Robotics 2020
Multi-Annual Roadmap

For Robotics in Europe

Call 1 ICT23 – Horizon 2020

Initial Release B 15/01/2014

Rev B: *TRL Examples updated; expanded roadmap structure section; table of contents added; text formatting changes.*

Contents

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 will be updated annually as priorities, technologies and strategic developments shape European research development and innovation (R&D&I). The annual update will follow 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.

Robotics is a diverse field and this roadmap relies on expert opinion in each domain and technical field to provide and verify the information within it. The annual review process will examine each key technical and market area to ensure material is brought up to date at least once per annum. This document and its associated Wiki provide a framework through which this additional information can be accessed.

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 then contributing to the Wiki and the associated Topic Groups.

1.1 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.

This document provides a detailed analysis of the development and application of robotics technology. It reviews robotics technology, market place and the business and academic infrastructure needed to create a viable robotics market in Europe.

The Roadmap provides a focal point of contact with the European Robotics community allowing both experts and non-experts to to engage with the community and understand and access information and resources.

1.2 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 are 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 startups 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 Roadmap Structure

The roadmap is divided into three main sections:

- Market Domains (mentioned in Call 1 ICT23 - 2014)
- System Abilities
- Technology clusters

There is considerable cross linkage between the information in each of these sections. Familiarity with the framework of description in the Strategic Research Agenda will be critical to understanding the content of each section.

1.3.1. Market Domains

This section details each of the Market Domains referenced in Call 1 (ICT23 - 2014). It provides background detail about each domain, and describes the currently perceived opportunities in that domain. Each section also outlines the requirements for technical capability and systems ability levels needed to impact on products.

In each section there is a brief overview of Europe's place in the domain, the types of stakeholder within Europe and a list of sub-domains and their opportunities. Key barriers to deployment are also outlined.

This background information should be sufficient to identify how a proposal might impact on a domain, or sub-domain, and indicate the dependence of a domain on particular technologies or system abilities.

1.3.2. System Abilities

Each of the system abilities is described in detail without reference to particular domains or applications. Abilities capture the generic characteristics of whole systems.

Each ability is also defined in terms of levels, each domain or more likely each type of application will have requirements for levels of ability.

Each ability level will in turn require an integration of multiple technologies to achieve a level of ability. Each technology will need to reach a capability, in the context of the task, in order to achieve a particular ability level.

Each ability section also lists key targets whereby achieving that target is expected to have a significant impact on markets and applications. Given that the objective of R&D&I investment is to raise these ability levels it is important to identify current ability levels and to identify the ability levels targeted at completion.

1.3.3. Technology Clusters

The different robotics technologies are divided into clusters, as detailed in the Strategic Research Agenda. In each technology section a brief overview of the techniques and methods used is given and an outline of the scope of the technology. It is inevitable that there will be some overlap at the boundaries between technologies.

The technology sections also detail step changes in technical capability that are expected to have an impact on markets and applications together with a review of benchmarks and metrics that may be able to indicate the current state of the art. Reviewing this impact and targeting step changes with broad impact will be an important part of achieving strategic objectives.

In many cases step changes in technology depend on progress in other technologies and in turn these step changes impact on other technologies and system abilities. There is also a brief indication of the impact on domains.

1.3.4. Targets and TRLs

In both the ability and technology sections targets are set. In the domain sections requirements are given for ability levels and technology capability. The goal of the closer to market funding in Horizon 2020 is to bring about step changes and a rise in ability levels that will impact on the market by bridging the gap between requirement and capability.

It is also important to measure the Technology Readiness Level of each technical step or ability level within each application or domain. To implement a technology in a product, by definition, requires that technology to be at TRL9. However raising a technology to that level will first require the development of techniques to bring it to TRL2, 3, 4, etc. It is also possible that this may only be achieved within a narrow domain of application. Although is some cases step changes will be generic and impact across many areas of application. In the context of assessing impact and the value of research it is important to understand that Ability Levels, Technology Steps and TRL levels all measure different aspects of progress.

1.4 Background

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 underlies this roadmap.

The SRA also acts as an introduction to the European robotics community for non-robotics specialists, policy makers, entrepreneurs and industries intending to use robotics technology or work within the robotics market.

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

Through the actions of euRobotics aisbl with inputs from the Topic Groups set up by euRobotics this document will be updated annually to maintain its relevance.

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 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.

This Roadmap will be reviewed and updated during the lifetime of Horizon 2020 for the following reasons:

- To reflect changes in strategic priority within the European robotics community.
- To reflect market and technology advances.
- To reflect changes in European strategy and direction.

1.4.1. Introduction to the PPP

The robotics Public Private Partnership (PPP) between the European Commission, the public side, and the robotics community, represented by euRobotics aisbl, provides the mechanism for implementing strategy within Europe.

euRobotics aisbl provides a forum for the robotics community to develop strategy and promote its needs both in terms of technology and resource to the Commission so that funding might be directed to ensure a vibrant and successful industry develops to the benefit of Europe and its citizens.

The European Commission and euRobotics aisbl members have joint responsibility for setting and prioritising R&D&I goals. This change combined with the shift in emphasis of Horizon 2020 closer to market led activities, and the establishment of instruments to support this, is reflected in the strategic emphasis of the robotics community.

This document sets out an aligned roadmap covering technical and application objectives. It represents a consensus viewpoint for the direction robotics must take in the coming decade.

1.4.2. Introduction to Horizon 2020

Horizon 2020 is the eighth European Framework Program. It builds on the success of the seventh Framework Program (FP7) while attaching greater importance to innovation and wealth creation resulting from research. Robotics continues to provide a strategic focus within Horizon 2020.

The shift in focus within Horizon 2020 closer to market is illustrated by the introduction of new funding instruments that enable near to market collaborative projects.

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

- Military

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

{Note: This release of the MAR is designed to cover Call 1 (ICT23) of Horizon 2020 and as such only elaborates the domains detailed in the first call}

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.

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

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.

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.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.

Manufacturing Sub-Domains:

2.2.10. Production

2.2.10.1 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.

2.2.10.2 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.

2.2.10.3 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.

2.2.10.4 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.

2.2.11. Food

2.2.11.1 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.

2.2.11.2 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.

2.2.11.3 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.

2.2.11.4 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 €1,017 billion
- 14.5% of household expenditure
- Exports €76,.2 billion
- Trade balance € 13.2 billion
- 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.}

2.2.11.5 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.

2.2.12. SME Manufacturing

2.2.12.1 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.

2.2.12.2 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.

2.2.12.3 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.

2.2.12.4 Barriers to Market

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

2.2.13. Soft Products

2.2.13.1 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.

2.2.13.2 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.

2.2.13.3 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.

2.2.13.4 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.

2.2.14. Craft and Bespoke

2.2.14.1 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.

2.2.15. Key System Ability Targets

2.2.15.1 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 for a wider range of mechatronic options that are user configurable.*
Introduction of Intuitive programming methods:	*Configurability Level 2*
Standardised interfaces for modular controller software:	*Configurability Level 3 for software configuration in plug and play architectures.*
Autonomous configuration of safeguarding strategies:	*Configurability Level 4 coupled to Safety Interaction ability at Level 3/4.*

2.2.15.2 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:	*Adaptability Level 3 - Process chain adaptation.*
Self-learning robot utilising reasoning algorithms:	*Adaptability Level 4 - Task Adaptation coupled to Cognitive reasoning ability Level 3 - Basic Environmental Reasoning.*

2.2.15.3 Interaction Capability

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.

Intuitive Human Robot Interfaces for use and configuration, teach or specify task using domain specific terminology:	*Human Interaction Level 4 - Domain Specific Interaction.*
Safe physical interaction.	*Safety Interaction Levels 3-6 depending on the level of operator risk.*
Autonomous interaction with other robots:	*Robot to Robot Interaction Level 4 - Team Communication.*
Learning through human-robot and robot-robot interaction.	*Cognitive Human Interaction at Level 4 - Constrained Command interaction, Knowledge Acquisition at Level 6 - Knowledge scaffolding, and Robot Robot Interaction at Level 5 - Team Co-ordination for Communicated Adaptation between systems.*

2.2.15.4 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 4 - Task dependability*
Self-maintenance between robots.	*Dependability Level 4/5 - Task/Mission dependability coupled to Robot Robot Interaction Level 5 - Team Coordination.*
Maintenance performed robots in hazardous places:	*Cognitive Action Ability Level 7 - Success Driven Action coupled to Robot Robot Interaction Level 5 - Team Coordination.*

2.2.15.5 Motion Capability

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.

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

fixturing, etc:	*arm.*
Mode Switching, from flexible motion (Human Interaction) to fixed motion (Autonomous), e.g. variable stiffness, controllable stiffness:	*Motion Capability Levels 7-9 provide for dynamic motion control.*
Motion planning for HRI vs. motion planning for autonomous operation, plus orderly transitions between the two:	*Motion Capability Levels 7-9 provide for dynamic motion control.*

2.2.15.6 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 2 - Tolerant pick and place. Some systems exist at Level 3 but without wide deployment.

Manipulation of flexible objects:	*Cognitive Object Interaction Level - Property Identification coupled to Level 8/9 of object perception, and Level 5 envisioning ability.*
Free-form, shape-adaptable manipulators and grippers:	*Level 5-8 of manipulation ability*
Human-robot collaborative manipulation, load-sharing:	*Level 3-5 of Human Robot interaction.*
Robustness in the face of uncertainties.	*Cognitive Reasoning Level 5 - Reasoning with conflicts.*

2.2.15.7 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 - Marker sensing, a limited number are at Level 3 - Multi-Parameter Sensing.

Standardised data model for robot, application, environment, etc:	*Cognitive Knowledge Acquisition Level 6 - Knowledge scaffolding.*
Integration of multiple sensors:	*Perception Ability Level 3 - Multi-Parameter Perception.*
Classification of status of perceived information, e.g. quality information,	*Dependability Level 4 - Task dependability.*

error conditions, etc:	
Context-aware perception to reduce uncertainties	*Perception: Object Recognition Level 6: Context Based Recognition*
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.*

2.2.15.8 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

Reacting to perceived status of application (error condition, production conditions, etc.)	*Decisional Autonomy Level 6 - Constrained task autonomy.*
Online rescheduling of tasks in HRI scenarios based on task, ergonomic and safety information.	*Decisional Autonomy Level 6 - Constrained task autonomy coupled to Safety Interaction Level 4 - Work Space Detection.*
Energy efficiency criteria for path planning:	*Decisional Autonomy Level 6 - Constrained task autonomy*
Decentralised production knowledge and decision-making instances to augment robustness of manufacturing task:	*Decisional Autonomy Level 10 - Distributed Autonomy and Robot Interaction Levels 3-6 depending on system complexity.*
Self-evolving systems capable of autonomous manufacturing decision making:	*Decisional Autonomy Level 10 - Distributed Autonomy coupled to Cognitive Reasoning Ability Level 8, and Knowledge Acquisition levels 9-11.*

2.2.15.9 Cognitive Abilities

In the context of manufacturing, the greatest potential is for functions which 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 of Acquired Knowledge, Level 2 for Human Interaction, Level 1/2 for Interpretive ability, Level 3 for Action ability, Level 1/2 for envisioning, Level 2 for Reasoning.

On the fly exchange of hardware (robot) (enabled by abstracted task	*Configuration ability Level 3/4 coupled to Decisional Autonomy levels 5-7*

representation with context-aware self-configuration).	
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 4 - Domain Specific Interaction coupled to Knowledge Acquisition Level 4-6.*
Cloud-based cognition with access to remote robot experience and ability:	*Cognitive Knowledge Acquisition Level 7 - 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 Knowledge Acquisition Level 7 - Distributed Knowledge*

2.2.16. 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.

2.2.16.1 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

2.2.16.2 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 replanning (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

2.2.16.3 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).

2.2.16.4 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

2.2.16.5 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

2.2.16.6 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)

2.2.17. 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.

2.2.18. 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 a 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 Agriculture Domain

2.3.1.1 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".

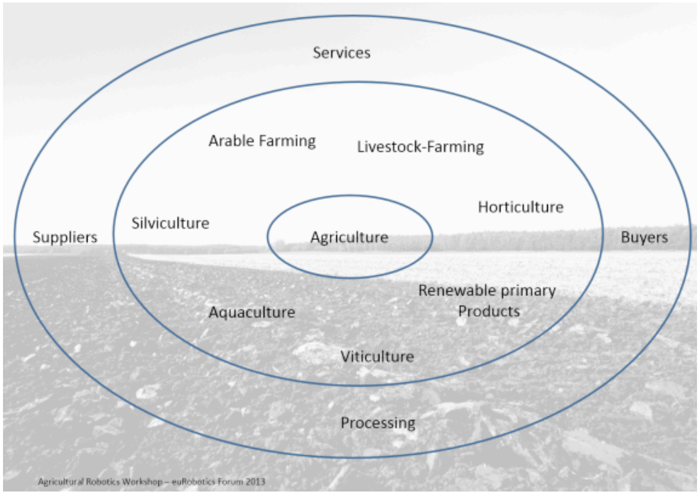

Figure 1: Simplified structure of agricultural production categories

Several interrelated drivers make agriculture a challenging business:

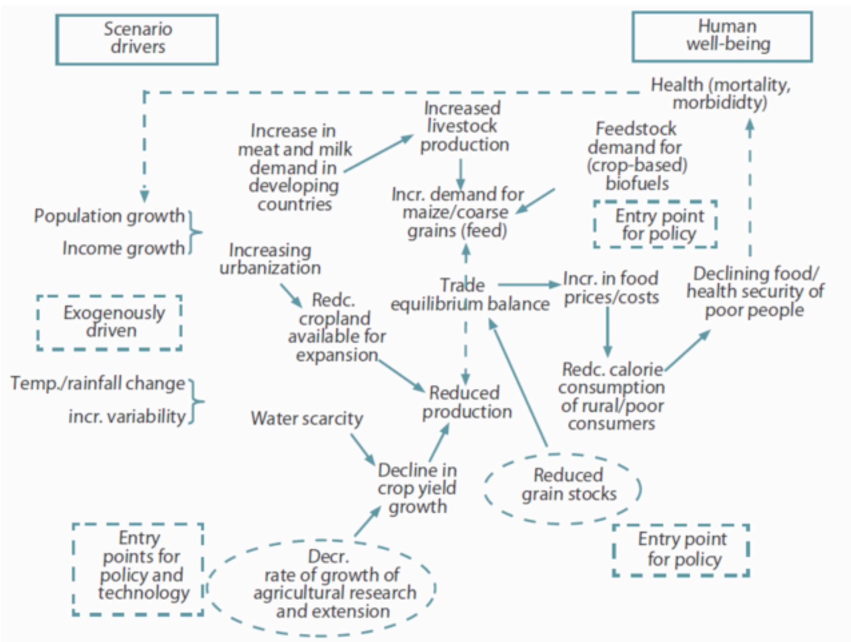

Figure 2: Interrelationships among key drivers of change in food systems, and their connection to human well-being

{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 7 Bn. to an estimated 10 Bn. 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 1.4 Bn. 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).

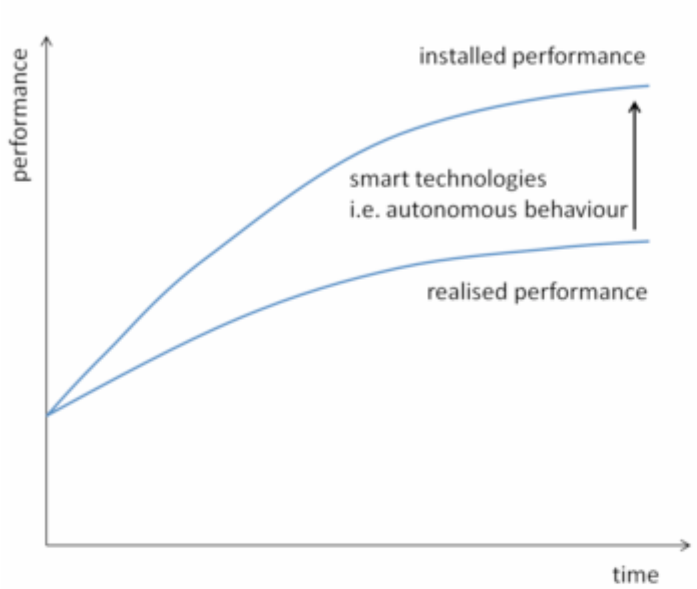

Figure 3: Gap between installed and realised performance

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?

2.3.1.2 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.

2.3.1.3 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.

2.3.1.4 Key Market Data

In 2007, gross value added in the agriculture sector amounted to €16.0 Bn. (production value €46.3 Bn; intermediate inputs €30.3 Bn) . 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 sideline. 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 €96 Bn. 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 €30 Bn can be assigned to the robotic market.

World production agricultural machines (VDMA, 2013 estimated)	*€96 Bn.*
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	*170 Mn. ha*

Table 1: 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

Table 2: 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 4 "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.

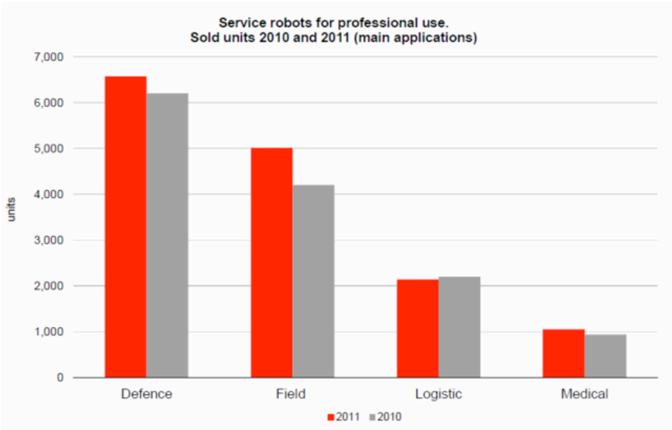

Figure 4: Source IFR statistical department

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.

2.3.1.5 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.

2.3.1.6 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 sen 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 1.5 €Bn. (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.

2.3.1.7 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 € 28 Bn. 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.

2.3.1.8 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 biofules 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 Saftety-Level of autonomous agricultural vehicles during process in terms of threads to humans, animals and tangible goods. 4 different types of sensors are combinde. 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

2.3.1.9 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 instaled 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:

2.3.2. Agriculture

2.3.2.1 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.

2.3.2.2 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 abel to selectively harvest ripe produce and those able to recognise the early signs of pest infestation or disease and selectively respond. Systems abel 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.

2.3.2.3 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.

2.3.2.4 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.

2.3.3. Forestry

2.3.3.1 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.

2.3.4. Fisheries

2.3.4.1 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.

2.3.5. Key System Ability Targets

2.3.5.1 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*

2.3.5.2 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.	*Adaptation Level 3-5*
Adapt to the long term dynamics in the farm cycle.	*Adaptation Level 3-5*
Adaptation to crops, new crops or sizes.	*Adaptation Level 3-5*

2.3.5.3 Interaction Capability

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*

2.3.5.4 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.	*Certification and Classification of Safety Levels* *{Note: This requires environmental safety guarantees}*
Proof of dependability	*Dependability: Certifiability Target*

2.3.5.5 Motion Capability

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	*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*

2.3.5.6 Manipulation Ability

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

Ability to control force and manipulate crops.	*Motion Capability: Level 5 Force constrained motion*
Livestock manipulation	
Handling of soft and delicate items e.g. Fruit harvesting.	

2.3.5.7 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 10 Animate Objects*

2.3.5.8 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 7 Multiple Task Autonomy.*

2.3.5.9 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	*Action Ability: Level 6 Plan driven actions*

planning based on Farmers Assistant.	
Autonomous experimentation with new strategies.	*Acton Ability: Level 7 Dynamic planning*

2.3.6. Key Technology Targets

2.3.6.1 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.

2.3.6.2 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.

2.3.6.3 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.

2.3.6.4 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.

2.3.6.5 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.

2.3.6.6 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.

2.3.7. 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 an non-expert user) to the current needs.

2.3.7.1 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.

2.4 Civil Domain

2.4.1.1 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.

2.4.1.2 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.

2.4.1.3 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.

2.4.1.4 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 $1,546 million 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 $1.96 Billion by 2017. The potential market in Europe for Unmanned Aerial Vehicles over the next 10 years could amount to about €11B. 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 £30 Bn. 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.

2.4.1.5 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 teleoperated robotics, aerial and space robotics markets.

2.4.1.6 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 150 Kg.

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.

2.4.1.7 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.

2.4.1.8 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	
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)*

2.4.1.9 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:

2.4.2. Civil Infrastructure

2.4.2.1 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.

2.4.2.2 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.

2.4.2.3 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.

2.4.2.4 Key Market Data

Annual exploitation costs for the 58 French reactors were estimated to 8.9 billion euros in 2010. At the same date, dismantling costs were estimated to 18.4billion euros. 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 £50 Bn 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.

2.4.2.5 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.

2.4.3. Search and Rescue

2.4.3.1 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.

2.4.3.2 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.

2.4.3.3 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.

2.4.3.4 Europe’s Place in the Market

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

2.4.4. Environment

2.4.4.1 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.

2.4.4.2 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.

2.4.4.3 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.

2.4.5. Law Enforcement

2.4.5.1 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.

2.4.5.2 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 boarder 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.

2.4.5.3 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.

2.4.6. Emergency Services

2.4.6.1 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 firefighting, hazard reduction, pollution control, and the provision of emergency aid and assistance.

2.4.6.2 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.

2.4.6.3 Relationship to other markets

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

2.4.7. Science Support

2.4.7.1 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.

2.4.7.2 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.

2.4.7.3 Future Opportunity

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

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

2.4.7.4 Relationship to other markets

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

2.4.8. 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.

2.4.8.1 Configurability

2.4.8.2 Adaptability

Real time real-world learning	*Adaptability: Level 4 - Task adaptation*

2.4.8.3 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.*

2.4.8.4 Dependability

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

2.4.8.5 Motion Capability

High speed and agile autonomous driving on uneven and sloping terrains *All terrain high speed and dexterous autonomous driving*	*Motion capability: Level 10 Dynamic motion*

2.4.8.6 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	*Motion capability: Level 10 Dynamic motion combined with Location perception: Level 5 Object coupled*

	location combined with Decisional autonomy: Level 8 Dynamic autonomy.

2.4.8.7 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.*

2.4.8.8 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.*
Adaptability to 3D Structured or unstructured underwater environments	
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

2.4.8.9 Cognitive Abilities

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

2.4.9. 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:

2.4.9.1 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

2.4.9.2 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 marine robots.
- Design of energy efficient autonomous robots for specific environments
- Multi-functional/multi-task and flexible end-effectors.

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.

Actuators

- Energy efficient propulsion systems in multiple environments.
- High efficiency miniaturised underwater propulsion systems
- Deep ocean propulsion systems

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.

2.4.9.3 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

2.4.9.4 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)

2.4.9.5 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 GPS 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.

2.4.9.6 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

2.5 Commercial Domain

2.5.1.1 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).

2.5.1.2 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.

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.

Inspection and Monitoring

There are many different types of inspection an monitoring industry, ranging from the inspection of manufactured parts to the inspection of buildings and land usage. These commercial organisations range from equipment suppliers to individual inspectors and service providers; for example the inspection of domestic drains. Robotics technology has the potential to significantly impact all aspects of this market from the automated inspection of large manufactured parts, to remote camera systems used by builders to assess a roof repair more quickly and completely.

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.

2.5.1.3 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 $10 million 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 €0.75 M per day.

It is clear that robotics technology could have a major impact on these figures warranting significant investment in R&D&I.

2.5.1.4 Relationship to other markets

There are strong links to the system deployed in the Civil domain and it is reasonable to expect common platforms and modules to be developed for both markets.

2.5.1.5 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.

2.5.1.6 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.

3. 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 of robots. Abilities allow the sate of the art to be identified future targets to be set for 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.

3.1 Configurability

3.1.1.1 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.

3.1.1.2 Current Technology Drivers

The following technology areas currently impact on the configurability of a system

- System Design
- System Architecture
- Mechanical Systems
- Human Machine Interface

3.1.1.3 Ability Levels

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.

3.1.1.4 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.

3.1.1.5 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.

3.1.1.6 State of the Art Exemplars

Level 0

Many robot systems in industrial automation employ static configuration. (TRL 9)

Level 1

Many systems exist that utilise start-up configuration based on configuration files or user input. (TRL 9)

Level 2

Many systems can be software configured by the user through a variety of different mechanisms. (TRL 9)

Level 3

Some industrial robot arms are able to change the end effector tool as they progress through different stages of a process. (TRL 9)

3.2 Adaptability

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 to a wide range of elements in 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.).

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.

3.2.1.1 Technology Drivers

The following technology areas impact on the adaptability of a system;

- Learning and Adaptation
- Perception
- Cognition

3.2.1.2 Ability Levels

The following are identified as different levels of adaptation within a robot system. Many current robots operate with little or no adaptation.

Level 0 - No Adaptation

The system does not alter its operating behaviour in response to experience gained over time.

Level 1 - Parameter adaptation

The system alters individual control parameters based on assessments of performance local to the module on which the parameter operates. For example 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 2 - Multiple parameter adaptation

The system alters several control 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 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 - Task adaptation

The task performed during the process cycle is adapted over time to optimise a particular parameter. 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 5 - Communicated 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 or simulated and of different types including non-robotic agents.

3.2.1.3 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 ability 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.
- *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.

3.3 Interaction Capability

3.3.1.1 Description

The ability of the system to interact both cognitively and physically 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.

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 covers three specific areas of interaction:

- Human robot interaction
- Robot robot Interaction
- Interaction safety

Each of these three types of interaction requires a set of ability levels. In a number of application scenarios two or more of these types of interaction ability will be mixed.

3.3.1.2 Technology Drivers

The following technology areas impact on the interaction capability of a system;

- Human Machine Interface
- Human Robot Collaboration
- Communications
- Perception
- Cognition

3.3.1.3 Current Ability Levels

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.

3.3.1.4 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 easer 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.

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.

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.

3.3.1.5 Ability Targets

The primary targets for interaction ability are concerned with providing increasing levels of interaction ability in the three sets of levels. 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.

3.3.1.6 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.

3.4 Dependability

3.4.1.1 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.

3.4.1.2 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.

3.4.1.3 Current Ability 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 the robot to interact with a human in a functional or intuitive manner.

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 3 - 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 4 - 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 5 - 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 6 - 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.

3.4.1.4 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.

3.4.1.5 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.

3.5 Motion Capability

3.5.1.1 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 or sand 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.

3.5.1.2 Technology Drivers

The following technology areas impact on the motion capability of a system;

- Mechanical Systems
- Actuators
- Control
- Perception
- Localisation and mapping

3.5.1.3 Current Ability Levels

The following are a set of ability levels for 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.

Level 8 - Compliant motion

The robot can execute motions that alter 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.

Level 9 - Reactive motion

The robot is able to react to externally applied forces contacting any part of the robot. 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 10 - Dynamic motion

The robot is able to alter its motion strategy in response to multiple external dynamic forces in order to optimise motion parameters. The robot is able to exert a force in a given direction relative to a dynamic body, or within an environmental medium while maintaining position or path.

Level 11 - Soft medium motion

The robot is able to move into and within a soft medium. It is able to maintain a position and path within this medium while optimising motion and force parameters as demanded by the task.

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.

3.5.1.4 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 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 a given force in a particular direction in the air or underwater to another object will also be fundamental to may applications.

- *Transition Environments:* The development of motion systems able to operate in transitionary environments for example in waterlogged ground, mud, sand, gravel etc and in transition between environments, for example between air and water.

- *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 abel 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 importantance 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.

3.5.1.5 Key Barriers

The primary barriers to achieving high levels of motion ability are technology limitations, Actuation technology, high resolution sensors, power densities, mechanical constraints etc.

3.6 Manipulation Ability

3.6.1.1 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)

3.6.1.2 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

Manipulation ability is the result of a combination of the other abilities. As a result each of the levels of manipulation ability relies on particular pre-requisite 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.

3.6.1.3 Current Ability Levels

Level 0 - No Manipulation Ability

Many robots will not require the ability to manipulate objects.

Level 1 - Simple pick and place

The robot is able to grasp an 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-grasping it. The robot may also use its movement ability to move the object in a particular pattern or to a particular location. Grasping uses open loop control.

Level 2 - Tolerant pick and place.

The robot is able to grasp an 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 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.

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.

Level 5 - Location unknown pick and place.

The robot is able to pick up a known object where the location and orientation of the object are not pre-defined. It is able to orient and align the object (this may be achieved without placement) and then place it within the context of a task.

Level 6 - Generic pick and place

The robot is able to pick up an object belonging to a certain parameterised type where the dimensions, location and orientation are unknown. It is able to orient and align the part and place it appropriately in the context of the task.

Level 7 - Object manipulation

The robot is able to pick up and manipulate an object belonging to a certain parameterised type where the object can be 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 Manipulation

The robot is able to pick up an unknown object and determine the generic grasping properties of that object. It is able to use those properties to determine how to manipulate and place the object. The robot may be able to categorise the object based on a set of known object types from its manipulation of the object.

Manipulation parameters

The following parameters significantly affect the assessment of manipulation ability:

- Object scale
- Object shape complexity
- Object properties; surface texture and material (smooth, rough, transparent, soft, hard etc.)
- Object dynamics; Object motion under load, compliance, stretch, flexibility and animate 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.

3.6.1.4 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.
- *Human level dexterity:* Everyday objects have the parameters 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.

3.6.1.5 Key Barriers

The main barriers to manipulation ability vary with application and size scale. Fundamentally they relate to the focusing of other abilities to support manipulation and to mechanical design, actuation and tactile sensing. 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.

3.7 Perception Ability

3.7.1.1 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.

3.7.1.2 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.

3.7.1.3 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
- Recognition ability
- Scene perception
- Location perception

Levels of perception ability

The following levels refer to the generic ability of a system to perceive:

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 - Single parameter sensing

A robot uses sensors that provide a single parameter output. For example a distance sensor, or a contact sensor. The robot utilises these outputs to directly alter behaviour within an operating cycle.

Level 2 - Marker 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 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 that it has detected in the environment through sets of grouped features and can use this identification to alter the system behaviour.

Level 7 - Property identification

The system is able to deduce the properties of objects in the environment 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.

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 - Flexible object tracking

It is possible to identify a flexible or deformable object and track it.

Level 5 - Animate objects

It is possible to identify and track an animate object and extract the pose of the object.

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 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 - 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 8 - 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 9 - 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 10 - 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 11 - 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 12 - Animate Objects

The system is able to detect animate objects and provide a classification appropriate to the task.

Level 13 - Pose estimation

The system is able to estimate the pose of an animate object within the environment.

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.

- *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).

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.

Levels of 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 such as GPS and GLONASS.

Level 3 - 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 4 - 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 5 - Self location

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 6 - 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.

3.7.1.4 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.

3.7.1.5 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.

3.8 Decisional Autonomy

3.8.1.1 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.

3.8.1.2 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.

3.8.1.3 Current Ability 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

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 - 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 6 - 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 7 - 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 8 Dynamic autonomy

The system is able to alter its decisions about actions 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 9 - 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 10 - 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 achieveability 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. 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.

3.8.1.4 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.

3.8.1.5 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 and cognitive ability.

3.9 Cognitive Ability

3.9.1.1 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.

3.9.1.2 Technology Drivers

The following technology areas impact on cognitive ability.

- Systems Design
- Perception
- Human Robot Interaction

3.9.1.3 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.

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.

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.

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.

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.

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.

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.

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.

3.9.1.4 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 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.

3.9.1.5 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.

3.10 MAR Technology Readiness Levels (TRLs)

The titles for each TRL level are taken from the definitions in agreed Horizon 2020 documentation that can be found here:

(http://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf)

However these titles are not obviously applicable to the robotics domain and so the following represent an expansion of terminology and a followed by a series of basic examples to clarify the intent at each level.

Level 1 - Basic Principles Observed

Idea: Basic technology research.
Document elaborated which describes a product / feature idea and/or potential market requirement:
Functional description, customer benefit, ideas for realisation.

Level 2 - Technology Concept Formulated

Concept Formation: Basic technology research.
Proof of principle developments including algorithm development and simulations.

Concept formulated with details on potential development risks, including coarse resource planning.

Level 3 - Experimental Proof of Concept

Experimental Development: Technology development.
Realisation of parts of the Concept to visualise the product / feature idea; proof of concepts, first components and interfaces developed;
lab experiments carried out; future technical scope of work identified.

Level 4 - Technology Validated in Laboratory

Experiment: Technology development.
Testing of system or major sub-systems; validation against established benchmarks;
Testing of internal and external inter-connectivity.
Initial normative testing with trained users possible.

Level 5 - Technology Validated in Relevant Environment

Lab prototype: Internal technology demonstration.
Main functionality of product / feature idea can be demonstrated.
Major risks for the realisation of a future product / feature have been documented as part of the description of the Demonstrator / realisation.

Level 6 - Technology Demonstrated in Relevant Environment

Functional model/First Field Trials: External technology demonstration.
Main functionality of a of product / feature idea is realised at a degree that selected customers can carry out tests, when accompanied by developers.

Level 7 - System Prototype Demonstration in Operational Environment

Engineering Prototype
Development of prototypes with final technology sub-systems or close analogues in a close to complete form factor.
All identified functionality is capable of being demonstrated.
Customer verification trials (independent of developer support) possible.

Level 8 - System Complete and Qualified

Production Prototype
Development of prototypes with final functionality and form factor.
Sufficient for end user testing in limited launch markets.
Initial batch production of the products.

Level 9 - Actual System Proven in Operational Environment

Series production and sales.

3.10.1.1 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.

4. 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.

4.1.1.1 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

4.2 Systems Development

"Better Systems and Tools"

As the processes required to develop robots become established the development and analysis of those processes becomes more important. 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, processes, and design systems 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.

4.2.1.1 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 of ever-increasing functionality becoming more and more available as commodity products from other sectors (mobile devices, communications, automobile driver assistance systems), the success of robotics will crucially depend on the ability to manage the integration of these complex systems into powerful and cheap robots.

As shown in the EFFIROB study,[2] "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 has yet to be properly addressed.

There is a demand for systematic and scientifically backed approaches for a hand-over of robot building blocks for system integration in form of modules with explicated properties from one stakeholder to the next. Such a system of modular integration 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 no support for system development processes (indicative of the lack of overall architectural models and methods).

Lack of decision support for package/module choice with a semantic description (machine interpretable) including additional information such as performance parameters, component level certification or standards met.

[2] http://www.ipa.fraunhofer.de/Wirtschaftlichkeitsanalysen_neuartiger_Servicerobotik-Anwendungen_und_ihre_Bedeutung_fuer_die_Roboti.1643.0.html

Available integration frameworks and middleware are diverse and ultimately narrow in scope. ROS, YARP, OROCOS, Open-RTM, SmartSoft, … are good for particular use, especially when specific functions are known to a developer.

Control theoretical approaches usually focus solely on mathematical models and methods while neglecting capabilities and limitations of both current computer systems and dependent higher-level software.

Safety and complexity of systems (autonomous/cognitive) are non-natively compatible, due to 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.

Explicated resource-awareness and Quality-of-Service attributes are missing. In consequence, one cannot configure or provide robotic systems with resources just adequate and sufficient for an application.

4.2.1.2 Key Techniques and Methods

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, 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

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 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, …)

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.

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.

Simulation and Hardware/Software-in-the-loop

4.2.1.3 Expected Step Changes

Technical step changes:

- New techniques for adding software-intensive components, for plug-and-play of smart devices and smart physical subsystems
- Standardisation (plug and produce as candidate for standardisation, programmability, etc)
- Semantic modelling and re-use of components (link to cognition, standardisation)
- Functional integration of complex systems and simulation of overall system behaviour including HW/SW-in-the-loop techniques.
- Mixed real-time system capability, explicated resource-awareness and Quality-of-Service attributes
- Advanced configuration (from programming to task specification) by user
- New processes for integration instead of adding components as long-term goal ("Science of integration")
- Development of design patterns and the creation of reference architectures.
- The import of best practice in Systems Design technologies from other market domains (e.g. Automotive, aerospace etc).

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).
- Establish Robotics Software Systems Engineering as a science in itself to enable innovation and to help build 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.

Systems Design

- Robot design methodologies that consider system integration
- Unified tools allowing for: graphical design, design verification, code generation, model-based verification, safety-by-design.
- Standardised metrics for robotic component quality
- Requirements engineering
- Methods for automated design/ configuration of robotic applications based on neutral models of production resources, products and processes
- Automated production system design and verification down to the process and control level

Systems Engineering

- 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.
- 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.
- To establish widely used standard interfaces that enable the modular construction of systems.
- Develop strong open source support structures within Europe to enable the wider use of modular systems.
- Definition of developer roles (component developers, system integrators, application experts, framework/ tool developers etc.)
- Software Product Lines: automatic selection of components - Automated testing and verification for components, systems and applications
- Generic process model for cross-market robot software development, providing dependable, safe, configurable, adaptable and reusable applications
- Tools and methods for engineering complexity in multi-robot systems.

Systems Architecture

- Development of modular system architectures with well defined interfaces
- Development of modular architectures able to allow system modification and the provision of additional capability.
- Cross domain architectural solutions and standardised interfaces
- Plug and play component systems
- Architectures based on multifunctional sub system blocks, for example allowing integrated sensing and actuation or multi modal sensing.
- System architectures that inherently support distributed systems components.
- Architectures that work across multiple operating environments and robot configurations.
- Reference architectures for several domains, considering mixed-real time aspects, resource awareness, dynamic deployment, communication topology, open architecture, and service modularity
- Instantiation and tool support for reference architectures (including verification, versioning etc.), support for distributed computing and control (cloud)
- Formulation of fault tolerance requirements - Mechanisms for ensuring fault tolerance, feedback for System architecture

- Architectures considering challenges in areas of security, usability and reliability, scalability, evolvability, human- machine interaction, user acceptance, ergonomics
- General reference architecture, able to be instantiated for different domains addressing the points mentioned under medium term

Systems Integration

- New processes for adding software-intensive components,
- Model-based verification (automatic transition from system design to deployed run-time system)
- Standardisation and integration of physical parts (hardware and mechanics)
- Off-the-shelf components with open interfaces verified on the field or with a significant TRL to base robotics application upon
- Integration of mixed-real-time systems in form of applications

- Reusable software components and model-based design components that meet requirements for industrial applications (safety, security, reliability, timing, throughput, response time, fault tolerance, verified, deployment, scalability, maintainability)
- System integration simulations.
- Methods for the creation of self identifying modules and self configuring systems.
- Methods and tools for implementing multiple instances of a system and adapting it to slight changes in specification
- Validation of such systems in production environment
- Tool support for component compatibility verification (“integration simulator”)

Modelling

- Complete description of mechatronic behaviour by merging mechanical and electrical modelling methods with computer science modelling methods - 100% virtual validation of the system
- Development of domain specific languages
- Models for the entire life-cycle of a robot
- Models for dealing with information and knowledge processing that are fused with models of physical world, involving concepts of time and space
- Multi physics modelling of robot components (fluid, current etc.) - integration in real time control

Knowledge Representation

- Semantic web technology, as already used in some projects
- Reasoning to connect information from different databases (data reflection)
- Standardised semantic description of multi-modal representation of environmental information, robotic resources (ontologies) and production processes
- Resources capable of automatically translating process data into resource-specific operation programs/parameters

4.2.1.4 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, toolchains) 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 an horizontal way.

4.2.1.5 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

Current Key Projects

EU projects

- BRICS http://www.best-of-robotics.org/
- ROSETTA http://www.fp7rosetta.org/
- Former project RoSta http://www.robot-standards.eu/ (still mention?)
- AUTORECON http://www.autorecon.eu

- X-act http://www.xact-project.eu
- National projects:
- iserveU / Service Robotics / BMBF ICT 2020 - Research for Innovations Model-Driven Software Development is being used to implement intelligent modular service-robotics functionalities in everyday environments by the example of a hospital robot
- ROAMFREE (Robust Odometry by Applying Multi-sensor Fusion to Reduce Estimation Errors, funded by Italian Ministry for University an Research, Italy) developed a general framework for robust pose estimation by sensor fusion in mobile robots and the corresponding component (in the form of open source C++ and Python library + ROS node)
- R2P (Rapid Robot Prototyping, funded by Regional and Private funds, Italy) developed an embedded framework for the rapid prototyping of robotics applications through off the shelf, low-cost, robotics components (e.g., motor control, inertial measurement unit, uROSnode gateway, proximity sensors, etc.) and a real-time communication middleware (based on a real-time protocol for CANbus).

4.2.1.6 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 but the application of these tools will allow the resulting systems to have specific properties and abilities resulting from a systematic development processes.

The following highlight the impact that Systems Development technologies can have on the achievement of System ability levels.

Configurability

- Open, standardised and simplified/ automated integration of individual components (e.g. sensors) – zero setup time.
- Fast, software based reconfiguration for a given product range
- Abstract (black-box) modelling of resource requirements, capabilities and variation points. Enhanced system synthesis methods for ensuring smooth system level composition,
- Self-configuring, modular systems capable of autonomously re-arranging the shop floor 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
- Advanced interfaces for enhanced and simplified programming by user

Adaptability

- Multi role capable equipment – Auto-selection of functional equivalent components according to system internal and external environment.

Interaction Capability

- Standardised communication protocols (machine – machine)
- Programming assistants
- Easy monitoring and diagnosis of system - runtime inspection

- Robot to robot contextual transactions for local cooperation in decision making and troubleshooting

Dependability

- Methods for error tolerance when dealing with mixed-real-time systems, application based
- Dependency aware update and maintenance of components and applications (updateability/ maintainability) - Self healing
- Preventive maintenance, in-time detection of imminent failures
- Overarching design patterns / architecture with best practices
- Fully automatic recovery of the system – self repair through changes in production operations or physical system structure

Perception Ability

- Sensorial networks / sensor fusion - real time diagnostics, fault analysis and classification

Decisional Autonomy

- Initial experiments with methods for error tolerance when dealing with mixed-real-time systems, application based
- Resource level autonomy – Selecting and implementing among pre-defined reaction scenarios
- Decentralised, service based control at line level - multi actor and multi-level decision making
- Resource level autonomy – Generating and implementing new reaction scenarios based on previous knowledge

Cognitive Ability

- Generalised, neutral task and resource modelling- Resource programming automatically achieved based on resource and task characteristics
- System architecture allows for smooth integration of cognitive functions with real-time control system and with safety functionalities
- Resources capable of autonomously assigning themselves with the tasks to execute

Programmabilty

Programmability is a system ability that uniquely relates to Systems Development technologies:

- Task-oriented programming, i.e. specification instead of functional text-based programming, (e.g. graphical programming environments, programming by demonstration techniques)
- 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)

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. The following provides an overview of these common linkages which point to the co-development of solutions:

4.2.1.7 Mechatronics

Communications

- Standardised component meta model to allow for better interoperability between different middleware
- Open and standardised communication architectures for integration of new resources with minimal time and effort
- Unified communication architecture/ protocols for all production related equipment from the tool to the production line levels
- Robots integrated into internet of things and making use of big data methods and semantic web technology
  Control
- Neutral format control models. Resource agents/controllers capable of generating/adjusting control setting based on task description

Human Computer Interaction

- Modelling and integrated development of interfaces
- Standard interfaces for human robot interaction, including physical interfaces.

Safety

- Safety by design.

4.2.1.8 Cognition

Cognitive Architectures

- 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.
- 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.

Action Planning

- Intelligent algorithms for the collaborative planning of tasks through real time system status awareness
- Unstructured generation and implementation of reaction plans based on full system reaction capabilities (tool, resource and system levels)
- System architectures that allow for distributed planning

Natural Interaction

- Intelligence in safety mechanisms
- Unification/ simplification of communication (modelling and real) channels between hardware and software
- Process models supporting distributed development and collaboration
- Service Oriented Open Architectures (selection of reconfiguration scenarios)
- Autonomous interaction and negotiation between resources for decision making

4.3 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.

4.3.1.1 Technology Description

Any of the proposed application areas for robotics technology involve human robot interaction. This interaction can take place at a number of different levels ranging from direct tele-operation to high level mission direction. Within these applications many of the proposed interactions are physical and it is this development of robust, safe and dependable physical human robot interaction that represents a technical step change in robotics technology.

This step change in interaction has been triggered by the increasing use of intrinsically elastic mechanisms equipped with embodied intelligence. The use of Series Elastic Actuation (SEA) or its generalisation Variable Impedance Actuation (VIA)) are key to this step change. Increased levels of physical interaction demand changes in systems design methods to ensure that physical contact is fully considered in the design phase. This is necessary to mitigate the possibility unintentional contacts through better system design.

Early systems of this type are now entering industrial markets. In the development of the next generation of interactive robots, Europe is clearly at the forefront and leading the innovation in embodying intelligence in the mechanical design of robots. {European examples needed to validate statement}

Potential applications range across all market domains with specific application in Healthcare, Manufacturing, Commercial and Civil domains.

Future developments expect to be able to take into account operator intention and create systems capable of longer term interaction sequences by integrating cognitive abilities. Key to this integrated approach are better bio-mechanical models and improved analysis of human injury.

Human robot interaction also covers the development of intuitive interfaces for the command and control both of individual robots and teams of robots. Many applications in the civil and commercial domains rely on single operators being able to monitor and control teams of autonomous systems carrying out tasks and missions. In these applications ensuring operators are fully aware of mission progress and able to issue clear commands will require novel forms of interaction design and multi-modal interfaces.

In contrast there are a number of application areas where there is close coupling between the user and the robot, either physical coupling or one to one via an interface. Typical examples are in Healthcare, surgical robots and rehabilitation systems, in Manufacturing, co-workers and tele-operated systems, and in logistics, warehouse systems and transport loading and unloading.

Future systems may be able to accurately and dynamically assess the safety of a workspace controlling interaction and providing warnings to the user. If such systems are to become a commercial reality certification and validation of safety will become a critical part of the development cycle.

Bio-compatible mechanisms are also a critical part of physical human robot interaction. While the design of these mechanisms is covered by the Mechatronics technology cluster the nature of the interaction rests in this cluster.

4.3.1.2 Barriers to market

- The identified barriers to market can be clustered into the following ones:
- Lack of safety standards.
- Lack of certification and validation processes for human robot interaction safety
- System Design tools for the integration of human robot interactions into systems.

4.3.1.3 Key Techniques and Methods

Historically robots have adopted the interaction methods of computer systems; keyboards, mice, and screens. More recently virtual reality and immersive systems have been used to interact with robot systems. The physically embodied nature of robots provides the opportunity to extend these interfaces to provide physical interaction. This can take place through haptic interfaces or by direct interaction with the mechanical systems of a robot. Recent advances in soft robotics have provided compliant interaction and this are now reaching commercialisation. However current technologies for interaction provide significant scope for future development.

4.3.1.4 Expected Step Changes

As with the other technology clusters there are considerable developmental links between the clusters, the following lists highlight areas of cross development where Human Robot Interaction technologies are impacted by technology developments in other clusters.

4.3.1.5 Systems Development

- System Design
- Design for high dependability of system components and interrelations
- Concepts for systematic dependability analysis in the physical human robot interaction domain
- Dependability analysis frameworks for complex distributed soft-robots in the physical human robot interaction domain

Systems Engineering

- Formal methods application to produce safety proof
- Numerical precision assessment of algorithms implementation
- Programming models for interaction

System Architecture

- System architectures for interactive robots
- Basic physical human robot interaction architecture for complex robotic devices

Systems Integration

- Integration methodologies for physical human robot interaction schemes

Modelling and Knowledge Engineering

- Model-based testing and validation
- Programming models for interaction

4.3.1.6 Mechatronics

Mechanical Systems

- Paradigms for human compatible robot design (soft-robotics design)
- Novel human-friendly designs through synergy analysis and understanding
- Intrinsic safety achieved through mechanical design
- Analysis of human musculo-skeletal system, sensorimotor control and biomechanics by embodiment analysis

Sensors

- Proprioceptive sensors for soft-robots (torque sensing)
- Tactile skins
- External sensors for workspace surveillance and interaction

Actuators

- Novel actuators and model based control principles for soft-robots, sophisticated interaction control
- New VIA actuators with human-like performances in weight, torque, stiffness, power and efficiency

Control

- Dynamic modelling of human-friendly robots
- Interaction control/soft-robotics control
- Reflex control for collision safety
- Embodied intelligence control methods for soft actuators

4.3.1.7 Human Computer Interaction

Human Machine Interface

- Multimodal interaction for interpretation of robot's state by the user including acoustic and tactile indicators.
- High resolution and multi-dimensional haptic feedback

Safety

- More systematic understanding of human injury in robotics with particular focus on representing the results in a robot centric view
- Bio-mechanical safety metrics and standards
- Industrial and domestic standards for human safety in physical human robot interaction
- Research targeted to meet international safety requirements

4.3.1.8 Perception

Sensing

- Human sensing for safety

Interpretation

- Human tracking and activity interpretation

4.3.1.9 Navigation

Motion Planning

- Human aware motion planning accounting for safety and ergonomics aspects
- Basic motion planners for physical human robot interaction tested in complex lab environments
- Bio-mechanically Safe Motion Planning
- Dynamic motion planning for online collision avoidance
- Risk-metric based motion planning
- Trading-off productivity with safety through multi-objective motion/trajectory planning
- Real-Time motion planning for safe physical human robot interaction

4.3.1.10 Cognition

Cognitive Architectures

- Systematic frameworks improving the unification of perception, planning, and control for physical human robot interaction
- Advanced cognitive architectures able to estimate intention and social intelligent behaviour based on physical human robot interaction frameworks

Learning Development and Adaptation

- Definition/taxonomy of interaction skill library and according role distribution
- Modelling adaptive interaction processes
- Learning and adaptation of interaction control
- Unified models for coordinated control & learning
- Modelling of complex contact and force interaction skills enabled by pHRI and imitation learning
- Execution and control of complex contact and force interaction skills by pHRI and imitation learning

Knowledge Representation and Reasoning

- Real-time dynamic modelling of external environment and planning/modifying actions accordingly.

Action Planning

- Reflex planning and behaviours for physical contacts
- Monitoring of interaction plans and behaviours
- Fault tolerant planning of interaction schemes
- Interaction planning for human-robot joint actions/tasks and according role distribution
- Planning/modifying actions in dynamic environments

Natural Interaction

- Robot feedback for intuitive and safe interaction

Interaction planning and learning solutions for rather complex and dynamic human-robot interaction scenarios

4.3.1.11 Benchmarks and Metrics

The effectiveness of Human robot interfaces has to be assessed by adapting HCI criteria to robotics. It is expected that a knowledge base of interation techniques will be built up over time as different types of interaction are tested.

For the assessment of physical interactions testing 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.

In addition to this type of interaction assessment it is critical to establish certification for physical human robot interactions and to formalise processes and methods that are able to provide confidence in the safety of robotic systems that physically interact with humans. This also requires fundamental assessments of the type and severity of injuries that could result from interaction with given types and designs of robot system. From data gathered about injury risk it will be possible to create levels of certification that can be applied to deployed systems.

The initial injury assessment process might consist of the following elements:

- The generation of 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
- Standard protocols for crash-testing (e.g. inspired from automobile crash-stesting, however, tailored to the needs of robotics)
- 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
- Crash-test dummy experiments can be used to assess the level of injury that the robot might cause to a human during different types of collisions. A crash test dummy needs to be specifically tailored for such experiments, since dummies used in car crash tests do not have all necessary sensors (for example collision of a robot with a human arm with or without clamping).
- Classification of injury in robotics based on medically accepted descriptions, large scale soft-tissue injury experiments that capture the inherent collision characteristics and making 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

From these results a set of concrete certification assessments can be developed in conjunction with a safety database. Data from benchmarks carried out against these certification assessments can potentially be used in international industrial and domestic robot standards for safety.

From this knowledge it should be possible to create safe systems. This will require the integration of many different technologies in all areas of robotics. As a consequence it will be important to define benchmarks to assess interaction safety which it is hoped will eventually lead to a process of certification. In some robot applications close to 100% dependability is required even under failure conditions and developing Systems Design and Mechatronic techniques to effect this will be a significant but vitally important challenge. Without being abel to sufficiently guarantee performance many potential application areas will be blocked. This is a critical area for R&D&I investment.

Benchmarks

Independently of the above safety related tests it is necessary to test human robot interaction systems for their performance. The field of physical human robot interaction is still developing and so testing performance is a critical part of making progress simply because human subjective experience of different scenarios needs to be captured. The following represent possible benchmarks that might be used:

- User studies rating the intuitiveness, complexity, … of the robot's interaction capabilities.
- Robotic devices that work in physical contact with a human also convey information through the physical connection. A number of parameters will be critical for efficient human-robot interaction. These parameters can be quantified either based on physical measurements, or through subjective assessments of user interactions.
- Human perception and state estimation is still at an early stage of development and needs further research to be suitable for benchmarking. It is important to begin to define metrics so that the required information needed can be used to prioritise research.
- Intention detection is a relatively new field of robotics research, thus no standardised benchmarks exist. Guidelines and benchmarks for evaluation of robot based intention detection will have to be proposed and evaluated.
- Future robots will increasingly cooperate with humans and will need to predict human actions based on the context of the cooperation and real time observation of human activities. In certain cases the robot will need to have close to 100% reliability, for example in the case of exoskeleton based power augmentation. Other applications may be less critical. Metrics are therefore required for the assessment of a robot's decision making competence.

4.3.1.12 Dependent Domains

The physical interaction with partially unknown environments in conjunction with humans, is a key ability for many advanced robotics applications; particularly in the Manufacturing, Healthcare and Civil domains. The potential impact of human robot interaction technology is expected to be significant. For example, rehabilitation and prosthetics are entirely reliant on safe highly dependable interaction.

4.3.1.13 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 which are reconfigurable.

Achieving safe and dependable human robot interaction is likely to become one of the most significant technical step changes in robotics.

4.4 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.

4.4.1.1 Description

Mechatronics, defined as the 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 within developments in mechatronics.

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 domains. Step changes in capability are likely to result in observable product steps, impact across markets and enhance competitiveness. Progress in mechatronics technologies will also impact on improved system abilities notably:

- Dependability
- Motion capability
- Perception ability

R&D&I progress is also expected to yield safer systems for close working with humans. Such systems will need to be highly adaptive to interaction constraints both in pre-programmed or in unplanned and accidental interactions while at the same time demonstrate efficiency and physical robustness.

It is expected that new principles of sensing, actuation and control will enable performance levels to be closer to human abilities, in dynamic range, scalability, adaptability, intrinsic compliance, damping, flexibility and dexterity. Developments will lead to robots which are robust against mechanical stress and able to store mechanical energy for highly dynamic motions, close to human athletic performance. Key to these developments will be a deeper integration of sensors in a fault-tolerant and synergistic way with control and actuation mechanisms.

The current interest in mechanically elastic actuation clearly illustrates the advantages of executing mechanical design at a system level rather than at the component level. Functionalities originally achieved by dedicated system components (including control and software) can be embodied at system level with superior performance and with a higher degree of integration. This holistic approach requires new design methods, new multidisciplinary simulation techniques, and a more general understanding of materials and manufacturing technologies. It is expected that the resulting "Smart Mechanics" will have a significant impact on the possible morphologies and functionalities of future robots.

In the future advanced manufacturing processes, particularly for micro-fabrication and where sensing, actuation and mechanism are manufactured as an integrated whole will provide higher levels of performance at the cost of complex production pathways including chemistry and physics. This type of integrated multi-process manufacturing will also require new design tools.

4.4.1.2 Key Techniques and Methods

The mechatronics cluster of technologies subsumes a range of individual technologies each with its own methods and techniques. Much of the expected progress in mechatronics comes form the integration of these technologies and in the exploitation of synergies between them.

Details for each individual component technology are given in the technology sections below detailing each underlying technology.

4.4.1.3 Expected Step Changes

The step changes for each underlying technology are detailed in the individual technology sections below, with respect to mechatronics as a whole and the goal of making "Better Machines" in particular the following represent major challenges and step changes:

- *Smarter mechatronic design:* Tighter integration during design utilising high-density sensor-actuator-mechanism integration, multiple articulation and adaptable compliant actuators, mechanically embodied functionality and macro to nano-scale robot manufacturing technologies.
- *Robust control methods:* Mechanical and control design concepts enabling full and continuous operation of the system even in case of individual joint failure. Requiring self-diagnoses and safe fallback states for joint mechanics and sensors as well as control modules for reconfigurable kinematic structures.
- *Smarter Mechanical System Design:* Design and simulation approaches that allow for a holistic system design that embodies functionalities using multiple components of the system including software and control.
- *Interface standardisation:* Standardisation of interfaces to sensors and actuators as well as definition of standard communication architectures, protocols and code generators for hard real time integration enabling high TRL levels for plug and play systems.
- *Modular mechatronic components:* Development of generic parts that can be used for different kinds of robots and in different domains that allow for high levels of integration. Mechatronic components such as sensors, actors, structures and communication electronics that can be produced in quantity at low cost.
- *Soft robotic systems:* Development of soft robotics approaches utilising non-rigid structures and actuators and by breaking up the boundaries between actuators and structures enabling mechatronic systems that intrinsically integrate compliance, damping and sensors.
- *Bio-compatible robotic components:* Development of mechatronic systems that allow the seamless integration of robotics technology with the human body both in healthcare and in terms of close coupled interaction systems. Ranging from interfaces between the nervous system and computers, bio-compatible materials and structures, implantable micro-sensors, bio-compatible actuators and light-weight materials including micro-robots for navigation and action inside the human body.
- *Reducing mechatronic component cost by a factor of ten:* This can be achieved by careful cost control and analysis better volume manufacturing yielding more cost effective sensors (torque, position, tactile). Through standardisation to widen the market for each component and plug and play design to allow system flexibility.

4.4.1.4 Benchmarks and Metrics

Typical metrics for mechatronic systems are:

- Cost per unit property
- Reliability
- Resilience
- Robustness
- Repeatability
- Accuracy
- Energy efficiency

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.

4.4.1.5 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.

Research led advances in mechatronics has the potential to enable new robot generations that have richer and more robust motion capabilities, are safer for human-robot interaction, and more energy-efficient than current robots.

4.4.1.6 Unknowns

One primary unknown is the impact of new materials technology on mechatronic systems. While new materials scuba as electro-active polymers or nano materials are often expected to yield major advances in performance that can take a considerable time to permeate to the market. It is therefore important to also incrementally improve systems by maximising the utility of known materials. While this conventional development approach is less likely to yield substantial improvements in performance the shorter time to market will allow the consequential impact to be more easily realised.

4.4.2. Mechanical Systems

4.4.2.1 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.

4.4.2.2 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.

4.4.2.3 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.

4.4.2.4 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.

4.4.2.5 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.

4.4.3. Sensors

4.4.3.1 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 at mass market costs.

4.4.3.2 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.

4.4.3.3 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.

4.4.3.4 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.

4.4.3.5 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.

4.4.3.6 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.

4.4.4. Actuators

4.4.4.1 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.

4.4.4.2 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.

4.4.4.3 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.

4.4.4.4 Benchmarks and Metrics

Metrics for assessing performances are:

- Force
- Strain
- Tensile stress
- Weight
- Power consumption.

4.4.4.5 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

4.4.5. Power Supply and Management

4.4.5.1 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.

4.4.5.2 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.

4.4.5.3 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.

4.4.5.4 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).

4.4.5.5 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.

4.4.5.6 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).

4.4.6. Communications

4.4.6.1 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.

4.4.6.2 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 teleoperation, 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 limi 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.

4.4.6.3 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.

4.4.6.4 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

4.4.6.5 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.

4.4.6.6 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.

4.4.7. Materials

4.4.7.1 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 nanoscale 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.

4.4.7.2 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.

4.4.7.3 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 muti-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

4.4.7.4 Benchmarks and Metrics

Benchmarks and metrics in materials is an established discipline owing to the consolidated physics and formalisation of the measurements of materials.

4.4.7.5 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).

4.4.7.6 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.

4.4.8. Control

4.4.8.1 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.

4.4.8.2 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 telepresence 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.

4.4.8.3 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 teleoperation of robots everywhere on Earth: Teleoperation 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.

4.4.8.4 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.

4.4.8.5 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.

4.4.8.6 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.

Perception, Navigation and Cognition

“Better action and awareness”

The cluster of technologies that make up perception, navigation and cognition are the ones that will have the greatest impact on the future performance of robot systems. Enhanced awareness, characterised by step changes in Perception, Navigation and Cognition, are at the core of all advanced robotics applications. Many of the applications with the greatest societal impact require step change improvements in this cluster of technologies.

4.5 Perception

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 distill 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.

4.5.1.1 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)

4.5.1.2 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.

4.5.1.3 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/).

4.5.1.4 Dependent Domains

Many advanced applications depend on perception to provide information about the operating environment.

4.5.1.5 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.

4.5.2. Sensing

4.5.2.1 Description

If a robot is to correctly interpret its environment it must be able to distill 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.

4.5.2.2 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.

4.5.2.3 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 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.

4.5.2.4 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.

4.5.2.5 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.

4.5.2.6 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.

4.5.3. Interpretation

4.5.3.1 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.

4.5.3.2 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.

4.5.3.3 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.

4.5.3.4 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.

4.5.3.5 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.

4.5.3.6 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.

4.6 Navigation

4.6.1.1 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.

4.6.1.2 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 this 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.

Motion planning

Trajectory planning and simple motion planning round obstacles is well understood. Complex motion planning for multiple degrees of freedom arms is well understood as an optimisation problem.

4.6.1.3 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 planing 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.

4.6.1.4 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.

4.6.1.5 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.

4.6.1.6 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.

4.7 Cognition

4.7.1.1 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.

4.7.1.2 Key Techniques and Methods

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.

The issues addressed in the field of KR&R have recently started to be also addressed by the robotics community, as a means to endow robots with the ability to represent and use higher level knowledge. Notable examples are the representation of higher level concept in semantic maps, and 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.

Knowledge-based 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.

Knowledge-based 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, the more sophisticated AI planning techniques available will need to be incorporated into robotic systems.

Machine learning

Machine learning techniques most often used in robotics can be roughly categorised to 1) supervised classification or regression; 2) unsupervised clustering; and 3) 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 labeled 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.

Machine learning 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 modeling, 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 labeled 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.

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 which 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 interaction is fairly advanced in many cognate technologies such as virtual reality, wearable computing, and smart phones. Key techniques include natural language processing, speech recognition and generation, gesture recognition and gestural communication, emotion recognition and expression, and indirect communication by observation. 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. As much as possible interaction should be seamless, and certainly human users will expect interaction to improve rapidly with familiarity of the task.

4.7.1.3 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:

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 spatial, causal, temporal, resource and still other types of knowledge must be considered.

Planning and reasoning under uncertainty: existing KR&R and planning techniques need to be extended to allow a realistic and tractable treatment of the uncertainty and incomplete knowledge inherent to the robotic domain.

Knowledge-based 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.

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.

Machine learning

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.

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.

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.

Adaptivity 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.

Neuromorphic engineering & learning: neuromorphic engineering comprises a set of techniques that imitate brain architectures at the hardware level. Recently progress in hybrid neuromorphic 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). Neuromorphic 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 neuromorphic neural network are now under investigation. One of the major advantages of the neuromorphic 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.

4.7.1.4 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.

4.7.1.5 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.

4.7.1.6 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).

This document has been prepared for euRobotics aisbl under the RockEU Coordination Action by iTechnic Ltd and RURobots Ltd

The content of this document has been assembled from submissions made to euRobotics via Workshops and Topic Groups.

A second revision of this document will be prepared for Call 2 (ICT24).