 13309:1995 Manipulating industrial robots - Informative guide on test equipment and metrology methods of operation for robot performance evaluation in accordance with ISO 9283
- ISO 13482:2014, Robots and robotic devices - Safety requirements for personal care robots. Harmonised standard
- ISO 13849-1:2006, Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design
- ISO 14539:2000 Manipulating industrial robots - Object handling with grasp-type grippers - Vocabulary and presentation of characteristics
- ISO TS 15066:2016, Robots and robotic devices - Safety requirements for industrial robots - Collaborative operation; under development.
- ISO 18646-1:2016, Robotics - Performance criteria and related test methods for service robot - Part 1: Locomotion for wheeled robots.
- ISO/WD 18646-2 Robotics – Performance criteria and related test methods for service robots – Part 2: Navigation
- ISO/DIS 19649 Robotics – Vocabulary for mobile robots
- ISO/NP TR 20218-1 Robotics – Safety requirements for industrial robots – Part 1: Industrial robot system end of arm tooling (end-effector)
- ISO/NP TR 20218-2 Robotics – Safety requirements for industrial robots – Part 2: Industrial robot system manual load stations

ISO/CD TR 23482-1 Robotics – Application of ISO 13482 – Part 1: Safety-related test methods

- ISO/CD TR 23482-2 Robotics – Application of ISO 13482 – Part 2: Application guide
- IEC/DTR 60601-4-1 Medical electrical equipment – Part 4-1: Guidance and interpretation – Medical electrical equipment and medical electrical systems employing a degree of autonomy

- IEC/NP 80601-2-77 Medical electrical equipment – Part 2-77: Particular requirements for the basic safety and essential performance of medical robots for surgery
- IEC/NP 80601-2-78 Medical electrical equipment – Part 2-78: Particular requirements for the basic safety and essential performance of medical robots for rehabilitation, compensation or alleviation of disease, injury or disability

Key standardisation targets

Table 4 Key targets of robot standardisation

Technology	Short-medium term	Medium-long term
1. Safety	Produce normative human safety related data based on scientific research and benchmarked in several EU countries and outside	Safety standard for the Human robot physical contacts interaction published (with a strong EU contribution) European products design and developments already in line with the Standard All EU products certified
2. Vocabulary	Contribute to harmonisation of robot vocabulary and ontologies	Update as domain evolves
3. Performance	Benchmark safety Benchmark performance	Benchmark modularity
4. Modularity	Support EU contributions to ISO TC299/WG6 as well as involvement of industry (& SMEs) and researchers	International standard published with a strong European contribution European products design and developments already in line with the Standard All EU products certified
5. Boundaries	Clarification of boundaries between industrial, service and medical-nonmedical	Clarification of boundaries to all other robot domains Revision of essential terminology like “robot” and “autonomy”
6. Complex processes	Clarification of the system description methods Setting of quality reference levels for complex robot output (processes) so users are able to quickly estimate the abilities of new robotic systems	Definition of basic standards of safety and performance Classification of research project results to achieve comparability, visibility and impact. Production engineers shall be able to compare, rate and evaluate results and establish regulatory support for real world applications
7. H-R interaction	Action to start a new ISO WG (including social interactions) as	International standard published with a strong European contribution

	well as supporting involvement of industry (& SMEs) and researchers	European products design and developments already in line with the Standard All EU products certified
8. Environmental impact	Introduce the 3Rs (Repair, Remanufacture, Recycle) approach and the use of related tools for LCA and Ecodesign for robotics Educate and support the industry, the SMEs, the research community in adopting this approach	All robotics products from EU companies (or sold in the EU) are designed, developed according to the 3Rs approach including LCA

6.2 MAR Technology Readiness Levels (TRLs)

The titles for each TRL level are taken from the definitions in agreed Horizon 2020 documentation. The titles used for each level are generic and it is not obvious how to apply them to the development and realisation of robotics technology products and systems. The following expands the Horizon 2020 terminology and is followed by a series of basic examples to further clarify the intent at each level.

The exact interpretation of each TRL depends on the focus of the deliverable it relates to. In order to provide some standard interpretation it is necessary to consider the types of project deliverable that might require the assignment of a TRL:

- Technology developments delivered as a module.
- Software modules delivered as part of a system.
- Systems consisting of multiple integrated technical elements.
- Platforms developed for a specific application.
- Deployed systems consisting of multiple platforms and support systems.

These different types of deliverable will need different interpretation of the levels and will progress through the levels at different rates. In addition there will always need to be a further degree of interpretation within each project depending on the types of test environment used, the ability to meet end user requirements and on the TRLs of the component parts of each system. It should be recognised that TRLs only apply to whole systems or to modules within a system and that the TRL of a whole system can never be greater than the lowest TRL of its component parts.

When assessing TRLs within a proposal it is important to carefully examine the cost of moving up the TRL scale as, typically, costs increase exponentially with TRL. For example, moving from TRL 0 to TRL 1 may only require the cost of a PhD student for a couple of years. While moving from TRL 8 to TRL 9 may well cost millions of euros. Even a small product may cost €2-3m to bring to market, and larger systems will cost multiples of this. As a very rough rule moving from one TRL level to the next can cost between 5 and 10 times the cost of the previous step (i.e the cost of moving form TRL5 to TRL6 will be 5-10 times the cost of moving from TRL4 to TRL5). This should be considered when claiming more than one or two TRL increments during a project life time.

It is also important to consider the outcomes required at the completion of each TRL step. Projects may stay at one TRL step for a significant part of the project duration and only achieve the upwards step at the end of the project. As a result it can take 10-20 years for an idea or product to move from TRL2 to TRL9.

Level 1 - Basic Principles Observed

Idea development: *Basic technology research*.

Technical feasibility is assessed, basic principles are laboratory tested, technology requirements established, comparative reviews conducted, similar technology in other areas of use assessed.

Outcome: Technically detailed document which describes a product, application, technical feature or module and indicates the potential market requirement and likely technical requirements. Typically includes a detailed functional description, customer benefit analysis, ideas for realisation, and a detailed technical progression plan.

Level 2 - Technology Concept Formulated

Concept Formation: *Basic technology research*.

Proof of principle developments including all engineering and systems development (e.g. algorithm development, physical schematics, and simulations). Critical parts of the system are tested in laboratory conditions to show how the technology operates and to provide insights into functional and practical limitations. Assessment of the integration between the proposed components.

Outcome: Bench demonstration of key technical concepts. Concept formulated with details of potential technical and development risks, including estimated resource requirements and test planning. Understanding of the design and engineering parameters and their inter-relationships with the desired system parameters and key requirements.

Level 3 - Experimental Proof of Concept

Experimental Development: *Technology development*.

Key technical elements developed as sub-systems to allow assessment of the core ideas and test practical realisation. Realisation of parts of the concept to assess the product (e.g. computer simualtion models, physical models, assessment of user interaction, consideration of deployment etc.). Bench development of key technical elements, features or modules able to validate the viability of the concept within the application parameters. Benchmark testing of system or module performance and comparative assessment with existing systems.

Outcome: Results and demonstrations that the concept is technically feasible, a first set of modules or components have been develop and tested to show performance compatible with the requirements. Interfaces developed between module and within systems. Detailed future technical scope of work identified.

Level 4 – Technology Validated in Laboratory

Experiment: *Laboratory demonstration*

Technology is demonstrated in a laboratory or development testing environment where testing parameters are designed to demonstrate the limits of the technology with respect to the requirements. Testing of system or major sub-systems validated against established technical benchmarks relevant to the end user. Testing of internal and external inter-connectivity and integration between components in the system. Demonstration and understanding of the impact of the underlying design and engineering parameters on system performance. Initial normative testing with trained users to provide initial usability information.

Outcome: Demonstration that the technology is expected to scale to achieve end user relevant technical requirements or shows sufficiently improved performance, over existing systems, using established benchmarks. Usability testing results providing insight into areas for future development and their prioritisation. Clear plan for integration and identification of technical risks and their potential impact and severity. Documentation of technical development plan.

Level 5 – Technology Validated in Relevant Environment

Laboratory based prototype: *Laboratory Validation*

Integrated system developed to perform in an environment that exhibits the main features of the expected operating environment. Performance is sufficient to validate that the technology could scale to achieve useful function in the intended application area. System contains all critical technical elements but not in the desired form factor (shape, size, power consumption etc.). Core functionality of product, feature or module can be demonstrated within system and operational context.

Outcomes: Identification and prioritisation of the major technical and application risks for the realisation of the product, feature or module. Performance characteristics are well understood. Clear evidence is delivered that the different technical components can be integrated into a unified component or system and can perform the intended function.

Level 6 – Technology Demonstrated in Relevant Environment

Functional system: *External technology demonstration*

Main functions perform sufficiently close to requirements such that technology can be validated in an environment that is equivalent to the operational environment. First field trials can be conducted when supported by developers to gain fine grained insight into the issues of product, feature or module development.

Outcomes: The main functionality of product, feature or module can be demonstrated in a realistic environment under realistic test conditions. The concept is realised to a degree such that there is good usability and impact data, gathered from developer supported customer trials. System design documentation is complete. Expected development plan is complete including a detailed technical progression.

Level 7 – System Prototype Demonstration in Operational Environment

Engineering Prototype : *Product prototype*.

System performance is close to the end product, feature or module end user requirement. Development of prototypes with final technology sub-systems or close equivalents in a near to complete form factor (size, weight, power consumption etc.). All functionality required in the end system is capable of being demonstrated. Customer verification trials (independent of developer support) carried out.

Outcomes: Significant reduction in technical risk. Product operation validated in actual end user environments. Product prototypes realised in close to final form and function. Plan developed for manufacture and deployment including full product testing and certification plan.

Level 8 – System Complete and Qualified

Production Prototype: *Close to market development*

Development of production prototypes with final functionality and form factor. System is sufficient for end user testing in limited launch markets over extended periods of operation. Initial batch production of the product using end manufacturing processes for most parts. Product material and functional quality is at production levels. Product certifiable for use in chosen market.

Outcome: Product validated for manufacture through extended customer trials, failure mode analysis complete. Certification obtained. All production processes validated and process variations assessed and tested. Full materials and part specifications complete. Product test data validated against end user requirements. Manufacturability fully assessed.

Level 9 - Actual System Proven in Operational Environment

Product Completed: *In production*

Set up of production facilities, production test systems completed, volume components sourced.

Outcomes: Series production and sales.

6.2.1.1 TRL Examples

TRL Level	Example Flying Inspection Robot	Example: Stroke Rehabilitation Robot	Example: Shared Assisted Living Robot
TRL 1	High Energy density propulsion system	Mass individualised stroke rehabilitation	Economically feasible assisted living support robot through shared use
TRL 2	Long duration flight capability using small flying robots	Method of safely adapting support and / or resistance for leg exercises	Concept for determining maximum utility tasks that can be achieved with minimum time and minimal robot functionality.
TRL 3	Realisation of long duration jet propulsion unit	Development of exoskeleton for adaptively supporting exercise	Development of an assessment system for determining maximum utility tasks that can be achieved within a given timescale and robot resources.
TRL 4	Development of long flight duration flying robot under tele-operation control	System for additive exercise, including motivational video feedback, tested with healthy volunteers	Development of a robot for efficiently undertaking maximum utility tasks in a lab from a limited range of tasks
TRL 5	Development of flying robot unit with ability to identify and follow wires in a relevant environment	System for assessing and applying clinically valid exercise regimes developed with clinician support and tested in a relevant environment	Development of a robot that assesses potential tasks to be undertaken in a relevant environment and performing those which achieve maximum utility for the user within a fixed time
TRL 6	Outdoor tests of flying robot capable of following high tension cables with manual supervision	Full system tested in limited clinical setting with close engineering and clinician support	Full system tested in an individual home setting with engineering support.
TRL 7	Testing of high tension cable inspection robot capable of following cables and collecting detailed data on anomalous areas	Full (improved) system tested in a clinical setting with limited engineering support and thorough clinical analysis compared with standard techniques.	Full system tested by a service provider in sequential multi-home settings with multiple use in each home. In depth user satisfaction studies performed.
TRL 8	Testing by utility company and developer of autonomous high tension inspection robot capable of being deployed and recovered by support vehicle	Full system linked to patient database available to trained clinicians for long term rehabilitation trials.	Full system deployed by service provider in long term tests with user driven robot request and allocation system.
TRL 9	Autonomous long duration high tension cable inspection robot commercially available	System available to clinicians and home users on a commercial basis.	Full system available to lease by local care authorities.