II: ERL Emergency Robots

- Rule Book -

This document is subject to change, refinement and development.
Please visit www.robotics-league.eu for the current version.

Note: changes from previous version 1.3 are highlighted in yellow

Content

List of acronyms

A Air

AUV Autonomous Underwater Vehicle

CSV Comma Separated Values

EU European Union

GNC Guidance Navigation and Control

H Height

ID Inner Diameter

L Land

LG Length

OD Outer Diameter

OPI Objects of Potential Interest

RIB Rigid Inflatable Boat

ROS Robotic Operative System

ROV Remotely Operated Vehicle

SAP Scenario Application Paper

S Sea

TBD To Be Defined

UAV Unmanned Aerial Vehicle

UGV Unmanned Ground Vehicle

USV Unmanned Surface Vehicle

W Width

WP Waypoint

1. Introduction

ERL Emergency Robots is a civilian, outdoor robotics competition, with a focus on realistic, multi-domain emergency response scenarios. Inspired by the 2011 Fukushima accident, the ERL Emergency Grand Challenge can only be overcome when land, underwater and flying robots successfully cooperate.

The competition itself requires international teams of various disciplines and organisations to survey the scene, collect data, search for missing workers and identify critical hazards, all in a race against the clock. After three successful years under the name of 'euRathlon' (www.eurathlon.eu), the latest iteration of the competition takes a step forwards as part of the European Robotics League.

To provide teams with realistic challenges that test their robots' abilities to face real-world situations, the ERL Emergency scenarios have been carefully designed by the project partners and reviewed by an advisory board of experts in field robotics. All the experts have contributed with ideas based on their experience in robotics competitions and in the nuclear and disaster-response sectors.

The following **user story** is the basis upon which the ERL Emergency competition is built:

> *A potent earthquake affects the area where a nuclear plant is located. Immediately after the earthquake, the reactors are automatically SCRAMMED and evacuation protocols followed, in accordance with safety and security procedures.*
>
> *Within an hour of the initial earthquake, a tsunami arrives and strikes the nuclear plant. The high wave overwhelms the building and floods the low sections where the emergency generators are located.*
>
> *The emergency response team arrives at the area soon after the tsunami. High levels of radioactive elements are present in the building and its surroundings so members of the response team must maintain a safe distance. For this reason, the use of robotic vehicles is essential.*
>
> *It is time for the emergency teams to act. The priorities are to find missing people, if the building and installations have suffered any serious damage and check if any pipe is leaking radioactive substances. It is known that a certain number of people were working in the building at that time. During a head-count, it is discovered that there are three workers missing.*
>
> *The robots have to search for these workers, find them as soon as possible and deploy a first-aid kit. At the same time, the robots must check any damage that the earthquake and tsunami may have caused to the structure of the building and to the pipes that connect the sea with the reactor for cooling purposes. In case any pipe is damaged and or leaking radioactive material, it has to be sealed by closing the corresponding valves both in the machine room and underwater to avoid radioactive contamination. Nevertheless, special care has to be taken as closing the wrong valves may cause a reduction in the amount of seawater available for cooling down the reactor.*

2. ERL Emergency Robots Organisation

2.1 ERL Emergency Management

The management structure of ERL Emergency Robots has been divided into three committees: *Executive Committee, Technical Committee* and the *Organisation Committee.*
The roles and responsibilities of those committees are described in the following paragraphs.

2.1.1 Executive Committee

The Executive Committee (EC) is represented by the ERL Emergency Robots partners. The committee is mainly responsible for the overall coordination of ERL Emergency Robots activities and especially for dissemination in the scientific community.

The ERL Emergency Robots competition is chaired by the University of the West of England, UWE Bristol, with local organisation by the Centre for Maritime Research and Experimentation (CMRE) and includes five partners:

- Centre for Advanced Aerospace Technologies (CATEC) (Spain)
- Centre for Maritime Research and Experimentation (CMRE) (Italy)
- Fraunhofer Institute for Communication, Information Processing and Ergonomics FKIE (Germany)
- University of Oulu (Finland)
- University of the West of England, Bristol (UWE Bristol) (UK)

2.1.2 Technical Committee

The Technical Committee (TC) is responsible for the rules of the league. Each member of the committee is involved in maintaining and improving the current rule set and also in the adherence of these rules. Other responsibilities include the qualification of teams, handling general technical issues within the league, make sure teams comply with safety, as well as resolving any conflicts inside the league during an ongoing competition. The members of the committee are further responsible for maintaining the ERL Emergency Robots Infrastructure.

The Technical Committee has the authority to modify the rules at any time. Reasons for modifications include, but are not limited to, the accommodation of promising but unexpected technical approaches that would have been prohibited by the rules and the exclusion of approaches that seek to participate without demonstrating the desired technical achievement in the vehicle's behaviour that is the purpose of the event. The Technical Committee will announce any modifications of the rules with an e-mail to all entrants and a corresponding statement on the ERL Emergency Robots page (www.robotics-league.eu). The Technical Committee may provide interpretation of the rules at any time and in any manner that is required.

Decisions of the Technical Committee are final.

- **Referee Team**

The referees are a group of officials designated by the Technical Committee. Referees are members of the Technical committee during the tournament event. The Technical committee is the final authority on all matters referred to in the rules and all matters affecting the operation of the ERL Emergency Robots competition.

The Referee Team is divided into three Referee Teams, one per domain. Each Referee Team is led by one Head Referee which manages the activity of the Referee Team.

The Technical Committee currently consists of the following members:

Chairs
- Dr Gabriele Ferri (Centre for Maritime Research and Experimentation, CMRE, Italy)
- Marta Palau Franco (University of the West of England, Bristol, UK)

Land Referees
- Dr Bernd Brüggemann (Fraunhofer FKIE, Germany)
- Dr-Ing Michael Gustmann (Kerntechnischer Hilfsdienst GmbH, Germany)*
- Dr Hans-Arthur Marsiske (Germany) *
- Prof Juha Röning (University of Oulu, Finland)
- Dr Frank E. Schneider (Fraunhofer FKIE, Germany)
- Prof Alan Winfield (University of the West of England, Bristol, UK)

Sea Referees
- Vladimir Djapic (SPAWAR Systems Center, San Diego, USA)*
- Andrea Munafo (National Oceanography Centre, Southampton, UK)*
- Prof Yvan Petillot (Heriot-Watt University, Scotland, UK)*
- Dr Darío Sosa Cabrera (University of Las Palmas de Gran Canaria, Spain)*

Air Referees
- Dr Antidio Viguria (Centre for Advanced Aerospace Technologies, CATEC, Spain)
- Francisco Javier Perez Grau (Centre for Advanced Aerospace Technologies, CATEC, Spain)
- José Antonio Cobano (University of Seville)*
- Prof Stjepan Bogdan (University of Zagreb)*

Safety pilots

- Carlos Albo (Centre for Advanced Aerospace Technologies, CATEC, Spain)

This committee also includes members of the Executive Committee.

*External referees, not members of the European Robotics League Organising Committee.

2.1.3 Organising Committee

The Organizing Committee (OC) is responsible for the actual implementation of the competition, i.e. providing everything what is required to perform the various tests. Specifically, this means providing setting up the test arena(s), providing any kind of objects (e.g. manipulation objects), scheduling the tests, assigning and instructing referees, recording and publishing (intermediate) competition results and any other kind of management and advertisement duties before, during and after the competition.

The organising committee of ERL Emergency Robots 2017 Major tournament in Piombino, Italy, is chaired by the Centre for Maritime Research and Experimentation (CMRE), and includes members of the five project partners.

Chair
- Dr Gabriele Ferri (Centre for Maritime Research and Experimentation, CMRE, Italy)

Co-Chair
- Dr Fausto Ferreira (Centre for Maritime Research and Experimentation, CMRE, Italy)

Members
- Carlos Albo (Centre for Advanced Aerospace Technologies, CATEC, Spain)
- Dr Bernd Brüggemann (Fraunhofer FKIE, Germany)
- Marta Palau Franco (University of the West of England, Bristol, UK)
- Francisco Javier Perez Grau (Centre for Advanced Aerospace Technologies, CATEC, Spain)
- Prof Juha Röning (University of Oulu, Finland)
- Dr Frank E. Schneider (Fraunhofer FKIE, Germany)
- Dr Antidio Viguria (Centre for Advanced Aerospace Technologies, CATEC, Spain)
- Prof Alan Winfield (University of the West of England, Bristol, UK)

3. ERL Emergency Award Categories

Awards will be given to the best teams in each of the ERL Emergency task benchmarks and functionality benchmarks that are described in Sections 6 and 7. In the ERL for every local/major tournament, and for every task and functionality benchmark, a score is computed by taking the median of the best (up to 5) runs. The final end of season score is computed by taking the median of the pooled runs that were used for scoring the best two Local/Major tournaments and teams are ranked based on this score. **Note: This season 2017/18 there is only one tournament for ERL Emergency Robots, because of that we will take the best of the runs instead of the median.**

The ERL Competition awards will be given in the form of cups for the best teams. Every team will also receive a plaquette with the ERL logo and a certificate.
Please note that in the specific case of ERL Emergency 2017 competition, teams need to participate only in the major tournament in order to obtain a score for the TBMs and/or FBMs that they intend to enter.

3.1 Awards for Task Benchmarks

The team with the highest score in each of the four task benchmarks of ERL Emergency Robots will be awarded with prize money and a cup ("ERL Emergency Robots. Best-in-class Task Benchmark <task benchmark title>"). The amount of the prize money will depend upon how much money the ERL organisation can award each season.
If only one team participates in a given task benchmark, the corresponding task benchmark award will only be given to that team if the Executive and Technical Committees consider the team performance of exceptional level.

3.2 Awards for Functionality Benchmarks

The teams with the highest score ranking for each of the four functionality benchmarks will be awarded a cup (“ERL Emergency Robots. Best-in-Class Functionality Benchmark <functionality benchmark title>” and “ERL Emergency Robots. Second-Best-in-Class Functionality Benchmark <functionality benchmark title>”). If less than three teams participate in a given functionality benchmark, only the “ERL Emergency Robot. Best-in-class Functionality Benchmark <functionality benchmark title>” award will be given to a team, and only if the Executive and Technical Committees consider that team's performance as excellent.

4. The ERL Emergency Location

The location for ERL Emergency Robots consists of the environment in which the competition will happen, including all the objects and artefacts in the environment, and possibly the equipment brought into the environment for benchmarking and monitoring purposes.

The ERL emergency competition will be held in the proximity of the Torre del Sale building, in Piombino, Italy. The building on the shoreline as shown in Figure 1 (and highlighted with a cyan rectangle). The WGS coordinates of the area are 42.954234° N, 10.599906° E.

Figure 1. Google Earth view of ERL Emergency 2017 competition area. (Source: Google Maps).

The Tor del Sale building represents the reactor building of a nuclear energy plant. The building is approx. 22 m long and 18 m wide. It has several floors, but only the ground floor will be accessible to robots. The building has no doors, and unobstructed corridors inside the building will be at least 70 cm wide. Teams should expect to find dead ends, sharp turns, obstructions and narrow passages inside the building. There will be stairs (3-4 standard dimensions steps) to access the machine room. There will be also the option to access the machine room using a ramp.

Static obstacles (i.e. debris, stones, holes, vegetation...) and dynamic obstacles (i.e. sea life, birds...) can be expected in the outdoor area. Loss of Wi-Fi signal can be expected. As with any outdoor competition, there is the possibility of rain, wind and muddy areas. If weather conditions are very poor the competition may be temporarily suspended for safety reasons.

Figure 2. The harbour and the Tor del Sale areas. (Photo: euRathlon)

Figure 2 and Figure 3 show the Torre del Sale building and the coastline, together with some indicative interior photos showing part of the ground floor.

Figure 3. Building, shoreline and interior. (Photo: euRathlon).

Figure 4. Areas for attendees and participants. (Source: Google Maps)

4.1 Aerial robots competition area

All the operations will be held in VLOS (Visual Line Of Sight) and daylight conditions with a maximum distance between the aerial robot and the safety pilot of 160 meters, and a maximum altitude above ground level of 40 m.

All flights must be conducted within the flight volumes defined by the Organisation Committee as shown in Figure 5. Blue, cyan and yellow prisms represent flight volumes with heights of 40 meters, 20 meters and 10 meters respectively. The coordinates that define each of the flight volumes will be provided to the teams in advance. In the case that an aerial robot exits a flight volume the safety pilot must take control, return it to the flight volumes and safely land it in the defined landing areas.

Two different take-off and landing areas have been set (shown as green rectangles in Figure 5). These areas will be prepared for this purpose so they will be flat solid surfaces marked with visible markers so it can be easily identified by the pilot. These zones will be about 3 x 3 meters with no obstacles in the surrounding area. (Figure 6) Each of these take-off and landing areas have an associated control area close to them from where team members can control the RPAS (Remotely Piloted Aircraft System) operation. Aerial robots will only be allowed to take-off and land in these areas (except in the case of an emergency). Aerial robots must land in these areas to be refuelled or when a battery change is needed. Aerial robots will not be allowed to enter inside the building.

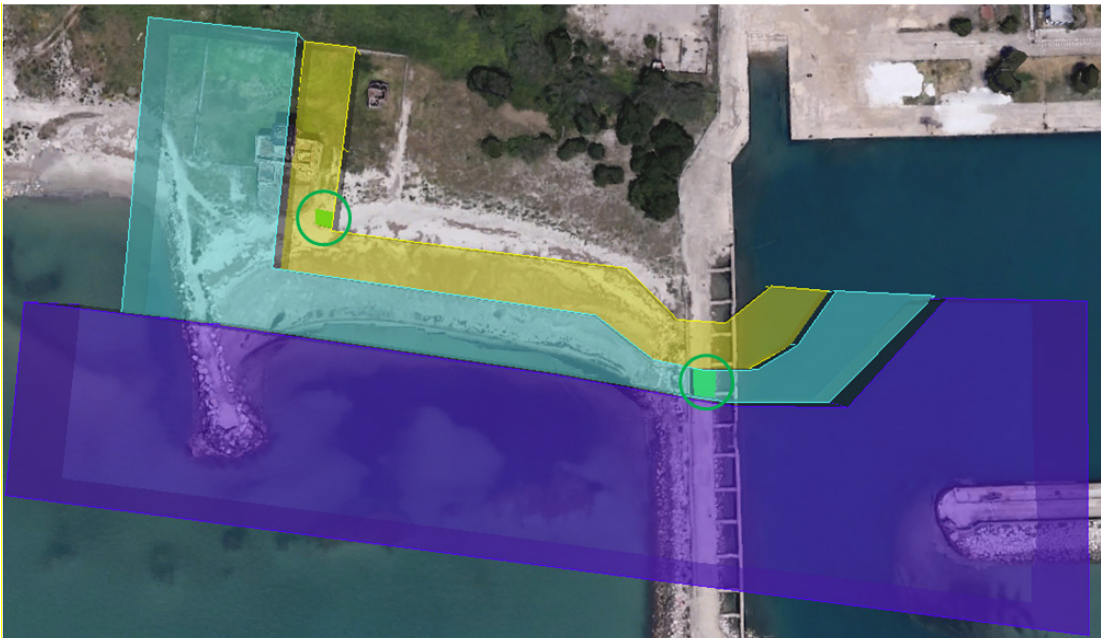


Figure 5. Flight volumes and take-off and landing areas defined (Source: Google Maps).

Figure 6. Example of take-off and landing areas. (Photos: euRathlon)

Flights will be conducted over an unpopulated area. There is no overhead electrical wiring in the competition area.

4.2 Land robots competition area

Ground robots will operate in the proximity of the building in the area shown in Figure 7. In this area, teams should expect static obstacles such as debris, stones, holes, vegetation, etc. As in every outdoor scenario, there is the possibility of rain, wind and muddy areas. Teams should also expect beach sand in the area.

Figure 7. Area where the ground robots will operate. This area is indicative (Source: Google Maps).

It is important to note that the area shown in Figure 7 is just indicative and it is subject to minor changes. Figure 8 and Figure 9 show some examples of the terrain at Torre del Sale area.

Figure 8. Examples of the terrain in the beach area during euRathlon 2015. (Photo: euRathlon).

Figure 9. Examples of different terrains at Torre del Sale area after a rainstorm. (Photo: euRathlon)

4.3 Marine robots competition area

Marine robots competitions will be held primarily inside the docks area as shown in Figure 10. The basin dimensions are L=132 m by W=110 m, the water depth is mostly between 3 m and 4 m, decreasing at the inner end of the basin, up to about 1.5-2 m in the area close to the northern docks wall. Currents are negligible inside the basin. Water temperature in September is around 20°C. The salinity can be measured and made available to the competitors if required. An average water density around 1025 Kg/m^3 has to be expected in the area. Water visibility varies between 1 and 2 metres depending on weather conditions. Magnetic compass behaviour is indeterminate at this stage. However, we expect magnetic compasses to be useable 1 meter away from any structure.

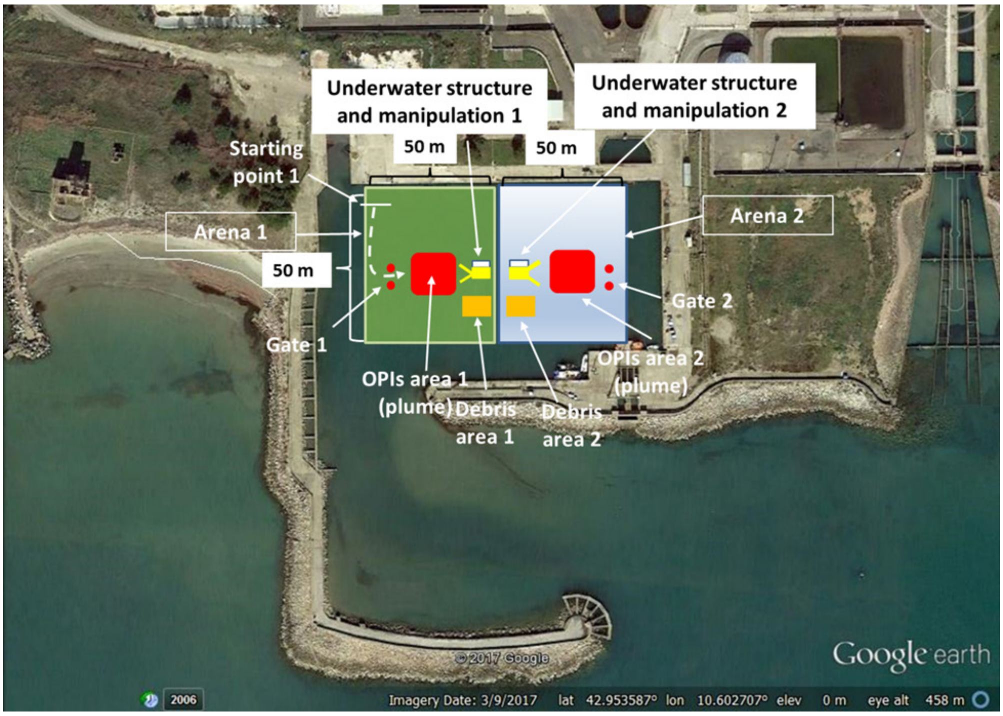


Figure 10. Area for marine robots showing the two Arenas. The waypoints (WPs) for long range navigation are indicative. The real waypoints will be provided to the teams before the Challenges days. (Source: Google Maps).

In the docks area two identical arenas containing the same objects will be built. One arena will be used for the competition and the other one for practice. The area where the Objects of Potential Interest (OPIs) will be deployed will be about 15 m x 15 m.

Each arena will include one gate marked by the two buoys (detectable both by the sonar and video camera), spaced 2 metres apart, and an anchoring line. The marine robots are required to pass through the gate.

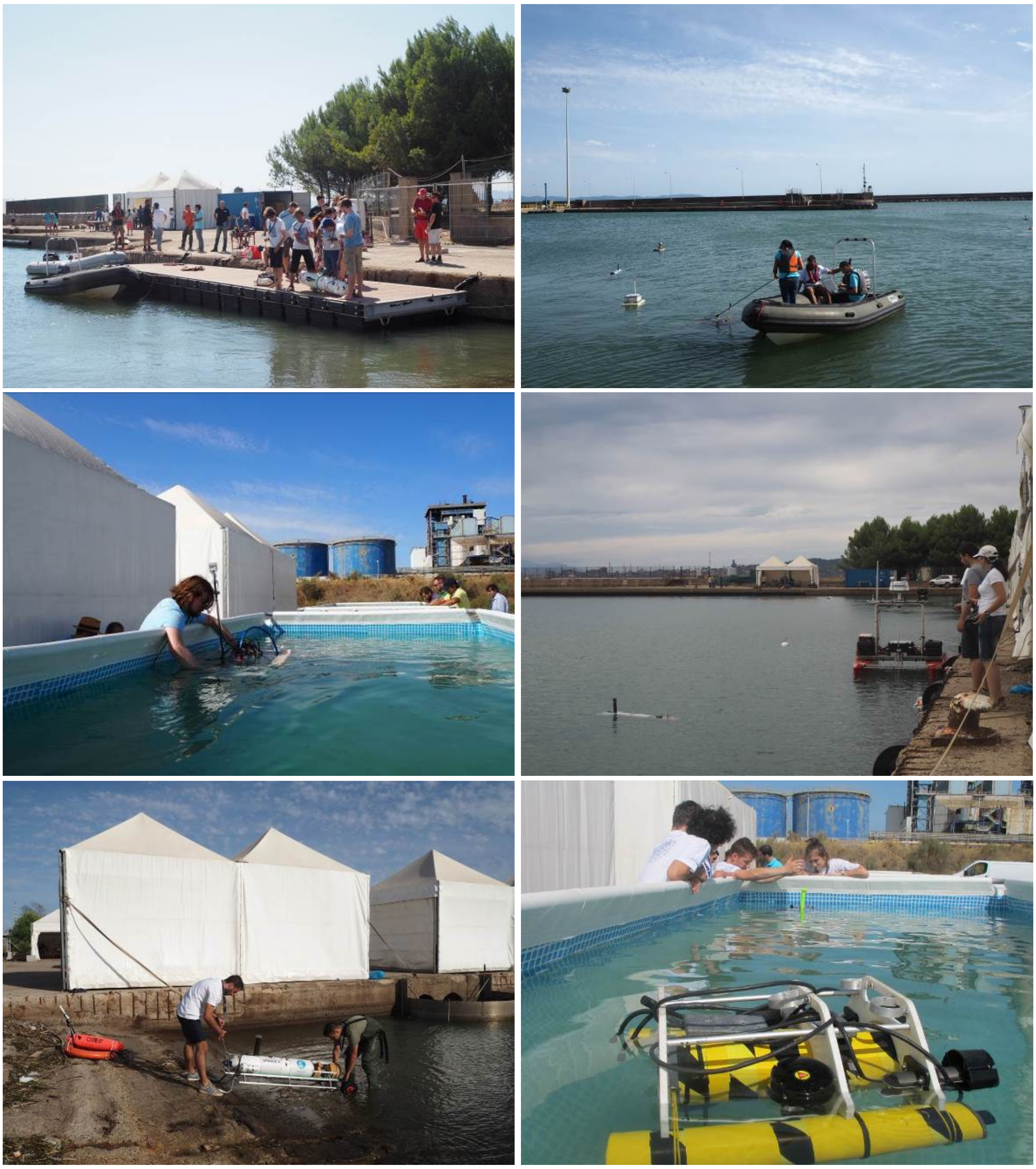


Figure 11. Examples of areas dedicated to marine robots. (Photo: euRathlon)

5. Robots and Teams

The purpose of this section is:

1. It specifies information about various robot features that can be derived from the environment and the targeted tasks. These features are to be considered at least as desirable, if not required for a proper solution of the task. Nevertheless, we will try to leave the design space for solutions as large as possible and to avoid premature and unjustified constraints.
2. The robot features specified here should be supplied in detail for any robot participating in the competition. This is necessary in order to allow better assessment of competition and benchmark results later on.

5.1 General Specifications and Constraints on Robots and Teams

There is no limitation on the number of robots in a team. However, for safety reasons, we will limit the number of robots in simultaneous use during competition, as follows:

Air: Only one aerial robot may be flying at any one time during the Task Benchmarks/ Functionality Benchmarks. The team may use more than one robot, but not simultaneously, in the allocated time-slot (up to a maximum of 3); in which case this must be communicated to judges prior the start of the Task Benchmark/Functionality Benchmark.
Land: Two ground robots may be concurrently used on field during one Task Benchmark/ Functionality Benchmark.
Sea: One underwater robot and/or one surface robot may be used during one Task Benchmark/ Functionality Benchmark. Note: marine robots tele-operated are only allowed in the manipulation tasks.

Teams with novel approaches that fall outside the guidelines above (i.e. multi-robot swarms) are strongly encouraged to enter, and contact the organisers. Multimodal robots (e.g. amphibious robots that can operate both on ground and at sea) may be used as long as they are registered for the domains in which it can operate.

Only robots registered under a team's name and approved by the Technical Committee through the Scenario Application Papers (SAP) may participate in the competition. The organisers will provide teams with the opportunity to register new robots under their name if they submit information for approval prior to the competition.

The teams may use different robots during different time-slots. For instance, one team may use one marine robot during the Monday time-slot and another one during the Tuesday time-slot. The referees must be informed of all robots that a team intends to use and each robot needs to pass a safety check before being used.

5.1.1 Mode of Operation

In the SAPs each team must explain how they plan to target each task benchmark, including the mode of operation of their robot(s). During the competition teams must inform the judges about changes in the modes of operation (in case they have changed from those specified in their SAPs). The three modes of operation are categorised as: autonomous, semi-autonomous and tele-operated. A robot may be operated in different modes depending on the scenario tasks. The categorisation will be verified and, if necessary, updated by the Technical Committee. The classification only applies to the mode of operation after the robot's launch/release and before the robot's retrieval/return. For example, in the case of aerial robots, an aerial robot will be considered autonomous if the tasks have been executed autonomously, but the take-off or/and landing has been tele-operated.

Robots in any mode of operation must be unmanned.

- **Autonomous Robot Operation**

For the purposes of this competition, autonomous operation is defined as operation in which a robot's low-level motor control including starting, stopping and steering, together with medium-level control such as navigation, are performed without human intervention.

In this mode direct control via an operator device is prohibited. Interaction is only allowed to provide the robot with necessary input data before the robot is launched and to receive result data from the robot after its retrieval.

However, even in autonomous mode, a robot may be monitored* and supervised passively by a human operator, who is able to intervene and assume manual control if necessary. If the robot or operator console signals an incident it cannot cope with autonomously, the operator (or, on the operator's request, the "technical assistant"/safety pilot) may interact with the system. Note, however, that any interaction between the technical assistant/team safety pilot and the robot is likely to have a negative influence on the resulting evaluation.

** In case of marine robots, monitoring can only be done through acoustic modems, no LBL or USBL are allowed. Neither WiFi is allowed to monitor the robot operations when the robot is submersed (for instance via a towed floating buoy).*

- **Semi-autonomous Robot Operation**

In semi-autonomous operation a robot operates autonomously, but the operator is allowed to send high-level commands to the robot. High-level commands are instructions such as "move to waypoint 1", "search for the OPI" or "close the valve" which the robot must interpret into a series of medium- or low-level control actions. The use of such high-level commands still requires the robot to have a closed loop control system with some autonomy. In this mode, full manual control of the robot via a remote interface with a joystick or other human interface, is prohibited.

At any time the operator (or, on the operator's request, the "technical assistant"/team safety pilot) may assume full manual control of the system. Note, however, that such interventions are likely to have a negative influence on the resulting evaluation.

For land robots a safety driver instead of a technical assistant is permitted by prior agreement with the organisers.

For marine robots, the high-level commands can be issued to the robot via an acoustic modem, either located on-shore or on the surface vehicle.

Note: For marine robots, only during the manipulation task, the team can use semi-autonomous operation mode via cable, In such a case the underwater robot will be permitted to surface near the area where the underwater valve is located, so that the Team Technical Assistants will be able to connect the cable to control the underwater robot without any penalty. In this specific case, the robot can be connected to a cable directly from the shore or from a surface robot/buoy acting as a communications relay.

- **Tele-operated Robot Operation**

Tele-operation is defined as full manual control of a robot via a remote interface with a joystick or other human interface.

For tele-operated robots the operator is allowed to control the robot at any time during the Task Benchmark/Functionality Benchmark. On the operator's request, the "technical assistant" may interact with the robot. Note, however, that any interaction between the technical assistant and the robot may have a negative influence on the resulting evaluation.

Note: For marine robots, tele-operation mode is only allowed for manipulation tasks. If the team decides to switch to tele-operation for the manipulation task, the underwater robot will be permitted to surface near the area where the underwater valve is located, so that the Team Technical Assistants will be able to connect the cable to allow control of the underwater robot without any penalty.

5.1.2 Cooperation

Cooperation is defined as the act of working together toward a common purpose. Robots from different domains can cooperate in different ways to complete the scenarios. This may be through direct cooperation (i.e. robot1–robot2) or mediated by human operators (i.e. robot1–human–robot2, robot1–human1–human2–robot2, etc).

5.1.3 Requirements for Ground Robots

Mass

There is an upper limit of 350 kg on the mass of ground robots. Teams with a ground robot > 350 kg must contact the organisers so that they can evaluate, in each case, the suitability of the robot for the terrain of the competition scenarios. Heavy robots will face difficulties in some scenarios, similarly exceptionally small/light land robots may face difficulties with terrain. Ground robots weighing more than 75 kg must be equipped with a recovery facility. Ground robots must be able to travel on an asphalt pavement without damaging the pavement surface.

Traction

Ground robots must be propelled and steered by traction with the ground. The type of ground contact devices (e.g. tyres, treads or legs) is not restricted. The robot must not damage the environment or any infrastructure at the ERL Emergency competition site.

Size

There are no size limitations for the ground robots, but teams should be aware that large robots are likely to have difficulties with the 'indoor' part of the scenarios.

Wireless Emergency Stop and E-stop mode

It is the sole responsibility of the team to properly install a wireless emergency stop (E-stop) system in its robot. The E-stop system must be fully functional for the participant to be eligible to participate in ERL Emergency. In case of emergency (i.e. imminent danger for individuals and/or the robot) the E-stop system must be activated immediately.

Triggering the E-stop mode must bring the motion of the robot to an immediate stop, with brakes applied to hold the robot even if it is on a slope. The E-stop mode should be latched so that its state cannot be changed unintentionally after initiation. Electrical connections to the E-stop must be ruggedized to ensure functionality even after exposure to adverse (damp or dusty) environmental conditions and a high vibration environment.

The robot should be ready to promptly resume motion as soon as the E-stop mode has ended. The E-stop mode may be entered numerous times during a run, and each E-stop event may last up to several minutes.

In the special case of a robot with a safety driver, entering the E-stop mode requires the driver to stop the robot immediately and completely. If applicable, additionally the handbrake must be put on and the gearbox/automatic transmission must be put into the neutral position.

Robot mounted Emergency Stop Unit
Each robot must be additionally equipped with an externally actuated emergency stop capability. Activating the emergency stop must promptly bring the robot into the E-stop mode, leading to an immediate and complete stop. At least one actuator and its labelling must be easily visible and accessible from anywhere around the robot. The manual emergency stop must be easy to identify and to activate, even if the robot is moving at a walking pace. The operation instructions for emergency stop actuators must be clearly labelled in English. The instructions must not be interfered with by any other labelling or advertising.

Warning Devices
Each robot shall display one or more flashing amber warning lights, the combination of which results in a visibility of 360 degrees azimuthally around the robot. The warning light(s) shall continuously operate whenever the robot is switched on. The robot may not commence movement until the warning light(s) have been in operation for 5 seconds. The warning light(s) shall comply with standards for warning lights and shall not produce light that can be confused with those of public safety vehicles such as law enforcement, fire or ambulance.

This warning light is mandatory for robots heavier than 20 kgs and recommended for vehicles lighter than 20 kgs.

General
Robots operation must conform to any regulations or restrictions imposed by the applicable land-use authority.

5.1.4 Requirements for Marine Robots

Mass
There is a limit of 100 kg for Autonomous Underwater Vehicles (AUVs) and a limit of 250 kg for Unmanned Surface Vehicles (USVs).

Size
There are no size limitations for any of the robots. A maximum of one AUV and one USV can be used at the same time during the runs even if the teams can bring spare robots. The robots to be used in a run must be communicated to the judges before the start of the run.

General

Power constraints: All entries must be battery powered. All batteries must be sealed. The open circuit voltage of any battery in an entry may not exceed 60 Volts DC.

No materials (except for compressed air) may be released by the entry into the waters of the arena. Any robot leaking a fluid will be deemed unsafe. All robots must carry a clearly legible 'label' showing the robot weight in air. All robots must have 2, 3 or 4 clearly identified lifting points onto which standard commercial lifting slings may be easily attached / detached – on land or in the water – in a safe manner.

All robots will be required to install strobe lights.

All entries must bear a clearly marked OFF switch that a diver can readily activate. The switch must disconnect the batteries from all propulsion components and devices in the AUV. Note that this does not have to kill the computer. Upon reactivation, the robot must return to a safe state (propellers do not start spinning). All entries must be positively buoyant by at least one half of one percent of their mass when they have been shut off through the OFF switch.

Robot operation must conform to any regulations or restrictions imposed by the applicable marine-use authority.

5.1.5 Requirements for Aerial Robots

- Only VTOL (Vertical Take-Off and Landing) aircraft will be allowed to participate in the competition. The area for taking-off and landing will be 3m x 3m
- The aircraft maximum take-off weight (MTOW) must be less than 25 kg.
- The UAS system must include a flight termination system that must be capable of being remotely activated from the ground by pressing a "crash button". When remotely activated, the flight termination system must stop the aircraft motors.
- A member of the organising team, an aerial expert, will be in charge of pressing the "crash button" in the event that safety is seriously compromised.
    - It is important to highlight that the flight termination system will only be activated in extreme circumstances in which is evident that the aircraft will put people in danger, crash against a critical building or element (e.g. a power plant) or is going so far that it is evident it won't be possible to recover its control.
    - The member of the organization in charge of the "crash button" will be a highly experienced and qualified UAS pilot.
- The device on ground used to activate the flight termination system must be completely independent from the rest of the system so if other parts of the system fail, the flight termination system will still work.
- Optionally, the flight termination system can also activate other complementary systems (e.g. activating a parachute) in addition to stopping the motors.
- The RC (Radio Control) radio used by safety pilots cannot operate in 2.4 GHz. Aircraft with a MTOW lower than 2 kg will be exempt from this requirement.
- Alternative bands such as 433 MHz could be used for this purpose. Teams using safety pilot radio links operating in the 5 GHz band must notify the organizing committee.
- It is compulsory that teams use RC radiolinks based on FHSS (Frequency Hopping Spread Spectrum) which makes the signal more robust against interference.

- The ERL Emergency Organising Committee does not impose any particular safety pilot radio system. Teams are free to choose the RC radiolink as long as it fulfils these requirements.
- Teams can bring multiple aerial robots to the competition (e.g. a back-up vehicle, different vehicles for different tasks, etc) but only one aerial robot will be allowed to fly at a time. All the aerial robots to be used during the competition must pass the validation tests and provide the documentation requested for registration.

5.1.5.1 Requirements for pilots

- Each aerial team must have one or more safety pilots.
- The safety pilot must be exclusively devoted to manually control the aircraft using the RC radio if needed. If the aerial team chooses to perform a mission task flying manually the safety pilot will be on charge of controlling the aircraft. If the aerial team chooses to perform a mission task flying autonomously, the safety pilot will supervise the operation and will take manual control of the aerial robot if any misbehaviour is observed during the flight.
- Safety pilots must be over 18 years old.
- Safety pilots must be properly identified with a photo ID during the competition.
- Only those pilots indicated in the documentation that has been submitted to the ERL Emergency Organising Committee will be allowed to fly.
- Not all the pilots that were included in the documentation must attend the competition (e.g. an aerial team can include in the documentation some pilots that might be attending the competition just in case that the main pilot gets ill).
- Safety pilots that intend to fly during the competition will have to perform the in-site validation flight tests.

5.1.5.2 Procedure for aerial team validation.

In order to be accepted as a participating team in ERL Emergency Robots, aerial teams will have to provide evidence showing that their aerial system is safe and they have enough knowledge and skills to safely operate it. When applying for participation, aerial teams must submit a good-quality video showing their aerial system performing the following operations:

- Take-Off operation, in manual mode.
- Hovering operation, in manual mode at 40 meters from the ground.
- Fly following a rectangular trajectory as the one shown in Figure 12, both clockwise and counter-clockwise, in manual mode. These flights must be performed at an altitude of 20 meters.

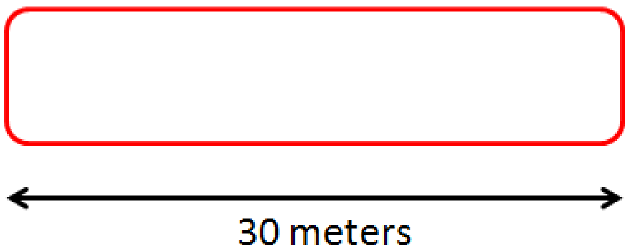


Figure 12. Flight trajectory for validation test.

- Perform vertical displacements of at least 20 meters, in manual mode.
- Landing, in manual mode.

- Execution of the flight termination functionality on the ground. The video must show how the motors are stopped when the crash button is pressed.

Teams will also have to submit the following documentation:

- Description of the aerial system and safety procedures (failsafe; GPS, signal or RC loss; battery, etc.).

Templates with guideline information on how to write this document are available at the ERL Emergency website. The submitted documentation and videos will be analysed by ERL Emergency Organising Committee. Based on this analysis the organisation will decide which teams are accepted for participation.

During the competition, flights will be subject to approval from the aerial expert designated by the Technical Committee at any time. Aerial experts will be properly identified so teams can recognise him/her. Aircraft will NOT be allowed to take-off and fly without the explicit authorisation from the ERL Emergency designated aerial expert. Teams may only fly their robots when an aerial expert from the organisation is physically present. Team pilots must follow the instructions of the ERL Emergency aerial experts at any time before, during and after the flight.

Before the actual competition, validation test flights will be carried out on-site to test that the aircraft can be flown safely by each of the team pilots. The operations that will have to be performed will be basically the same as required for the video. However, ERL Emergency aerial experts will be able to request any additional operation. ERL Emergency aerial experts will determine if a team has proven they can operate the aerial robot safely and hence that they are cleared to perform the aerial missions.

5.1.5.3 Safety pilot radio link

As the name suggests, the Remotely Piloted Aircraft Systems (RPAS) must be remotely controlled by a pilot on the ground. When operating in manual mode, the pilot is in charge of directly controlling the aircraft. When operating in autonomous mode, the aircraft is controlled by the autopilot and the pilot on the ground is in charge of taking manual control of the aircraft when any issue is experienced during flight of the aerial robot. Hence, this pilot is normally referred as the safety pilot. A specific radio link must be used exclusively as the safety pilot radio link.

It is critical that the safety pilot can take control of the aerial robot when needed. Therefore, this radio link must assure connectivity between the safety pilot and the aircraft. Most of the commercial radio links used by safety pilots operate in the 2.4 GHz ISM band. It is widely known that the 2.4 GHz ISM band is very populated as it’s used by a lot of radio systems including WiFi devices, Bluetooth, etc. For this reason, RC radio links use Frequency Hopping Spread Spectrum (FHSS) techniques in order to increase the robustness against interference. However, some interference issues affecting 2.4 GHz radio links have been reported and experienced in the past. Although these issues are not common, their effects can be catastrophic and hence it is preferred to avoid any risks. In a multi-domain robotic competition as ERL Emergency Robots, it is expected that many 2.4 GHz radio devices are used by the different robots for different communication tasks (and control, telemetry or payload sensor management). For these reasons, it is mandatory that safety pilot radio links operate in a different frequency band of the spectrum.

Note: The use of 2.4 GHz RC radiolinks is only allowed in aircrafts with a MTOW lower than 2kg. For more information please, read the section about the requirements for aerial robots.

The ERL Emergency Robots organising committee does not impose any particular safety pilot radio system. Teams are free to choose the system that best fits their requirements as long as it doesn´t operate in the 2.4 GHz band. Nevertheless, after analysing the different commercial solutions available in the market, ERL Emergency organising committee proposes using LRS (Long Range System) devices as they can be easily integrated with existing systems with minimum effort.

5.1.5.4 LRS radiolinks.

Long Range Systems (LRS) operate in the 433 MHz band. In addition to an extended range, using lower frequencies also increases the penetration of the radio frequency signals into buildings.

Figure 13. LRS module installed on a transmitter.

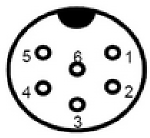
RC radio transmitters are the most expensive component of the safety pilot's radio link. Additionally, safety pilots are often reluctant to changing the radio transmitter that they normally use. Fortunately, LRS transmitters are sold as modules that can be connected to RC transmitters via what is called the trainer port as shown in Figure 13. The output of the trainer port is a PPM (Pulse Position Modulation) signal that contains the values of the different channels as commanded by the transmitter controls. When operating with an LRS module it is important to disable the 2.4 GHz radio of the RC transmitter to avoid extra radiation in that band.

Figure 14. Elements of a LRS system.

In order to use LRS, adequate LRS receivers and antennas must be installed on-board the RPA. Figure 14 shows the elements that form the LRS system including the transmitter, receiver, transmitting and receiving antennas, and cables.

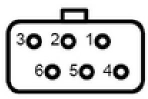
Futaba

Pin	Designation
SHIELD	GROUND
1	$V_{ENCODER}$
2	PPM_{OUT}
3	PPM_{IN}
4	V_{ENC2}
5	$V_{BATTERY}$
6	UNKNOWN

Connector: 

Futaba

Pin	Designation
1	NC
2	GROUND
3	PPM_{OUT}
4	$V_{BATTERY}$
5	$V_{ENCODER}$
6	PPM_{IN}

Connector: 

Hitec

Pin	Designation
1	$V_{SWITCHED}$
3	PPM_{OUT}
2	PPM_{IN}
4	$V_{SWITCHED}$
5	$RF_{DISABLE}$
6	GROUND
SHIELD	GROUND

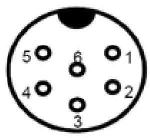
Connector: 

Figure 15. Futaba and Hitec trainer-port connectors.

When choosing a LSR device it is important to check the compatibility with commercial RC transmitters (basically this is a matter of electrical and physical characteristics of the connector). Figure 15 shows some examples of trainer ports. The cables that are used for connecting the RC transmitter to another device via the trainer port are commonly called buddy box cables.

5.1.5.5 LRS products

There are a wide variety of commercial of the shelf LRS products that are available in the market. Some of these commercial systems are presented below.

It is very important to configure failsafe in the crash button channel to keep alive motors if a radio loss in the safety pilot transmitter occurs. Otherwise it may cut power off if radio signal is not consistent enough.

ImmersionRC

ImmersionRC EzUHF transmitter (http://www.immersionrc.com/) costs between 170-200 €. It uses a 4-pin round connector (as an S-Video connector). This device can be connected to the trainer port of the following RC radios:

- Futaba radios with square connector (see Figure 16).
- Futaba radios with round connector (see Figure 17).
- Radios with jack connectors (Spektrum, JR, Turnigy, Hitec, Graupner radios).
- Radios with Multiplex DIN connectors.

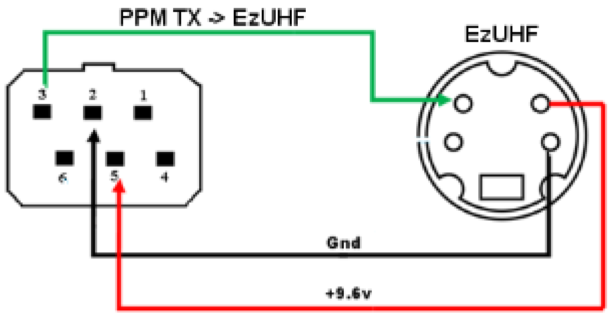


Figure 16. Connection between Futaba with square connector and EzUHF.

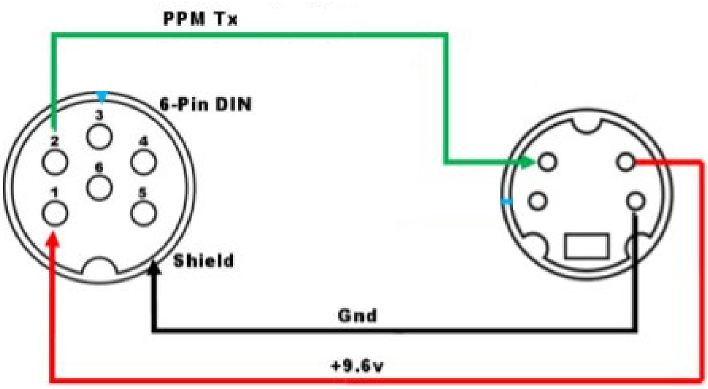


Figure 17. Connection between multiplex DIN connector and EzUHF.

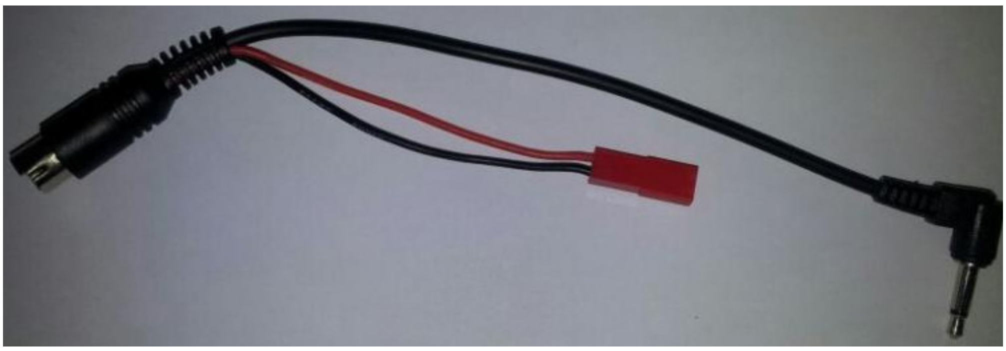


Figure 18. Buddy cable for EzUHF and Spektrum, JR, turnigy, Graupner, Fly Sky and Hitec radios.

With regards to the receiver devices, there are two suitable options:

- 8 channels with antenna diversity: 100 €.
- 8 channels without antenna diversity: 85 €

EzUHF receivers can be connected to PixHawk, APM2 and Paparazzi autopilots which are the most common open source autopilots. A complete kit including the transmitter, receiver, cables (for a specific RC radio) and antennas can be bought for around 270 €.

Dragon Link
Dragon Link transmitters cost $138 for the V2 and $238 for the V3 (http://www.fpvpro.com/store/transmitters). It uses a flat cable with 3 pins. This device can be purchased with cables for connection with the following radios (via the trainer port):

Futaba radios with square connector.
Radios with jack connectors (Spektrum, JR, Turnigy, Hitec, Graupner radios).

Receivers for this radio link have a cost, for a single unit, of $98. A complete kit including the transmitter, receiver, cables (for a specific RC radio) and antennas can be bought for $238 for the V2 and $336 for the V3 (http://www.fpvpro.com/store/complete-systems).

Orange OpenLRSng
Orange system is based on the open source LRS system called OpenLRSng (http://openlrsng.org/). This system is compatible with JR and Turnigy radio device. It can be used with Ardupilot. However, it is worth mentioning that the setup and use of OpenLRSng requires computer programming skills and basic Arduino experience. It is not a "plug and play" system. The complete kit can cost around 80-100 €.

5.1.6 Classified Data and Devices

No classified data or devices may be used by a team in preparation for or during the ERL Emergency.

5.2 Safety Check and Robot Inspection

During the set-up days, all robots will be checked by the ERL Emergency Technical Committee for compliance with the specifications and constraints described in Section 5.1. Teams will be asked to show the safety mechanisms of their robots and to demonstrate their use. A live demonstration is necessary: for example, pushing an emergency stop button while the robot is moving and verifying that the robot immediately stops. If the robot has other mechanical devices (e.g. a manipulator), their safety must be demonstrated as well.
This inspection can be done at any time during the set-up days. When teams are ready for an inspection, they can request one to the ERL Emergency Technical Committee. The inspection can be repeated at any time during the competition days, upon request of the ERL Emergency Executive or Technical Committees. Referees, organisation and technical members, team members and any other user who is interacting with the robot are always allowed to operate the safety mechanisms when there is a clear risk for the safety of any person or for the damage of any part of the environment.

Robots that are not considered safe by the Technical Committee or the Organisation Committee are not allowed to participate in the competition!

Note: The organisers do not guarantee the safety of any robot entered in the ERL Emergency competition, notwithstanding any rule or the organisers' acceptance of any application document, robot specification sheet, video demonstration or any inspection or demonstration required for participating in the ERL Emergency Robots.

5.2.1 Specific Aerial Robots Safety

Before the competition starts, all the aerial teams must attend a workshop and safety briefing given by the organising committee.

During the first day of the competition, the organisation committee will inspect all the aerial robots to be sure that they fulfil with the description provided during the application and registration phases. Flight termination mechanism will be tested on the ground to check that, when actuated, the motors are stopped. The teams whose aerial robots have passed the inspection test will have to perform a controlled flight in the competition area (with no public) according to a flight plan provided by the organising committee, so teams can show that they can operate their system in safe conditions and that they follow all the safety rules for its operation.

Safety briefings will be held at the beginning of each competition day.

Aerial teams will have to provide the organisation committee with the flight plan that will be performed during the competition in advance, at least an hour before their participation. The organisation committee can require the teams for introducing modifications in the flight plan to ensure safe flight operations. The flight plan will have to be approved by the organising committee before the flights can be authorised. Before authorising the flights each team will have to conduct pre-flight checks under the supervision of ERL Emergency safety pilots. Pre-flight checks will include at least:

- Visual structural inspection of the aerial robot and wiring.
- Testing the security radio link between the aerial robot and the safety pilot checking that movements of control surfaces are coherent with the commands issued by the safety pilot.
- Checking that GPS signal is good enough and GPS data are available for the autopilot and ground control station.

The team safety pilot of the aerial robot will be out of the Control Station tent and may enter the competition arena in order to have line of sight with the aerial robot when flying outdoors.

Two ERL Emergency safety pilots will be responsible for the safety of flights. One of the ERL Emergency safety pilots will be side by side with the team safety pilot for the whole flight time, monitoring the aircraft in line-of-sight. The other ERL Emergency safety pilot will stay with the aerial robot operator of the team (who is in charge of the Ground Control Station).

One of ERL Emergency safety pilots will be in charge of pressing the "crash button" only in the case that safety is seriously compromised. It is important to highlight that the flight termination system will only be activated in extreme circumstances in which is evident that aerial robot will put people in danger, crash against a critical building or element (e.g. a power plant) or going so far that is evident that it won't be possible to recover its control.

Team pilots must always follow the instructions of the ERL Emergency aerial experts at any time before, during and after the flight. Not doing so will cause the disqualification of the team from ERL Emergency Robots competition.

During ERL Emergency, teams must not fly anywhere if ERL Emergency safety pilots are not present. Not doing so will cause the disqualification of the team from ERL Emergency Robots competition.

ERL Emergency safety pilots will be considered as the ultimate authorities for aerial operations as they are responsible for safety. Hence, they will always have the final word with respect to the operation of the aircrafts.

5.2.2 Health & Safety Standards

All teams and robots must comply with all applicable safety regulations (see http://europe.osha.eu.int/ for details).

All teams must obey the health & safety rules and laws of the host country including the rules of ENAC (Italian Civil Aviation Authority) for the aerial robots.

5.3 Environmental Impact

Any aspect of robot activity or operation that has an unacceptable impact on the environment is prohibited. These activities include destructive robot behaviour, the use of abnormally hazardous substances or materials, and generally reckless operation. Potentially hazardous equipment or activities must be identified to the organisers for review in the vehicle (robot) specification sheet and at the site visit. Going out of the competition area or/and impacting the sensitive dune area will lead to disqualification of the team.

5.4 RF and other communication equipment

Please note that the participants must take care of the frequency regulations themselves but the organisation committee has the right to verify and enforce the regulations.

Teams must bring their own communication devices between team members. Note that the ERL Emergency Robots organisation will not provide them.

No antenna of any RF or other communication equipment used by the team shall exceed the overall height of 2.5 m.

5.4.1 Restrictions for aerial robot communications

The aerial robots cannot use the 2.4GHz for safety pilot communication. We recommend the 433 MHz channel for safety pilot communication. Other bands such as 5GHz can also be used.

Note: The use of 2.4 GHz RC radiolinks is only allowed in aircrafts with a MTOW lower than 2kg. For more information please, read the section about the requirements for aerial robots.

Aerial teams are required to specify the intended communication channels using the dedicated robot specification sheets.

Further restrictions might be added to avoid communication interference on the basis of the number of teams, robots and preferred channels.

5.5 Position Determination

Robots may be equipped to receive and process electronic position determination signals (such as GPS, GLONASS, Galileo, WAAS, EGNOS etc.) that are openly available to all teams. Any costs associated with any subscription service are borne by the team.

GPS signals might not be available throughout the route at all times (e.g. inside the building). Be aware that GPS alone might not provide adequate navigation information to the robot. Additionally, visual navigation of robots may be disturbed (i.e. dust and other visual obscurants on the route) and visual-spectrum-only sensing may not be adequate under these conditions.

5.6 Set-up and Pre-Competition Testing

Testing of robots or components is the sole responsibility of each team. The use of public lands (including aerial volume) or private spaces for this purpose is at the team's own risk and must be in accordance with the applicable country's laws.

Teams will be based in gazebos and will be provided with the following resources:

- About 16 square metres including tables and benches.
- 220 V mains electricity supply.
- Internet access.

Teams will have access to the following shared facilities:

- Pools (and possibly areas in the dock, when not in use for competition) for sea robots
- Areas for land and air robots test and set-up.

Note that:

- Teams must provide their own consumables, hand tools, drill bits and test equipment, etc.
- All team members must be skilled in the operation of all tools and equipment utilised.
- Only low voltage battery powered tools and equipment will be permitted within 2 metres of the pool.

Inspection of the competition area by any participants is not allowed without the organiser's agreement. Entering the building or inspecting through windows and/or doors the inside is completely prohibited, and will cause the disqualification of the team. Note: aerial robots may be allowed, during their time slot to approach the building.

Land robots will be given time slots and will be able to practice in a specific practice area designated by the organisers. Practising outside that specific area (e.g. practising in the competition area) without permission from the organisation will lead to disqualification of the team.

Aerial robots will be given time slots and the practise will be supervised by one of the organisation safety pilots. The robots will be allowed to fly above the building, in the area designated by the organisation. Practising outside time slots or the aerial volumes designated by the organisation and/or without the supervision of the organisation safety pilot will cause the disqualification of the team.

Marine robots will be given time slots and will be able to practise in the competition arena and pools. There will be a plume and valve for practising. Practising in the competition arena without permission from the organisation will lead to disqualification of the team.

6. Task Benchmarks

Details concerning rules, procedures, as well as scoring and benchmarking methods, are common to all task benchmarks.

Rules and Procedures

There are mandatory pre-competition safety-checks described in Section 5 of this Rule book. Only teams that successfully pass the safety checks will be able to participate in the competition.
Random safety-checks may be performed before some runs if required by the Organising Committee, the Technical Committee or another team. In the case of aerial robots, there will be also safety checks performed before each run.

The team members must inform at least one of the Organising Committee or Technical Committee member, present during the execution of the task, of any change done to the robots since the safety-check was performed.

Members of the Organising Committee/ Technical Committee present during the execution of the task will make sure if the robot complies with the other safety-related rules and robot specifications presented in Section 5.

All teams are required to perform each task according to the steps mentioned in the rules and procedures sections for the tasks.

A **trial** is an attempt to complete the Task Benchmark during a time-slot. A **run** is an attempt of completing a trial. Multiple runs are allowed within the trial time-slot and the final score of the trial will be the best run score.

Scoring and Ranking

Evaluation of the performance of a robot according to task benchmarks is based on performance equivalence classes.

The criterion defining the performance equivalence class of robots is based on the concept of *tasks required achievements*. The ranking of the robot within each equivalence class is obtained by looking at the performance criteria. In particular:

- The performance of any robot belonging to performance class N is considered as better than the performance of any robot belonging to performance class M whenever $M < N$
- Considering two robots belonging to the same class, then a penalization criterion (penalties are defined according to task performance criteria) is used and the performance of the one which received less penalization is considered as better.
- If the two robots received the same amount of penalization, the performance of the one which finished the task more quickly is considered as better (unless not being able to reach a given achievement within a given time is explicitly considered as a penalty).

Performance equivalence classes and in-class ranking of the robots are determined according to three sets:

- A set *A* of **achievements**, i.e. things that should happen (what the robot is expected to do).
- A set *PB* of **penalised behaviours**, i.e. robot behaviours that are penalised, if they happen, (e.g., manual intervention).
- A set *DB* of **disqualifying behaviours**, i.e. robot behaviours that absolutely must not happen (e.g. leave the flight volumes defined by the organisation).

Scoring is implemented with the following 3-step sorting algorithm:

1. If one or more of the elements of set *DB* occur during task execution, the robot gets disqualified (i.e. assigned to the lowest possible performance class, called class 0), and no further scoring procedures are performed.
2. Performance equivalence class X is assigned to the robot, where X corresponds to the number of achievements in set A that have been accomplished.
3. Whenever an element of set *PB* occurs, a penalisation is assigned to the robot (without changing its performance class).

One key property of this scoring system is that a robot that executes the required task completely will always be placed into a higher performance class than a robot that executes the task partially. Moreover the penalties do not make a robot change class (also in the case of incomplete task).

6.1 General Procedures

This section specifies the roles of the team members, the robot control and the procedures that will be followed for the start, restart or exit of each Task Benchmark (TBM).

6.1.1 Roles of team members

Each team must designate a single individual to serve as the **Team leader**. The team leader will serve as the primary point of contact with the organisers. The Team Leader, and only the Team Leader, will speak for the team during the competition.

For each robot one **Operator** is allowed to control/monitor (when applicable) the robot from a dedicated Control Station. Robot operators will be located in an operations tent located close to the competitions arena. They will not have line of sight with the robots all the time. In the case of aerial robots, one of the ERL Emergency safety pilots will stay with the operator to supervise the operation and ensure its safety.

One “**Command and Control Operator**” is allowed to manage the overall control of the team and supervise the coordination between robots. The Command and Control Operator has to stay in the Control Station.

For aerial robots, the **Team Safety Pilot** will be present in the competition arena within visual line of sight of the aerial robot. The safety pilot must stay in the indicated area close to the arena and only will be allowed to enter the arena to manual recovery of the robot (e.g. after it crashes) if authorised by the ERL Emergency pilots. One of the ERL Emergency safety pilots will stay with the team safety pilot to supervise the operation and ensure its safety.

For marine robots, one or two team members, the **Technical assistants** can accompany their robot (when applicable) along the run on the organisation support boat.

For ground robots, one or two team members, the **Technical assistants** can accompany their robot (when applicable) along the run.

For example, in a multi-domain team with 1 aerial robot, 2 ground robots, 1 underwater robot and 1 surface robot the people involved in the management of the team competition would be:

- 1 team leader
- 5 operators @Control Station
- 1 command and control operator @Control Station
- 2 technical assistants for sea robots
- 2 technical assistants for land robots
- 1 Safety Pilot for aerial robot.

During a task benchmark run, members of other teams (than the one participating) will not be allowed in the control stations. Red/white tape will delimit the perimeter of the tent and prevent other teams/people to come inside or stay around.

Maximum number of people allowed (excluding referees and organisers) inside the control station is 8 people (i.e. the team leader, 5 operators, the command and control operator and the safety pilot)

Teams must behave respectfully keeping a distance and quiet environment near the control stations while another team is competing. Entering in the control stations while another team is competing is completely prohibited and is cause of disqualification. Showing disrespectful behaviour may also be grounds for disqualification.

Team members are kindly asked to respect referees' decisions.

Teams are welcome to watch the competition from the spectators' areas.

6.1.2 Robot Control

There are three control stations (physical location) in the competition area. The control station for marine robots is located in the dock area near the marine competition arena. The control station for the aerial robots is located next to the fence that separates the dock area from the beach. The control station for ground robots is located in the beach area, near the spectators' area. The three operators with all their control equipment will be located in the respective control station. The control stations are part of the starting area (see Figure 19).It is not possible to see the entire competition area from the control stations. The operators must not leave their respective control stations during the Task Benchmark.

Figure 19. Example of the area of the Control Stations. (Source: Google Maps)

Only the operator/safety pilot is allowed to control the robot. The exact kind of permitted interaction depends on the chosen mode of operation, as defined in Section 5.1.1.

The technical assistants accompany the robot during the Task Benchmark, and operate the E-stop (ground robots). For marine robots, the technical assistants can accompany the robot in the rubber boat and interact with it as defined in Section 5.1 for navigation tasks. They can also interact with the robot in the manipulation tasks as defined in section 5.1.3 and 5.1.4. At any time in the preparation phase and during a scenario run an ERL Emergency official may prompt the technical assistant to put the robot in emergency stop mode due to safety or operational reasons. As soon as the official agrees, the robot may be resumed from emergency mode. In the case of aerial robots, ERL Emergency safety pilots will be in charge of the emergency stop system.

In case of emergency (i.e. imminent danger for individuals and/or the robot) the technical assistant must self-reliantly activate the emergency stop. In the case of aerial robots, ERL Emergency safety pilots will activate the emergency stop system in case of emergency.

Only due to an explicit request of the operator or safety reasons, the technical assistant/team safety pilot may interact with the robot. Without the operator's request, the technical assistant/team safety pilot may interact with the robot only in case of emergency (i.e. imminent danger for individuals and/or the robot) and only after activation of the emergency stop

In the special case of a ground robot with a safety driver, the driver may interact with the robot only in case of emergency (i.e. imminent danger for individuals and/or the robot).If so he/she must put the robot immediately into E-stop mode.

Any other unauthorised interaction between the technical assistant/safety driver and the robot will lead to the abortion of the run.

This does not apply for manipulation tasks as defined in section 5.1.1 and 5.1.3 for navigation tasks as defined in section 5.1.4

The organisers will take measures to stop a robot that does not respond promptly to an emergency stop command, even if these measures may result in damage to the robot.

Specific for marine robots:

A surface robot can use its sensors to perform tasks (e.g. mapping). Some tasks can only be performed by using an underwater robot (passing the gate, manipulation). A surface robot can collaborate with an underwater robot during the Task Benchmark via an acoustic link. The underwater robot can receive messages directly from the Control Station on-shore through an acoustic link. The type of messages allowed are navigational helps and commands to surface to get a GPS fix (when applicable) from the surface robot or orders to switch/abort tasks (or general high level commands – see the description of Semi-autonomous Mode of operation in section 5.1.1) either from the surface robot or from the Control Station. . For instance, if a team cannot perform a long range navigation task, it can decide to interrupt it and start the next subtask from a closer point. Penalties are applied for manual intervention to move the robots to a different starting point.

The underwater robot MUST remain fully submerged at a depth ≥ 1 m in all tasks. Surfacing at any time will result in termination of the Task Benchmark run except when explicitly stated. In those cases, the underwater robot can emerge for GPS fixes.
The underwater robot cannot communicate via radio link with an operator neither emerge to use GPS, unless explicitly stated in this rules document.

No physical link is admitted (wires or cables) to communicate/tele-operate the robots (except in the manipulation task). A surface robot and a underwater robot can communicate via wireless, no wire or cable between them is admitted (except in the manipulation task).

The surface robot must be autonomous and provided of a radio tele-operation system. No tele-operation is allowed except for safety reasons. Teams can perform a manual intervention (with a penalty point) to stop the surface robot without restarting the run but that surface robot is considered “lost” and cannot perform any more achievements during that run. Referees will be able to forbid a team using the surface robot if it is considered unsafe.

To close a valve, the robot should rotate the handle counterclockwise, by at least 90 degrees. A negligible friction has to be expected to perform the handle rotation. Details on the valve type can be found in the OPIs section of this document.

6.1.3 Start Procedure

Each team has to name one or two “technical assistants” and an “operator”. For aerial robot, each team has to identify also the “team safety pilot”.

Each team will be allocated a time slot for their participation in the competition.

Map and waypoints will be given on site, prior the start of the Task Benchmark.

Each robot must be enabled for operation within 5 minutes after entering the start area. Robots must be prepared and waiting in the start area up to 10 minutes before the task benchmark starts. At the designated starting time the robot must be waiting in the start area, readily prepared for operation. As soon as the departure signal is given by an ERL Emergency official (referee, safety pilot), the robot can depart from the start point.

During the departure procedure, the robot(s) will be put into operation and prepared for the start. All required material has to start being moved by the team from the unload location to the start area or deployment area (marine robots) 30 minutes before their allocated time slot. A team must place its robot in the start area prior to enabling it for operation. Note that there will be no support at this location (no table, no chair, no electricity, etc.). The support will be located at the Control Station, nearby the starting points of the land and aerial robots and of the deployment point of the marine robots.

As an example, if your time slot is at 10:00, you should start moving your robots and materials at 9:30. At 9:50 your robot(s) should be in the start point prepared and waiting for the referees' signal. At 9:55 the robots should be enable for operation. At 10:00 referees will give the start signal and the task benchmark will start. Not all the robots need to start after the referees' signal, as it will be decision of the team when they enter in action. However, all the robots participating in that task benchmark must be prepared and waiting in the starting points. The team will have first to communicate to the referee that they want to start and when given the approval, they will have 5 minutes to enable the robots before the referee gives the start.

Teams must respect their official time slot and be ready to start on time. If there is a delay on the starting time of the task benchmark, the referees may decide, depending on the factors that have cause the delay, to reallocate time-slots or to disqualify the team for that task benchmark run.

The technical assistants are responsible for operating the emergency stop systems (i.e. E-stop for land robots). Thus, he/she will leave the starting area (and the control station) and will accompany the robot as soon as the start signal has been given. In the case of aerial robots, the ERL Emergency safety pilots will be in charge of operating the emergency stop system. The whole run will be supervised by the ERL Emergency officials.

Only the referees can signal the start of operations. Only competition officials may deploy and recover the robots (i.e. marine robots) or supervise the robot deployment/recovery by teams (i.e. aerial and ground robots). This is to prevent unsafe actions in an attempt to speed the deployment and recovery processes.

Aerial robots must take off and land at the specified areas (the landing area may be different to the take-off area).

<u>Specific regulations for marine vehicles at start</u>

A surface robot can be used to support underwater robot operations with navigational helps and commands to emerge and get GPS fixes. The starting point is the same for both robots and will be given by the organisation in WGS decimal latitude and longitude coordinates as well as the set of waypoints.

For "passing the gate" task, the underwater robot has to submerge and navigate around 15 meters since the starting point until the gate. The teams will be allowed to specify robot's orientation at the beginning of the run. The robot should traverse at the controlled depth towards the centre of the arena, make a 90 degree turn, and pass through the validation gate without contacting any part of the gate. A surface robot can only be used to support the underwater robot operations but the gate has to be passed by the underwater robot.

6.1.4 On Route Procedure

While a robot is on the route, the Technical Committee might follow it.

The route will include mobile obstacles and on-the-fly modifications. For example, a dead-end can appear where the previous participant had a free road.

The robot must avoid collisions with any obstacles, moving or static, on the route. The organisers will place obstacles along the route (before the Task Benchmark run) to test obstacle avoidance capabilities. Incidental or non-damaging contact with obstacles may not result in the abortion of the run.
During the Task Benchmark there will be no communication between the operator and other individuals, especially other team members, with the exception of communication with:

- ERL Emergency officials.
- Technical assistants on the rubber boat
- The team safety pilot.
- Other team's operators (one per domain), i.e. to indicate what his/her robot(s) has detected, mapped, etc.

A part from the technical assistant, no team member will physically intervene in any aspect of robot operation or physically participate in robot tracking from the time the robot clears the start area until it is returned to the team. A robot is returned to the team after the Task Benchmark is aborted or after the robot returns to the respective starting point or designated landing area.

During the Task Benchmark refuelling or charging batteries of ground and marine vehicles is not permitted. Teams are allowed to change batteries or refuel the combustion engines of aerial robots. The time-clock will not be stopped, so any penalty will be on the time lost, not on the points. Teams will only be able to change batteries and/or refuel aerial robots combustion engines at the take-off and landing areas which will also be used as a pit stop area.

A part from designated viewing areas, teams may not operate any robot or position any team members on or near a route at any time during the ERL Emergency Robots event.
If the ERL Emergency officials determine that letting a robot proceed on the route would hinder subsequent ERL Emergency operations, the Task Benchmark can be aborted. The team may apply for a second attempt.

A team may perform multiple runs during the time-slot operations period. A trial is an attempt at completing one Task Benchmark. A trial is a set of runs during a time-slot.

<u>Specific regulations for marine vehicles on route</u>
For underwater robots in "pipe following" and "piping assembly inspection" sub-tasks:

- In the pipe following, a constant distance from the pipe should be maintained and evidence of the pipe following should be provided to the referees. In the piping assembly inspection, the robot can start at any point and circle around maintaining a constant distance (team decision).

The underwater robot can surface up to a maximum number of times defined per each Task Benchmark to communicate with other robots/Control Station in the competition arena, but without the possibility of navigating at the surface. In this case it can communicate via radio with other robots/Control Station receiving direct commands from the operator.

6.1.5 Restart Procedure

A team can request for a restart per domain at any time during a run. There is not a maximum of restarts. In this case the team is allowed to bring the robot outside the competition arena and perform any operation on the robot. It is not allowed to work on the robot on the competition area (unless the robot is stuck in a position that requires intervention on site. This will be decided by the Technical Committee). Whenever the robot is ready, it can re-enter the competition area and start a new run from the beginning. In case of having more than one robot per domain, all the robots of the domain that asks for a restart, will start a new run from the beginning. No penalties will be given for a restart. But any score achieved in the domain (by any of the robots of that domain) before the restart will be cancelled and the time will not be stopped during the restart procedure.

6.1.6 Exit Procedure

One trial ends when any of the following occur:

- The time-slot ends.
- Referees order the end of a trial.
- The Team Leader requests the end of the trial.

The same applies to each run that is part of a trial.

After the end of the time-slot, and thus the trial, as communicated by the referee(s), the robots must quickly exit the competition areas from the designated exits. The team members are allowed to manually drive, push or lift the robot. A penalty (in terms of an absolute negative score) will be given to the team if the robots are not outside the arenas 15 minutes after the end of the time-slot.

6.1.7 Abortion Procedure

A robot must not continue on the route if the Task Benchmark was aborted. The organisers will coordinate the recovery of the robot or robots together with the team. Teams may enter the competition area only if directed by the Technical Committee.

An abortion procedure can be done at any point during a run.

A team may decide to abort one domain and continue the run with the rest of domains. The referees will inform the operators of the domain that has aborted the run.

If a team aborts a trial (after aborting several runs) in one or more domains because of technical difficulties, the Technical Committee may allow repeating it, depending on available start slots.

6.2 TBM-1: *The Grand Challenge (Land +Sea+Air) – Task Benchmark*

This three-domain task benchmark is focused on acquiring knowledge about the environment and its explicit representation; and to cooperate between domains to search for the missing workers and give them assistance. The ground, underwater and aerial robots are required to understand the changes in the environment and interact with it either through cooperation between them (autonomous robot-robot) or their operators (human-robot interaction) or with a mixed approach.

Note: A minimum of one land robot, one aerial robot and one underwater robot is required to participate in this task.

6.2.1 Task Description TBM-1

A potent earthquake affects the area where a nuclear plant is located. Immediately after the earthquake, the reactors are automatically SCRAMMED and evacuation protocols followed, in accordance with safety and security procedures.

Within an hour of the initial earthquake, a tsunami arrives and strikes the nuclear plant. The high wave overwhelms the building and floods the low sections where the emergency generators are located.

The emergency response team arrives at the area soon after the tsunami. High levels of radioactive elements are present in the building and its surroundings so members of the response team must maintain a safe distance. For this reason, the use of robotic vehicles is essential.

It is time for the emergency teams to act. The priorities are to discover missing people, if the building and installations have suffered any serious damage and check if any pipe is leaking radioactive substances. It is known that a certain number of people were working in the building at that time. During a head-count, it is discovered that there are three workers missing. The robots have to search for these workers, find them as soon as possible and deploy an emergency kit. At the same time, the robots must check any damage that the earthquake and tsunami may have caused to the structure of the building and to the pipes that connect the sea with the reactor for cooling purposes. In case any pipe is damaged and or leaking radioactive material, it has to be sealed by closing the corresponding valves both in the machine room and underwater to avoid radioactive contamination. Nevertheless, special care has to be taken as closing the wrong valves may cause a reduction in the amount of seawater available for cooling down the reactor.

This task benchmark comprises three missions' goals:

- **Mission-A**: Search for missing workers.
- **Mission-B**: Reconnaissance and environmental survey.
- **Mission-C:** Pipe inspection and stemming the leak.

A concept schematic showing the outdoor, indoor and sea areas of this Task Benchmark is shown on Figure 20. This figure shows the three indicative locations of the missing workers (on land indoors and outdoors, and trapped underwater).

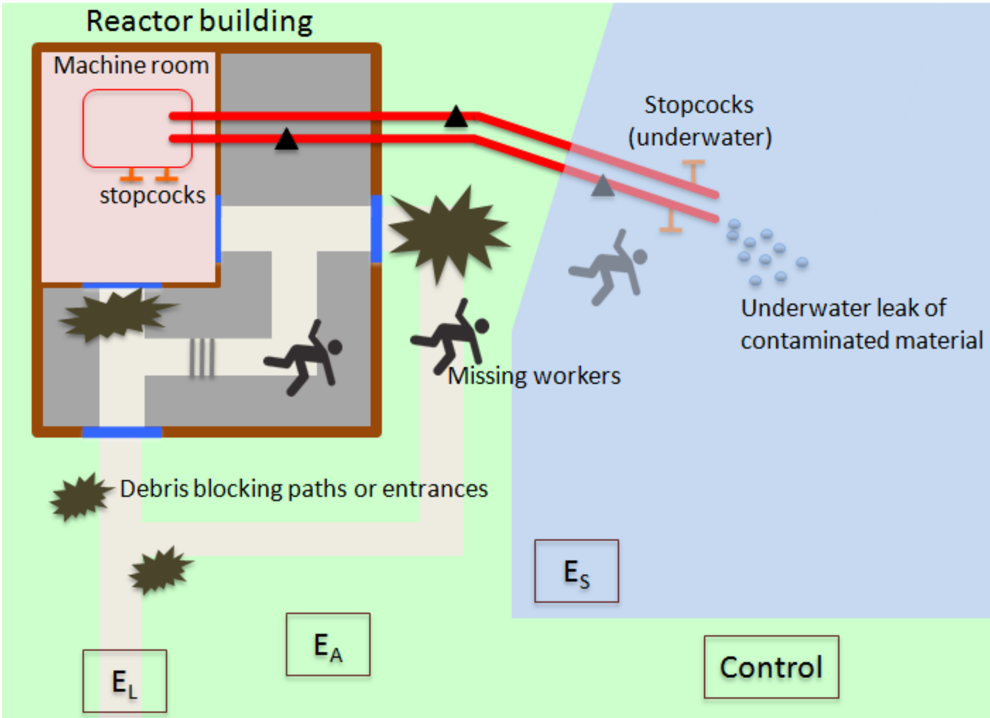


Figure 20. Concept schematic of the Grand Challenge Scenario. (EL, EA, ES : Entry/launch points for Land, Air and Sea robots) (Source: ERL Emergency)

6.2.2 Feature Variation TBM-1

The following elements may feature a variation and be rearranged before the run:

- Missing workers.
- Blocked/unblocked entrances.
- Outdoor/Indoor Obstacles
- Damages on the walls.
- Pipe damages on land
- Pipe leak on land
- Pipe leak underwater

6.2.3 Input Provided TBM-1

The teams will be able to test in the competition areas during the set-up days in dedicated time slots given by the organisation committee. Teams cannot test in the competition arenas without authorisation of the Technical Committee.

A schematic map of the building will be given to the teams at the beginning of the task. However, it will not have all detailed dimensions and may not be up to date. Entrances, corridors, rooms and the machine room are shown on the map. Teams need to be aware that the earthquake and the tsunami have probably damaged part of the external and internal structure of the building, blocking some paths and entrances. The map will indicate the Area 1 and Area 2 that must be inspected.

A set of waypoints the aerial and ground robots must reach will be given to teams during the competition days. An example is shown on Figure 21

Figure 21. Example of waypoints that robots must reach. (Source: Google Maps)

The points that define the walled search areas described in the achievements will be given to teams during the competition days.

The Objects of Potential Interest (OPIs) are summed up in the following chart:

Underwater	**Outdoor**	**Indoor**	**General**
1 Plume (made of 5 orange buoys) 1 Pipe leak Debris (4 objects) 1 gate (made of 2 orange buoys) 1correct valve (of two valves)	2 Blocked entrances. 1 unblocked entrance. 3 damages on the walls 3 Pipe damages on land 1 Pipe leak on land	1 Machine room entrance. 2 damages on the walls 1correct valve (of four valves)	3 Missing workers.

The exact location of the objects is unknown and their location may vary from one run to another. Teams can expect an unknown number of obstacles outdoors and indoors. These obstacles are fixed and will not be changed between runs.

Information and images on the OPIs can be found on Appendix I of this Rulebook.

6.2.4 Expected Robot Behaviour or Output TBM-1

Mission-A: Search for missing workers.

Search for 3 workers that are missing in the area in and around the nuclear plant. The three workers that are missing must be found as quickly as possible.

One worker is missing inside the building, another one left the building and was last seen outdoors and the third one is known to have been dragged by the tsunami to the sea and it is expected to be trapped underwater. Workers on land found during the first 30 minutes of the Task Benchmark have a good chance to be rescued alive. The worker trapped underwater is considered a casualty, but his/her position and the status of the area around him/her need to be known for emergency brigades to recover the body.

Once found, the (two) missing workers on land will require immediate first-aid assistance. For this reason, they must be provided with a first-aid kit as soon as possible. Since they could also be trapped or unable to move, this kit must be deployed near the workers.

Mission-B: Reconnaissance and environmental survey

Inspect the reactor building to evaluate the damage and find the safe path to the machine room, in which the valves are located. Inspect the underwater pipes area and find the leak (plume). This will require robots to reconnoitre the area in order to provide situational awareness to the emergency response team. For this purpose, they must create a map of the building and its surrounding area and a map of the submerged pipes area.

Robots must inspect the submerged pipes area and find the leak. They must create a 2D or 3D map of the submerged area and of the leak (plume).

Robots must enter the building and find a safe path to the machine room (a path that a ground robot can follow). For the ground robot to enter the building, an unobstructed entrance must be found first as well as a safe and unblocked path from the starting position of the ground robot. Robots will have to create a floor (2D) or 3D map of the indoor part of the building as well as a 2D or 3D map of the outdoor area surrounding the building. Robots will have to create accurate representations of a vertical wall of the building in which interesting structures may be present, in order to obtain valuable information for the emergency response team, such as the size or height of blocked/unblocked entrances or windows.

Mission-C: Pipe inspection and stemming the leak

The cooling system uses pipes that connect the reactor to the sea. After the earthquake and tsunami, these pipes might have been damaged and substances might be leaking from them. The valves that close and open the pipes are located inside the building (in the machine room) and underwater, as shown in Figure 22.

Figure 22. Each pipe has a valve in the machine room and another one underwater. (Source: ERL Emergency).

If any leak or damaged is detected, the robots must stem it by closing the correct valves in the machine room and underwater. Special care has to be taken as closing a wrong valve (in land or underwater) may cause a reduction on the amount of water provided for cooling the reactor, which can cause additional accidents in the plant.

Expected output

The output provided by the teams is a set of files that must be saved in a USB stick given to the teams before the test. The USB stick will be formatted with NTFS file system and all the files should be saved in a folder with the name of the team.

The following information will be evaluated:

- Built map of the vertical wall with width and heights required.
- Built maps with OPI marks and positions as well as the path to the machine room and the path to the entrance of building.
- OPI images, class and associated positions.
- The robot communication data
- Timing data

Vehicle Navigation Data: this must be in KML (Keyhole Markup Language) format and has the following requirements

- The data sampling frequency: 1 Hz, i.e. a data sample every one second.
- Time: UTC time
- Position: Latitude, Longitude (in decimal degrees)
- Heading: (in degrees)
- Altitude: Air/Sea domains (in meters)

Mission Status Data: This gives the information related to the status of the mission undertaken must be in KML format with the following requirements:

- Subtask undertaken: Text
- Key decision message and event message (e.g. the detection of an OPI has to be recorded here): Text
- Time: UTC time. Should be a series of Time corresponding to a series of events, e.g. the subtask starts, the subtask ends, start to close a valve, finish closing the valve, etc. The Time can be used as one of the measurements for Functionality Benchmarking.

Each team will produce a log file with the mission data. **The data must be provided to the referees 60 min for this Task Benchmarks from the end of the team's time- slo**t. The log file(s) has/have to clearly show the actions of the robot(s) during the tasks.

Map Information: this must include the following information and formats:
- The map file: (KML format – Keyhole Markup Language). KMZ files with a kmz extension
- Abstract Level information: OPIs, Features. This should be integrated in the kmz file
- 2D/3D map in raster or vector format with geo-reference information for high bandwidth data.

Vertical Map Information: this must include the following information and formats:
- File with the name 'vertical_map' containing the built map of the designated vertical wall. If the map is 2D, an image in a standard format must be provided (e.g. JPEG, PNG…), and a scale factor must be specified within the same image or inside a text file with the same filename as the map image ('vertical_map.txt'). If the map is 3D, the file type must be readily accessible using open tools such as MeshLab or CloudCompare.
- Text file with the name 'vertical_wall.txt' containing the five requested measurements in millimetres, each one in a different text line (width of the entrance door, height of the entrance door, width of the window in the first floor, height of the window in the first floor, and distance from the bottom side of the window in the first floor with respect to the ground).

Object Recognition Information: this information must be stored in KML format and include the following:
- Target ID: Text/Number
- Target position (Latitude, Longitude, Depth)
- Target image: image files (JPEG, PNG, BMP, PPM).

Robot-Robot communication data: the log of the message exchanged (with timing information) has to be provided. The teams must provide the Technical Committee a brief description of the communication protocol used between domains until to the day before the run. The teams need to let the referees know before the run if there is going to be robot-robot communication or not. If there is, the team will have to specify when (during which tasks) and between which robots, and provide logs of the messages exchanged.

Note: Maps will be accepted in different formats. Files must be provided in accessible formats, either image files or 3D maps accessible through open software such as MeshLab or CloudCompare, which support a large number of formats and are usually not unfamiliar to ROS users. However, for benchmark purposes we would appreciate that the teams try to submit the map in KML format. A KML tutorial can be found in the following link: https://developers.google.com/kml/documentation/kml_tut

All data requirements have to be met (see data exception regarding maps format). Submitted data which do not comply with the formats specified will not be accepted.

All data submitted will be used for the Functionality Benchmarking when required and as shared data as planned for the ERL Emergency Robots competition.

6.2.5 Procedures and Rules TBM-1

The Grand Challenge (GC) Task Benchmark is successfully met if all the three missions are accomplished within the Task Benchmark time. How teams decide to tackle the GC Task Benchmark is their decision. The starting locations will be given to the teams. Robots do not need to start at the same time. Teams are free to decide if they want to tackle the mission goals in parallel or in sequence and in which order. Not all of these decisions need to be communicated to the judges in advance and may be taken and changed during the run[1]. The success of the team might thus not only depend on their robots' performance, but also on their team strategy.

How many and which type of robots to deploy and how and when the tasks are going to be done is a decision of the team (as long as they do not exceed the limits established in this section).

Robots may communicate directly or via their operators at the control station (e.g. to know if an area has already been explored and if all workers have been found).

Mission-A: Search for missing workers.

The workers will be represented by mannequins. There will be a worker on the outdoor (land) area of the building, one inside the building and one underwater. There won't be any worker on the sea surface. The workers will be located in supine or prone position. The mannequins will not move during the mission.

The first-aid kit for the worker found outdoors must be deployed by the aerial robot within a radius of 2 metres of the mannequin. The first-aid kit for the worker found inside the building must be transferred from the aerial robot to the ground robot (e.g. deployed and picked up) within a radius of 1m. The ground robot will have to enter the building and leave the first-aid kit within a radius of 1 metre of the mannequin.

The first-aid kit will be a commercial one with dimensions smaller than 30x30x30 cm and weight less than 1Kg. It will be made from a material that will not break if dropped to the floor. The kit will also have a handle or handling system (made of soft or hard material). It is possible for teams to design their own handling system to be applied or adjusted to the object. There will be two first-aid kits, one for each worker found on land.

The underwater robot must look for the worker trapped underwater. The mannequin will be trapped and surrounded by debris and objects that keep it underwater. For emergency brigades to be able to recover the body is necessary to know his/her location and position, and inspect the objects that have him/her trapped.

The ground area where the mannequins will be located is shown in Figure 7. The underwater area where the mannequin can be located is the OPI areas of the sea arenas (the red square areas shown in Figure 10).

Mission-B: Reconnaissance and environmental survey

From the starting points, inspect and map the area shown in Figure 23 and Figure 10 (red area). Besides, inspect and map with the aerial robot a vertical wall of the building (the wall will be determined by the organisers and will be the same wall for all the teams). The aerial robot must keep a

[1] Although GC teams will be asked to advise referees of changes of strategy, as the competition unfolds.

minimum safety distance of 5 m from the wall. Impacts against the wall will be disqualifying behaviour.

Teams must find an unblocked entrance that can be used by a ground robot to enter the building. The aerial robot cannot enter the building. A safe path from the starting point of the ground robots to the unblocked entrance must also be found. Different markers will be used for indicating blocked and unblocked entrances.

A ground robot must then enter the building and reach and enter in the machine room. The building must also be mapped from the inside. The building has different levels, but only the ground floor must be inspected. There will be unobstructed paths (at least 70 cm wide) to the machine room from the entrance of the building. The entrance to the machine room will be open (i.e. there will be no door) and it will be marked. Robots will not be required to go up or down stairs.

Figure 23. Outdoor area to be mapped during the Grand Challenge mission-B.

The underwater robot (optionally, with the help of a surface robot) must inspect the underwater pipes area and find the leak (plume). It will have to create a 2D or 3D map of the submerged area and of the leak (plume). There will be debris and several objects in the area.

Mission-C: Pipe inspection and stemming the leak

There will be 4 pipe sections on land and 4 pipe sections underwater. Each of the 4 pipe sections on land will be logically connected to one of the underwater pipe sections. There will be two piping assemblies underwater. Two of the underwater pipe sections will be connected to one of these assemblies while the other two will be connected to the other assembly. Each assembly will have one valve which closes the two piping sections connected to the assembly. In the machine room there will be 4 valves, each of them logically associated with one of the pipes. Figure 24 shows a schematic representation of the piping structures and valves, and Figure 25 shows an example of the distribution of the pipe sections and valves on the competition venue.

The piping sections will consist of cylindrical yellow shapes. The pipe sections and valves will not be moved during the competition (i.e. they will be fixed). Their positions will also determine the correspondence between valves and pipes. A schematic map will be provided to the teams indicating this correspondence. As an example, consider the correspondence shown in Figure 25 and Figure 24. If a team finds that the pipe sections located more west of the two at the beach is leaking (see Figure 25), then they know the damaged pipe system is the number 2. To identify pipe 2, teams can either use the schematic map or identify the ID number written on the pipe. With this information they can look for pipe 2 underwater and close the correct valve, in this case, valve 1 underwater. The same happens if the underwater robot finds the leaking pipe and communicates to the aerial/land robot the number of the pipe to be inspected and of the valve to be closed. For example if the underwater robot follows the plume and finds the OPI that marks the leak on pipe 4, the valve that must be closed in the Machine room (see Figure 24) is valve number 4.

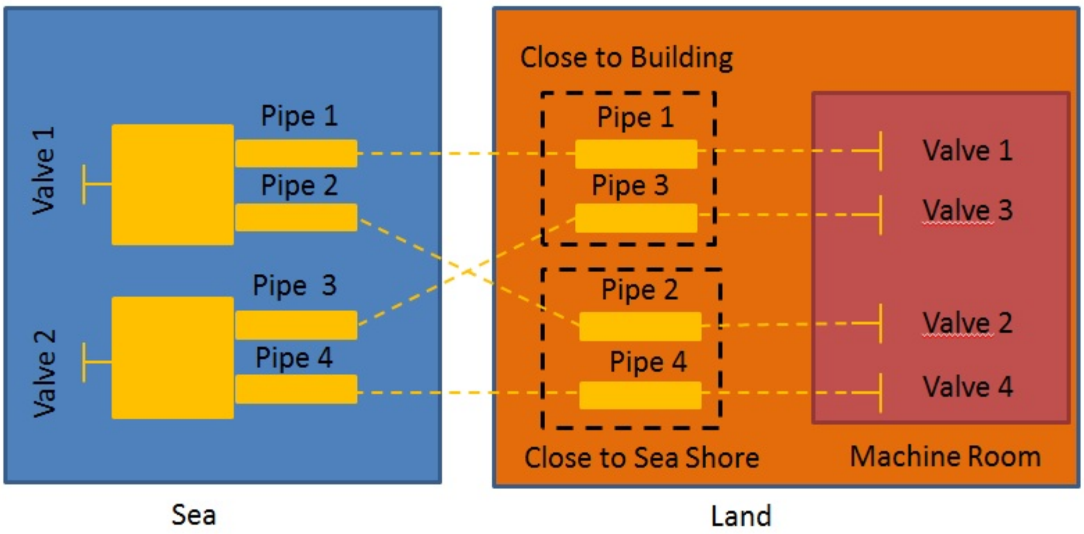


Figure 24. Schematic representation of the distribution of piping sections and valves and their correspondence. (Source: ERL Emergency).

Figure 25. Example of pipes distribution. (Source: Google Maps).

Robots must localise the pipes at land and sea. They must look for any damage on the land pipes and also the marker that represents a leak of contaminating substances. In the case of sea robots, they have to follow the plume of contaminated water to reach the pipe area and find the orange marker on the pipe that indicates a leak. They also have to follow the pipe to reach the piping assembly where the valve is mounted. Different markers will be used for representing damages, the plume and the leaks. There will be different OPIs and markers, each team will be assigned randomly a set of them. *Note: there will be no real contaminating leaks during the competition.*

After locating the damage, the robots must reach the valves at the machine room and underwater. They must then close the correct valves at the same time (i.e. synchronise the process of closing them). Closing one wrong valve underwater will incur in a disqualifying behaviour. Closing more than one wrong valve on land will incur in a disqualifying behaviour.

Robots may communicate directly or via their operators at the control station to determine both which valves must be closed and when.

The robots must find the OPIs that mark obstacles, blocked/unblocked entrances, damage to the wall, the machine room, the missing worker, etc. When an OPI is found, images must be acquired and the positions of the OPIs with respect to the map(s) built must also be provided. No recovery of OPIs is required.

The metric map will not be evaluated specifically in this Task Benchmark, it will be evaluated in the Functionality Benchmarks. However, a poor quality metric map or an out-of-date map can affect the evaluation of the position of the objects selected for the task or the path the robot has to follow. The metric map must contain the information requested and be legible by an end-user/external person.

The Task Benchmark ends when the robots accomplished all the requested achievements or when reaching the time limit (**Time limit: 100 min**), whatever occurs first. No manual intervention is allowed to save files on the USB stick during the run.

The first collection of data must be provided to the Technical Committee when the team's time-slot just finishes, this data will allow referees to check if a task has been performed autonomously or not. Teams must provide the processed data (i.e. 2D/3D maps, etc.) to the referees **within 60 min** of the end of the team's time-slot.

6.2.6 Acquisition of Benchmarking Data TBM-1

During this Task Benchmarks, the Internal Data defined in Section 6.2.4 will be collected for the following Functionality Benchmarks:

- FBM-3: Object Recognition (Sea)
- FBM-4: Vertical Wall Mapping (Air)

6.2.7 Scoring and Ranking TBM-1

The set A of achievements (in no specific order) for this task are:

Set A1: Outdoors

- An aerial robot reaches WP1A, WP2A, WP3A, within a radius of 5 meters with autonomous navigation. Waypoints can be reached in no specific order and the team can suggest additional waypoints to their flight plan.
- A ground robot reaches WP1L with a precision of 3 m avoiding obstacles along the route.
- A ground robot reaches WP2 L with a precision of 3 m avoiding obstacles along the route.
- A ground robot reaches WP3 L within a precision of 3 m in autonomous navigation avoiding obstacles along the route.
- A ground robot reaches land piping area WP4 L within a precision of 3 m in autonomous navigation avoiding obstacles along the route.
- A ground robot reaches WP5L within a precision of 3m avoiding obstacles along the route.
- A ground robot reaches WP6 L within a precision of 3m with autonomous navigation, avoiding obstacles along the route.
- Within first 30 minutes of the start of the run, a robot reports correct location (within radius of 5 m) of the missing worker outside the building
- An aerial robot deploys the first-aid kit within a radius of 2 m from the worker found on land outside the building.
- An aerial robot transfers the first-aid kit to the land robot outside the building. (It must be directly deployed on the platform or within a radius of 1 m from it).
- A robot detects the leak marker on the pipe.
- A robot reports which pipe is leaking on land.
- A robot recognises the number on the leaking pipe on land.
- Robots report which pipe(s) are damaged on land (one achievement per damage).
- Robots recognise the damages outside the building (1 achievement for damage – each damage can only be scored once).
- A robots localises the unobstructed entrance in real-time in automatic way.
- Robots localise the obstructed entrances.
- Robots find a safe and unobstructed path to the unblocked entry of the building for the ground robot (the safe path - collision free from obstacles and structures - from the starting point to the unobstructed building entrance must be showed on the map).
- The aerial robot builds a 2D or 3D map of the designated vertical wall.
- The aerial robot builds the map on board during the flight. The map must be shown to the referees just after the flight finishes.
- Robots build an outdoor map of the land pipes area with OPIs (North-West side). Use the information from each domain and from each robot to provide only one map.
- Robots build an outdoor map of the land pipes area with OPIs (North-East side).Use the information from each domain and from each robot to provide only one map.
- Robots build an outdoor map of the land pipes area with OPIs (South-West side). Use the information from each domain and from each robot to provide only one map.
- Robots build an outdoor map of the land pipes area with OPIs (South-East side).Use the information from each domain and from each robot to provide only one map.

Set A2: Indoors

- A ground robot enters the building.
- Within first 30 minutes of the start of the run, a ground robot reports correct location of missing worker inside the building
- The missing worker is detected in real-time in an automatic way.
- A ground robot deploys the first-aid kit within a radius of 1 m from the worker found inside the building.
- The ground robot(s) recognise the damages inside the building (1 achievement for damage – each damage can only be scored once).
- A ground robot finds a safe and unobstructed path to the machine room. (The safe path - collision free from obstacles and structures - from the building entrance to the machine room must be showed on the map).
- A ground robot recognises the machine room sign in real-time and in automatic way.
- A ground robot enters the machine room.
- The ground robot(s) build a geometric indoor map of the building (Area1). (Use the best map or a combination of ground robots maps).
- The ground robot(s) build a geometric indoor map of the building (Area2). (Use the best map or a combination of ground robots maps).
- The ground robot recognises the ID of the correct set of valves in the machine room.
- The ground robot closes the correct valve. The robot must close one valve of the set autonomously and the other one manually. The process must be recorded by the on board camera of the robot.

Set A2: Underwater

- The underwater robot provides acoustic and optical images of the gate.
- The underwater robot passes through the gate without touching it.
- The underwater robot passes through the gate within the first 30 minutes from the start of the run.
- The underwater robot detects the five plume buoys in real time. Images are needed.
- The underwater robot recognises the number on the five plume buoys.
- The underwater robot produces a geometric map of the plume (Area: B1+B2). Father area from the piping assembly.
- The underwater robot produces a geometric map of the plume (Area: B3+B4+B5). Closer area to the pipping assembly.
- The underwater robot detects the leak marker on the pipe in real time.
- The underwater robot recognises and provides images of the black number stamped on the leaking pipe.
- The underwater robot reports which is the number of the leaking pipe by its geometric position.
- The underwater robot inspects the 4 pipes underwater.
- Following the leaking pipe up to the assembly structure, the underwater robot provides an image mosaic of the first half of the leaking pipe.
- Following the leaking pipe up to the assembly structure, the underwater robot provides an image mosaic of the second half of the leaking pipe.
- The underwater robot provides images of the structure sides (North, South, East and West).
- The underwater robot provides a 3D reconstruction of the structure (front and rear).
- The underwater robot localises the missing worker underwater within a radius of 5 meters.

Provide images and latitude/longitude.

- The underwater robot gives the dimensions and geometrical shape of the closest object to the worker.
- The underwater robot provides 3D reconstruction of the worker.
- The underwater robot provides a 2D acoustic or optical map of the debris (Area 1 and Area 2)
- The underwater robot provides a 3D reconstruction of the manipulation console where the correct underwater valve is.
- The underwater robot closes the correct valve with a rotation of the first 45 degrees. The process must be recorded by the on board camera of the robot.
- The underwater robot closes the correct valve with a rotation of the last 45 degrees (the process must be recorded by the on board camera of the robot).

Set A4: Cooperation

- The underwater robot communicates the correct underwater leaking pipe to the aerial or to the ground robot. Directly or through the surface robot.
- The aerial or ground robot receives and decodes the message with the correct leaking pipe sent directly by the underwater or through the surface robot.
- The aerial or ground robot communicates the correct land leaking pipe to the underwater robot (directly or through the surface robot).
- The underwater robot receives and decodes the message with the correct land leaking pipe sent by the aerial or ground robot directly or through the surface robot.
- The land robot and the underwater robot close the correct valves in a synchronised process.
- The aerial robot communicates to the ground robot the safe path to the building.

Set A5: General

- The ground robots return to the landing area all the tasks have been done.
- The underwater robot surfaces in a controlled way once all the tasks have been done.
- The aerial robots return to the landing area once all the tasks have been done.
- Benchmarking data is delivered appropriately (time and format)
- The ground robot(s) transmits live position and images/video to the control station during the run.
- The aerial robot(s) transmits live position and images/video to the control station during the run.
- The marine robot(s) transmits live position and images/video to the control station during the run or the manipulation task.

The set **PB of penalised behaviour** for this task are:

- The robot needs manual intervention (e.g. a robot gets stuck). Zero intervention is permitted for marine robot and up to a maximum of two interventions are permitted for land robot, and one for the aerial robots. Note: when the maximum number of interventions reaches the allowed maximum, the run is considered terminated and a new run is restarted.
- A ground robot leaves the operating area.
- A ground robot hits the obstacles.
- The ground robot changes batteries or is refuelled during the run. Maximum one change/refuel during the run.
- The marine robot needs to change batteries. Only one change permitted.

- The underwater robot surfaces at any point (where GPS fix can be obtained) and re-submerges. When it reaches a maximum of two times, the run is terminated and the team must restart a new run. A surface to prepare the robot for the underwater manipulation is allowed without penalisation.
- The aerial robot does not keep the safety distance of 5 m with the building wall. Maximum two.

Additional penalised behaviours may be identified and added to this list if deemed necessary.

The set **DB of disqualifying behaviours** for this task are:

- A robot damages competition arena (including obstacles).
- A robot does not conform to safety regulations for the competition.
- A robot impacts the sensitive dune area.
- A robot enters any of the upper floors of the building.
- The aerial robot leaves the flight volumes defined by the organisation.
- The aerial robot impacts the building.
- The aerial robot enters the building.
- A marine robot is tele-operated (except for safety reasons agreed by the technical committee and the manipulation task).
- A robot closes a wrong valve underwater.
- A robot closes more than one wrong valve on land.

Additional disqualifying behaviours may be identified and added to this list if deemed necessary. These sets will be completed in later rule revisions.

6.3 TBM-2: *Survey the building and search for missing workers (Land +Air) – Task Benchmark*

This two-domain task benchmark is focused on acquiring knowledge about the environment and its explicit representation; and to cooperate between domains to search for the missing workers and give them assistance. The ground and aerial robots are required to understand the changes in the environment and interact with it either through cooperation between them (autonomous robot-robot) or their operators (human-robot interaction) or with a mixed approach.

Note: A minimum of one land robot and one aerial robot is required to participate in this task. No marine robots will be allowed to participate in this task.

6.3.1 Task Description TBM-2

The ground and aerial robots must perform a reconnaissance mission of the area in order to increase the situation awareness of the emergency response team. For this purpose, they must create a map of the surroundings of the building.

The emergency response team needs to discover the damages the building has suffered and find a safe path to the machine room. In order to enter the building, an unobstructed entrance must be found as well as a safe and unblocked path from the starting point of the ground robots.

Additionally, the robots need to find 2 missing workers. One worker is missing inside the building and another was last seeing outside the building. Workers found during the first 30 minutes of the task have a chance to be rescued alive. After 30 minutes the probability of a worker being found alive is low. Once found, the missing workers will require immediate first-aid assistance. For this reason, they must be provided with a first-aid kit as soon as possible. Since they could also be trapped or unable to move, this kit must be deployed near the workers.

The land robot and the aerial robot may be deployed simultaneously to search the different areas. Robots may communicate directly or via their operators at the control station (i.e. to know if an area has already been explored and if all workers have been found).

6.3.2 Feature Variation TBM-2

The following elements may feature a variation and be rearranged before the run:

- Missing workers.
- Blocked/unblocked entrances.
- Outdoor/Indoor Obstacles
- Damages on the walls.

6.3.3 Input Provided TBM-2

The teams will be able to test in the competition areas during the set-up days in dedicated time slots given by the organisation committee. Teams cannot test in the competition arenas without authorisation of the Technical Committee.

A schematic map of the building will be given to the teams at the beginning of the task. However, it will not have all detailed dimensions and may not be up to date. Entrances, corridors, rooms and the machine room are shown on the map. Teams need to be aware that the earthquake and the tsunami have probably damaged part of the external and internal structure of the building, blocking some paths and entrances. The map will indicate the Area 1 and Area 2 that must be inspected.

A set of waypoints the aerial and ground robots must reach will be given to teams during the competition days. An example is shown in Figure 21.

The points that define the walled search areas described in the achievements will be given to teams during the competition days.

The Objects of Potential Interest (OPIs) are summed up in the following chart:

Outdoor	Indoor	General
2 Blocked entrances. 1 unblocked entrance. 3 damages on the walls	1 Machine room entrance. 2 damages on the walls	2 Missing workers.

The exact location of the objects is unknown and their location may vary from one run to another. Teams can expect an unknown number of obstacles outdoors and indoors. These obstacles are fixed and will not be changed between trials.

Information and images on the OPIs can be found on Appendix I of this Rulebook.

6.3.4 Expected Robot Behaviour or Output TBM-2

From the starting points, robots must inspect and map the area shown in Figure 7. During the inspection task, teams must find an unblocked entrance that can be used by a ground robot to enter the building (either by using a ground robot or an aerial robot). A safe path from the starting point of land robot(s) to the unblocked entrance must be also found. Different markers will be used for indicating blocked and unblocked entrances.
A ground robot must then enter the building and reach the machine room to enter it. The aerial robot cannot enter the building. The building must also be mapped from the inside. The building has different levels, but only the ground floor must be inspected. Neither the ground nor the aerial robots will be allowed to enter the upper levels due to safety reasons. There will be unobstructed paths (at least 70 cm wide) to the machine room from the entrance of the building. The entrance to the machine room will be open (i.e. there will be no door) and it will be marked. The robots won't be required to go up or down stairs.

The workers will be represented by mannequins. There will be a worker on the outdoor (land) area of the building and one inside the building. The workers will be located in supine or prone position. The mannequins will not move during the mission.

The first-aid kit for the worker found outdoors must be deployed by the aerial robot within a radius of 2 metres of the mannequin. The first-aid kit for the worker found inside the building must be transferred from the aerial robot to the ground robot (e.g. deployed and picked up). The ground robot will have to enter the building and leave the first-aid kit within a radius of 1 metre of the mannequin.

Expected output

The output provided by the teams is a set of files that must be saved in a USB stick given to the teams before the test. The USB stick will be formatted with NTFS file system and all the files should be saved in a folder with the name of the team.

The following information will be evaluated:

- Built map with OPI marks and positions as well as the path to the machine room.
- OPI images, class and associated positions.
- Robot communication data
- Timing data

Vehicle Navigation Data: this must be in KML (Keyhole Markup Language) format and has the following requirements
- The data sampling frequency: 1 Hz, i.e. a data sample every one second.
- Time: UTC time
- Position: Latitude, Longitude (in decimal degrees)

- Heading: (in degrees)
- Altitude: Air/Sea domains (in meters)

Mission Status Data: This gives the information related to the status of the mission undertaken must be in KML format with the following requirements:
- Subtask undertaken: Text
- Key decision message and event message (e.g. the detection of an OPI has to be recorded here): Text
- Time: UTC time. Should be a series of Time corresponding to a series of events, e.g. the subtask starts, the subtask ends, start to close a valve, finish closing the valve, etc. The Time can be used as one of the measurements for Functionality Benchmarking.

Each team will produce a log file with the mission data. **The data must be provided to the referees 60 min for this Task Benchmarks from the end of the team's time- slo**t. The log file(s) has/have to clearly show the actions of the robot(s) during the tasks.

Map Information: this must include the following information and formats:
- The map file: (KML format – Keyhole Markup Language). KMZ files with a kmz extension
- Abstract Level information: OPIs, Features. This should be integrated in the kmz file
- 2D/3D map in raster or vector format with geo-reference information for high bandwidth data.

Object Recognition Information: this information must be stored in KML format and include the following:
- Target ID: Text/Number
- Target position (Latitude, Longitude, Depth)
- Target image: image files (JPEG, PNG, BMP, PPM).

Robot-Robot communication data: the log of the message exchanged (with timing information) has to be provided. The teams must provide the Technical Committee a brief description of the communication protocol used between domains until to the day before the run. The teams need to let the referees know before the run if there is going to be robot-robot communication or not. If there is, the team will have to specify when (during which tasks) and between which robots, and provide logs of the messages exchanged.

Note: Maps will be accepted in different formats. Files must be provided in accessible formats, either image files or 3D maps accessible through open software such as MeshLab or CloudCompare, which support a large number of formats and are usually not unfamiliar to ROS users. However, for benchmark purposes we would appreciate that the teams try to submit the map in KML format. A KML tutorial can be found in the following link: https://developers.google.com/kml/documentation/kml_tut

All data requirements have to be met (see data exception regarding maps format). Submitted data which do not comply with the formats specified will not be accepted.

All data submitted will be used for the Functionality Benchmarking when required and as shared data as planned for the ERL Emergency Robots competition.

6.3.5 Procedures and Rules TBM-2

Robots do not need to start at the same time. Teams are free to decide if they want to tackle the task achievements in parallel or in sequence and in which order.

Robots will start from their starting points and take off areas. The objects that have variations may be moved from the original position to a different position. See Section 6.1 General Procedures for more information.

From the starting point the robots must find a safe path to an unobstructed entrance of the building for a ground robot. This path must be shown on the map of the environment. Once the ground robot(s) reaches the building, it will have to inspect the building and find an unobstructed path to enter in the machine room.

The robots must search for the two workers (one outside and one inside the building) and find them within the first 30min. There will be two first-aid kits positioned at the starting point. Once found the worker outside the building, the aerial robot will deploy a first-aid kit within a radius of 2 m from the worker found on land outside the building. In the case of the worker inside the building, the aerial robot must transfer the first-aid kit to the ground robot outside the building that will deploy it within a radius of 1 m from the worker found inside the building.

The robots must find the OPIs that mark obstacles, blocked/unblocked entrances, damage to the wall, the machine room, the missing worker, etc. When an OPI is found, images must be acquired and the positions of the OPIs with respect to the map(s) built must also be provided. No recovery of OPIs is required.

The metric map will not be evaluated specifically in this Task Benchmark, it will be evaluated in the Functionality Benchmarks. However, a poor quality metric map or an out-of-date map can affect the evaluation of the position of the objects selected for the task or the path the robot has to follow. The metric map must contain the information requested and be legible by an end-user/external person.

The Task Benchmark ends when the robots accomplished all the requested achievements or when reaching the time limit (**Time limit: 45 min**), whatever occurs first. No manual intervention is allowed to save files on the USB stick during the run.

The first collection of data must be provided to the Technical Committee when the team's time-slot just finishes, this data will allow referees to check if a task has been performed autonomously or not. Teams must provide the processed data (i.e. 2D/3D maps, etc.) to the referees **within 60 min** of the end of the team's time-slot.

6.3.6 Acquisition of Benchmarking Data TBM-2

During this Task Benchmarks, the Internal Data defined in Section 6.3.4 will be collected for the following Functionality Benchmarks:

- FBM-1: 2D Mapping (Land + Air)
- FBM-2: Object Recognition (Land + Air)

6.3.7 Scoring and Ranking TBM-2

The set A of achievements (in no specific order) for this task are:

Set A1: Outdoors

- An aerial robot reaches WP1A, WP2A, WP3A, within a radius of 5 meters with autonomous navigation. Waypoints can be reached in no specific order and the team can suggest additional waypoints to their flight plan.
- A ground robot reaches WP1L with a precision of 3 m.
- A ground robot reaches WP2 L with a precision of 3 m.
- A ground robot reaches WP3 L within a precision of 3 m in autonomous navigation.
- A ground robot reaches land piping area WP4 L within a precision of 3 m in autonomous navigation.
- Within first 30 minutes of the start of the run, a robot reports correct location (within radius of 5 m) of the missing worker outside the building
- An aerial robot deploys the first-aid kit within a radius of 2 m from the worker found on land outside the building.
- An aerial robot transfers the first-aid kit to the land robot outside the building. (It must be directly deployed on the platform or within a radius of 1 m from it)
- Robots recognise the damages outside the building (1 achievement for damage – each damage can only be scored once).
- Robots localise the unobstructed entrance in an automatic way.
- Robots localise the obstructed entrances.
- Robots find a safe and unobstructed path to the unblocked entry of the building for the ground robot (the safe path - collision free from obstacles and structures - from the starting point to the unobstructed building entrance must be showed on the map).
- Robots build an outdoor map of the land pipes area with OPIs (North-West side). Use the information from each domain and from each robot to provide only one map.
- Robots build an outdoor map of the land pipes area with OPIs (North-East side).Use the information from each domain and from each robot to provide only one map.
- Robots build an outdoor map of the land pipes area with OPIs (South-West side). Use the information from each domain and from each robot to provide only one map.
- Robots build an outdoor map of the land pipes area with OPIs (South-East side).Use the information from each domain and from each robot to provide only one map.

Set A2: Indoors

- A ground robot enters the building.
- Within first 30 minutes of the start of the run, a ground robot reports correct location of missing worker inside the building
- The missing worker is detected in real-time in an automatic way.
- A ground robot deploys the first-aid kit within a radius of 1 m from the worker found inside the building.
- The ground robot(s) recognise the damages inside the building (1 achievement for damage – each damage can only be scored once).
- A ground robot finds a safe and unobstructed path to the machine room. (The safe path - collision free from obstacles and structures - from the building entrance to the machine room must be showed on the map).

- A ground robot recognizes the machine room sign in real-time and in automatic way.
- A ground robot enters the machine room.
- The ground robot(s) build a geometric indoor map of the building (Area1). (Use the best map or a combination of ground robots maps).
- The ground robot(s) build a geometric indoor map of the building (Area2). (Use the best map or a combination of ground robots maps).

Set A3: Cooperation
- The aerial robot communicates to the land robot the safe path to the building.

Set A4: General
- The aerial robots return to the landing area once all the tasks have been done.
- The ground robots return to the landing area all the tasks have been done.
- Benchmarking data is delivered appropriately (time and format)
- The ground robot(s) transmits live position and images/video to the control station during the run.
- The aerial robot(s) transmits live position and images/video to the control station during the run.

The set **PB of penalised behaviour** for this task are:

- The robot needs manual intervention (e.g. it the aerial robot falls and needs to be manually moved to the take-off area to restart the mission). One penalty per intervention. Zero intervention is permitted for marine robot and up to a maximum of one intervention is allowed for aerial robot and two interventions for land robot. Note: when the maximum number of interventions reaches the allowed maximum the run is considered terminated and a new run is restarted.
- A ground robot leaves the operating area.
- A ground robot hits the obstacles.
- A ground robot changes batteries or is refuelled during the run. Maximum one change/refuel during the run.
- The aerial robot does not keep the safety distance of 5 m with the building wall. Maximum two.

Additional penalised behaviours may be identified and added to this list if deemed necessary.

The set **DB of disqualifying behaviours** for this task are:

- A robot damages competition arena (including the obstacles):
- A robot does not conform to safety requirements for the competition.
- The aerial robot leaves the flight volumes defined by the organisation.
- A robot enters any of the upper floors of the building.
- A robot impacts the sensitive dune area.
- The aerial robot impacts the building.
- The aerial robot enters the building.

Additional disqualifying behaviours may be identified and added to this list if deemed necessary. These sets will be completed in later rule revisions.

6.4 TBM-3: *Pipe inspection and search for missing workers (Sea +Air) – Task Benchmark*

This two-domain task is focused on acquiring knowledge about the environment on land and underwater; and to cooperate between them to assist the missing workers and find the pipes leaking. The robots are required to understand the changes in the environment and interact with it either through cooperation between them or user interaction or automatically or with a mixed approach.
Note: A minimum of one underwater robot and one aerial robot is required to participate in this scenario. No land robot will be allowed to participate in this sub-challenge.

6.4.1 Task Description TBM-3

The cooling system uses pipes that connect the reactor to the sea. After the earthquake and tsunami, these pipes might have been damaged and radioactive substances might be leaking from them. The emergency team has to find out if the earthquake and tsunami have damaged any of the pipes on land or underwater.

Additionally, the robots must find two workers that are missing. One worker left the building and was last seeing in the outdoor area near the building and the other one is known to have been dragged by the tsunami to the sea and it is expected to be trapped underwater. The worker found on land during the first 30 minutes of Task Benchmark has a good chance to be rescued alive. After 30 minutes the probability of the worker being found alive is low. The worker trapped underwater is considered a casualty, but his/her position and the status of the area needs to be known for emergency brigades to recover the body.

Once found, the missing worker on land will require immediate first-aid assistance. For this reason, he/she must be provided with a first-aid kit as soon as possible. Since he/she could also be trapped or unable to move, this kit must be deployed near the worker.

The marine robot and the aerial robot may be deployed simultaneously to search the different areas. Robots may communicate directly or via their operators at the control station (i.e. to know if an area has already been explored and if all workers have been found).

6.4.2 Feature Variation TBM-3

The following elements will be rearranged before the run:

- Missing workers
- Pipe damages on land
- Pipe leak on land
- Pipe leak underwater

6.4.3 Input Provided TBM-3

The teams will be able to test in the competition areas during the set-up days in dedicated time slots given by the organisation committee. Teams cannot test in the competition arenas without authorisation of the Technical Committee.

The points that define the walled search areas described in the achievements will be given to teams during the competition days.

The OPIs are summed up in the following chart:

Underwater	On land (Outdoors)	General
1 Plume (made of 5 orange buoys) 1 Pipe leak Debris (4 objects) 1 gate (made of 2 orange buoys)	3 Pipe damages on land 1 Pipe leak on land	2 Missing Workers

6.4.4 Expected Robot Behaviour or Output TBM-3

From the starting points, robots must inspect and map the area shown in Figure 23 for the aerial robot and the OPIs area of Figure 10 for the sea robot.
There will be 4 pipe sections on land and 4 pipe sections underwater. Each of the 4 pipe sections on land will be logically connected to one of the underwater pipe sections. There will be two piping assemblies underwater. Two of the underwater pipe sections will be connected to one of these assemblies while the other two will be connected to the other assembly. Figure 26 shows a schematic representation of the piping structures for this Task Benchmark. Like in the Grand Challenge Task Benchmark, the aerial robot can identify the pipe by its position on the map (Figure 25) and communicate it to the other robot (and vice-versa).

The piping sections will consist of cylindrical yellow shapes. The pipe sections will not be moved during the competition (i.e. they will be fixed). A schematic map will be provided to the teams indicating this correspondence. In this Task Benchmark only one pipe assembly in the sea will be used.

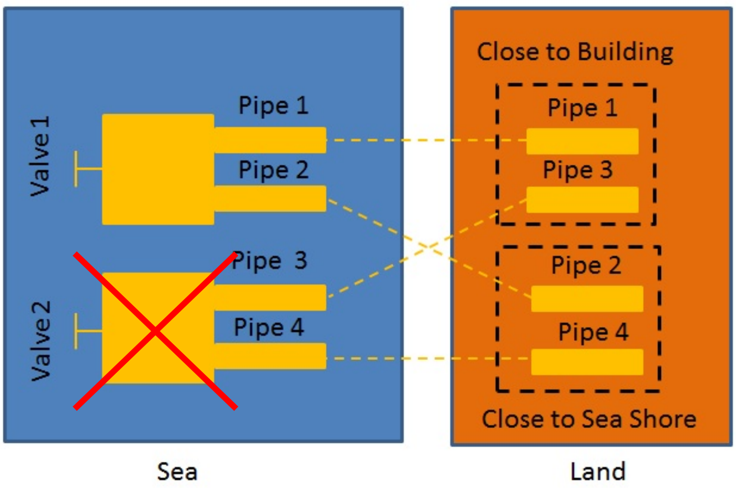


Figure 26. Schematic representation of the distribution of piping sections and valves and their correspondence for Task Benchmark TBM-3 Air+Sea. (Source: ERL Emergency)

Robots must localise the pipes at land and sea. They must look for any damage on the pipes and the pipe that leaks contaminating substances. In the case of marine robots, they have to look for the plume of contaminated water and follow it to reach the pipe that is leaking. In this Task Benchmark, only one piping assembly structure with two pipes will be present. Only one pipe will contain the leak marker. They also have to follow the pipe to reach the piping assembly where the underwater valve is mounted. Different markers will be used for representing damages, the plume and the pipe leak. The position of the markers will be changed between participations. *Note: there will not be real radioactive substances. The radioactive substances will be indicated by markers.*

The workers will be represented by mannequins. There will be a worker on the outdoor (land) area of the building and one underwater. The workers will be located in supine or prone position. The mannequins will not move during the mission.

The first-aid kit for the worker found outdoors must be deployed by the aerial robot within a radius of 2 metres of the mannequin. The worker trapped underwater is considered a casualty and does not require a first-aid kit. The first-aid kit will be a commercial one with dimensions smaller than 30x30x30 cm and weight less than 1Kg. It will be made from a material that will not break if dropped to the floor. The kit will also have a handle or handling system (made of soft or hard material). It is possible for teams to design their own handling system to be applied or adjusted to the object. There will be one first-aid kit for the worker found on land.

The marine robot(s) must look for the worker trapped underwater. The mannequin will be trapped and surrounded by debris and objects that keep it underwater. For emergency brigades to be able to recover the body it is necessary to know his/her location and position, and inspect the objects that have him/her trapped. Teams must create a 2D and/or 3D map.

Once the marine robot(s) find(s) the worker, the marine robot must surface above the mannequin or near it (within a 2m radius) to communicate the position of the worker to the aerial robot. Alternatively, it can communicate to a marine surface robot the position and the surface robot needs to move to that position (within a 5 m radius) and communicate to the aerial robot. The aerial robot must take a picture of the harbour area that shows the underwater robot (or surface robot) on the surface and geolocalise it. Note: the aerial robot must take the picture from within the authorised aerial volumes. These volumes include the take-off/landing areas.

The land and sea area where the workers can be located on land or underwater is shown in Figure 7 and Figure 10.

Expected output

The output provided by the teams is a set of files that must be saved in a USB stick given to the teams before the test. The USB stick will be formatted with NTFS file system and all the files should be saved in folder with the name of the team.

The following information will be evaluated:

- The positions and images of the damaged pipes and the missing worker.
- Maps with the area inspected including the OPIs.
- The robot communication data
- Timing data

- **Vehicle Navigation Data:** this must be in KML (Keyhole Markup Language) format and has the following requirements:
  - The data sampling frequency: 1 Hz, i.e. a data sample every one second.
  - Time: UTC time
  - Position: Latitude, Longitude (in decimal degrees)
  - Heading: (in degrees)
  - Depth: Sea Domain only (in meters)
  - Altitude: Air/Sea domains (in meters)

- **Mission Status Data:** This gives the information related to the status of the mission undertaken must be in KML format with the following requirements:
  - Subtask undertaken: Text
  - Key decision and event message (e.g. the detection of an OPI has to be recorded here): Text
  - Time: UTC time. Should be a series of Time corresponding to a series of events, e.g. the subtask starts, the subtask ends, start to close a valve, finish closing the valve, etc. The Time can be used as one of the measurements for Functionality Benchmarking.

  Each team will produce a log file with the mission data. The data must be provided to the referees within two hours (Task Benchmark (Land+Sea+Air) Grand Challenge) and one hour for the rest of Task Benchmarks from the end of the team's time- slot. The log file(s) has/have to clearly show the actions of the robot(s) during the tasks.

- **Map Information:** this must include the following information and formats:
  - The map file: (KML format – Keyhole Markup Language). KMZ files with a kmz extension
  - Abstract Level information: OPIs, Features. This should be integrated in the kmz file
  - 2D/3D map in raster or vector format with geo-reference information for high bandwidth data.

- **Object Recognition Information**: this information must be stored in KML format and include the following:
  - Target ID: Text/Number
  - Target position (Latitude, Longitude, Depth)
  - Target image: image files (JPEG, PNG, BMP, PPM).

- **Robot-Robot communication data:** the log of the message exchanged (with timing information) has to be provided. The teams must provide the Technical Committee a brief description of the communication protocol used between domains until to the day before the run. The teams need to let the referees know before the run if there is going to be robot-robot communication or not. If there is, the team will have to specify when (during which tasks) and between which robots, and provide logs of the messages exchanged.

Note: Maps will be accepted in different formats. Files must be provided in accessible formats, either image files or 3D maps accessible through open software such as MeshLab or CloudCompare, which support a large number of formats and are usually not unfamiliar to ROS users. However, for benchmark purposes we would appreciate that the teams try to submit the map in KML format. A KML tutorial can be found in the following link: https://developers.google.com/kml/documentation/kml_tut

All data requirements have to be met (see data exception regarding maps format). Submitted data which do not comply with the formats specified will not be accepted.

All data submitted will be used for the Functionality Benchmarking and as shared data as planned for the ERL Emergency Robots competition.

6.4.5 Procedures and Rules TBM-3

Robots will start from their starting points and take-off areas. The objects that have variations will be moved from the original position to a different position. See Section 6.1 General Procedures for more information.

The aerial robot must reach the pipes area, report the pipes damaged or leaking and build a map the outdoor area. The underwater robot must reach the underwater pipes area, follow the plume that leads to the piping assembly and find the pipe that is leaking underwater. It also must build a map of the pipes area.

The robots must search for the two workers (one outside the building and one underwater) and find the one on land within the first 30min. Once found, the aerial robot will deploy a first-aid kit within a radius of 2 m from the worker on land. In the case of the worker underwater, it is considered a casualty; the underwater robot will have to inspect and provide images of the objects that keep the worker trapped underwater. The underwater robot will have to surface above the mannequin within a radius of 5 metres of it; and communicate to the surface robot or directly to the aerial robot its position. The aerial robot will take a picture (from the authorised aerial volume) of the harbour area showing either the underwater robot or the surface robot on the position that marks where the mannequin is. (The image must include the location).

The robots must find the OPIs that mark damages, pipe leaks, the missing worker, etc. When an OPI is found, images must be acquired and the positions of the OPIs with respect to the map(s) built must also be provided. No recovery of OPIs is required.

The metric map will not be evaluated specifically in the Task Benchmark, it will be evaluated in the Functionality Benchmark. However, a poor quality metric map or an out-of-date map can affect the evaluation of the position of the objects selected for the task or the path the robot has to follow. The metric map must contain the information requested and be legible by an end-user/external person.

The Task Benchmark ends when the robots accomplished all the requested achievements; or when reaching the time limit (**Time limit: 45 min**) whatever occurs first. No manual intervention is allowed to save files on the USB stick during the run.

The aerial robot must return to the landing area and the underwater robot surfaces after completing the tasks. No manual intervention is allowed to save files on the USB stick during the run.

The first collection of data must be provided to the Technical Committee when the team's time-slot just finishes, this data will allow referees to check if a task has been performed autonomously or not.

Teams must provide the processed data for benchmarking purposes (i.e. 2D/3D maps, etc.) to the referees **within 60 minutes** of the end of the team's time-slot.

6.4.6 Acquisition of Benchmarking Data TBM-3

During this Task Benchmarks, the Internal Data defined in Section 6.4.4 will be collected for the following Functionality Benchmarks:

- FBM-3: Object Recognition (Sea)

6.4.7 Scoring and Ranking TBM-3

The set A of achievements (in no specific order) for this task are:

Set A1: Outdoors

- An aerial robot reaches WP1A, WP2A, WP3A, within a radius of 5 meters with autonomous navigation. Waypoints can be reached in no specific order and the team can suggest additional waypoints to their flight plan.
- Within first 30 minutes of the start of the run, an aerial robot reports correct location (within radius of 5 m) of the missing worker on land.
- An aerial robot deploys the first-aid kit within a radius of 2 m from the worker found on land.
- An aerial robot reports which pipe(s) are damaged on land (one achievement per damage).
- An aerial robot detects the leak marker on the pipe.
- An aerial robot reports which pipe is leaking on land.
- The aerial robot builds an outdoor map of the land pipes area with OPIs (North-West side). Use the information from each robot to provide only one map.
- The aerial robot builds an outdoor map of the land pipes area with OPIs (North-East side). Use the information from each robot to provide only one map.
- The aerial robot builds an outdoor map of the land pipes area with OPIs (South-West side). Use the information from each robot to provide only one map.
- The aerial robot builds an outdoor map of the land pipes area with OPIs (South-East side). Use the information from each robot to provide only one map.
- The aerial robot builds the maps on board during the flight. The maps must be shown to the referees just after the flight finishes.

Set A2: Underwater

- The underwater robot provides acoustic and optical images of the gate.
- The underwater robot passes through the gate without touching it.
- The underwater robot passes through the gate within the first 30 minutes from the start of the run.
- The underwater robot detects the five plume buoys in real time. Images are needed.
- The underwater robot recognises the number on the five plume buoys.
- The underwater robot produces a geometric map of the plume (Area: B1+B2). Father area from the piping assembly.

- The underwater robot produces a geometric map of the plume (Area: B3+B4+B5). Closer area to the pipping assembly.
- The underwater robot detects the leak marker on the pipe in real time.
- The underwater robot recognises and provides images of the black number stamped on the leaking pipe.
- The underwater robot reports which is the number of the leaking pipe by its geometric position.
- Following the leaking pipe up to the assembly structure, the underwater robot provides an image mosaic of the first half of the leaking pipe.
- Following the leaking pipe up to the assembly structure, the underwater robot provides an image mosaic of the second half of the leaking pipe.
- The underwater robot provides images of the structure sides (North, South, East and West).
- The underwater robot provides a 3D reconstruction of the structure (front and rear).
- The underwater robot provides a 2D acoustic or optical map of the debris (Area 1 and Area 2).
- The underwater robot localises the missing worker underwater within a radius of 5 meters. Provide images and latitude/longitude.
- The underwater robot gives the dimensions and geometrical shape of the closest object to the worker.
- The underwater robot provides 3D reconstruction of the worker.
- The underwater robot surfaces within a radius of 2 meters from the worker position.

Set A3: Cooperation

- The underwater robot communicates directly or through a surface robot to the aerial robot the position of the underwater worker (within a radius of 5 meters).
- The aerial robot receives and decodes the message with the position of the worker sent by the underwater/surface robot.
- The aerial robot, upon receiving the position of the underwater worker, takes a picture (from the authorised aerial volume) of the harbour area showing either the underwater robot or the surface robot on the position that marks where the worker is. (The image includes location).
- The underwater robot communicates the correct underwater leaking pipe to the aerial robot.
- The aerial robot receives and decodes the message with the correct leaking pipe sent by directly by the underwater or through the surface robot.
- The aerial robot communicates the correct land leaking pipe to the underwater robot (directly or through the surface robot).
- The underwater robot receives and decodes the message with the correct land leaking pipe sent by the aerial robot or the surface robot.

Set A4: General

- The aerial robots return to the landing area once all the tasks have been done.
- The underwater robot surfaces in a controlled way once all the tasks have been done.
- Benchmarking data is delivered appropriately (time and format)
- The aerial robot(s) transmits live position and images/video to the control station during the run.
- The marine robot(s) transmits live position and images/video to the control station during the run or the manipulation task.

The set **PB of *penalised behaviour*** for this task are:

- The robot needs manual intervention (e.g. it the aerial robot falls and needs to be manually moved to the take-off area to restart the mission). Zero intervention is permitted for marine robot and up to a maximum of one intervention is allowed for aerial robot. Note: when the maximum number of interventions reaches the allowed maximum the run is considered terminated and a new run is restarted.
- The underwater robot surfaces at any point (where GPS fix can be obtained) and re-submerges. When it reaches a maximum of two times, the run is terminated and the team must restart a new run.
- The marine robot needs to change batteries. Only one change permitted.
- The aerial robot does not keep the safety distance of 5 m with the building wall. Maximum two.

Additional penalised behaviours may be identified and added to this list if deemed necessary.

The set **DB of *disqualifying behaviours*** for this task are:

- A robot damages competition arena.
- A robot does not conform to safety regulations for the competition.
- The aerial robot leaves the flight volumes defined by the organisation.
- A marine robot is tele-operated (except for safety reasons agreed by the technical committee).
- The aerial robot enters the building.
- The aerial robot impacts the building walls.

Additional disqualifying behaviours may be identified and added to this list if deemed necessary. These sets will be completed in later rule revisions.

6.5 TBM-4: *Stem the leak (Land + Sea) – Task Benchmark*

This two-domain task is focused on acquiring knowledge about the environment and its explicit representation to find the pipes that are leaking on land and underwater; and to cooperate between them to close the correct valves to stem the leaks. The robots are required to understand the changes in the environment and interact with it either through cooperation between them or user interaction or automatically or with a mixed approach.
Note: A minimum of one underwater robot and one land robot is required to participate in this scenario. No aerial robot will be allowed to participate in this sub-challenge.

6.5.1 Task Description TBM-4

The land robot must reach the building (from a starting point given near it) while the underwater robot has to reach the pipes underwater. Robots must inspect the pipes on land and underwater to find which ones are leaking. The land robot(s) must enter the building and find a safe path to the machine room. The robots must close the correct valves to prevent the pipes leaking. Special care must be taken, as closing incorrect valves may cause a reduction of the amount of water provided for cooling the reactor. Land and marine robots must cooperate to discover the correct valves and synchronise the process of closing them. Robots may communicate directly or via their operators at the control station to decide which valves must be closed and when.

6.5.2 Feature Variation TBM-4

The following elements will be rearranged before the run:

- Blocked/unblocked entrances.
- Outdoor/Indoor Obstacles.
- Pipe leak on land.
- Pipe leak underwater.

6.5.3 Input Provided TBM-4

The teams will be able to test in the competition areas during the set-up days in dedicated time slots given by the organisation committee. Teams cannot test in the competition arenas without authorisation of the Technical Committee.

A schematic map of the building will be given to the teams at the beginning of the task. However, it will not have all detailed dimensions and may not be up to date. Entrances, corridors, rooms and the machine room are shown on the map. Teams need to be aware that the earthquake and the tsunami have probably damaged part of the external and internal structure of the building, blocking some paths and entrances.

A set of waypoints the ground robots must reach will be given to teams during the competition days.

The OPIs are summed up in the following chart:

Underwater	Outdoor	Indoor
1 Plume (made of 5 orange buoys) 1 Pipe leak Debris (4 objects) 1 gate (made of 2 orange buoys) 1correct valve (of two valves)	1 Pipe leak on land 3 damages on the building wall	1 Machine room entrance 1correct valve (of four valves)

The exact location of the objects is unknown and their location may vary from one run to another. Teams can expect an unknown number of obstacles outdoors and indoors. These obstacles are fixed and will not be changed between trials.

Information and images on the OPIs can be found on Appendix I of this Rulebook.

6.5.4 Expected Robot Behaviour or Output TBM-4

The land robots will start from a given area near the building. The marine robot has to reach the piping area.

The land robot(s) must search for a leak on the pipes on land and the underwater robot must look for the pipe that is leaking contaminating substances underwater. In the case of marine robots, they have to look for the plume of contaminated water and follow it to reach the pipe that is leaking and communicate it to the land robot. Markers will be used for representing the plume and the leak. The position of the markers will be changed between participations. *Note: there will not be real radioactive substances. The radioactive substances will be indicated by markers.*

The land robot(s) must enter the building and find a safe path to reach the machine room so it/they can close the correct valve on land. Land and marine robots must cooperate to discover the correct valves and synchronise the process of closing them.

There will be 4 pipe sections on land and 4 pipe sections underwater. Each of the 4 pipe sections on land will be logically connected to one of the underwater pipe sections. There will be two piping assemblies underwater. Two of the underwater pipe sections will be connected to one of these assemblies, while the other two will be connected to the other assembly. Each assembly will have one valve, which closes the two piping sections connected to the assembly. In the machine room there will be 4 valves, each of them logically associated with one of the pipes. However, in this task benchmark, it is known that the pipes on land close to the shore are not damaged or leaking (so no inspection of them by the land robots is required). (See Figure 27)

Figure 27. Example of pipes distribution for the Sub-Challenge: Stem the leak. (Source: Google Maps).

The piping sections will consist of cylindrical yellow shapes. The pipe sections and valves will not be moved during this task (i.e. they will be fixed). Their positions will also determine the correspondence between valves and pipes. A schematic map will be provided to the teams indicating this correspondence. As an example, consider the correspondence shown in Figure 27 and Figure 28. If a team finds that the pipe leaking on land is the one located more west of the two near the building (see Figure 27), then they know the damaged pipe is the number 3. To identify pipe 3 underwater or on land, teams can either use the schematic map (see Figure 28) or identify the ID written on the OPI.

With this information they can look for pipe 3 underwater and close the correct valve, in this case, valve 2 underwater. The same happens if the underwater robot finds the leaking pipe and communicates to the land robot the number of the pipe to be inspected and the valve to be closed. For example if the underwater robot follows the plume and finds that pipe 4 is leaking (a marker on the pipe will represent the leak), the valve that must be closed in the Machine room (see Figure 28) is valve number 4. *(Note: the red cross in Figure 28 only affects the search on land, not the correspondence of underwater pipes with the valve on land)*

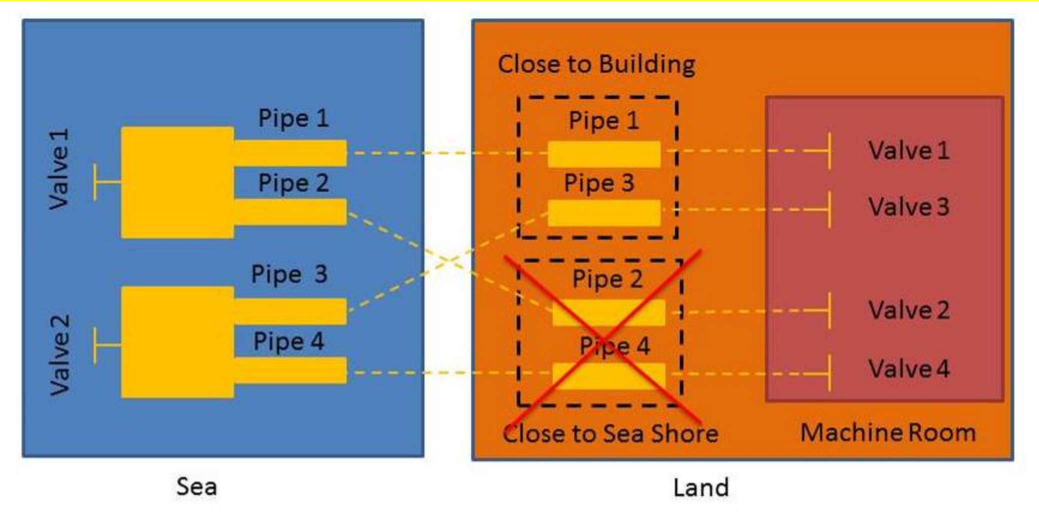


Figure 28. Schematic representation of the distribution of piping sections and valves and their correspondence for the TBM: Stem the leak. (Source: ERL Emergency).

Robots may communicate directly or via their operators at the control station to pass each other the identifying numbers of the valves that must be closed.

Expected output

The output provided by the teams is a set of files that must be saved in a USB stick given to the teams before the test. The USB stick will be formatted with NTFS file system and all the files should be saved in folder with the name of the team.

The following information will be evaluated:

- Images and position of OPIs (only relevant ones will be scored).
- Map with OPIs correctly positioned.
- The robot communication data
- Timing data

– **Vehicle Navigation Data:** this must be in KML (Keyhole Markup Language) format and has the following requirements
  - The data sampling frequency: 1 Hz, i.e. a data sample every one second.
  - Time: UTC time
  - Position: Latitude, Longitude (in decimal degrees)
  - Heading: (in degrees)

- Depth: Sea Domain only (in meters)
- Altitude: Air/Sea domains (in meters)

- **Mission Status Data:** This gives the information related to the status of the mission undertaken must be in KML format with the following requirements:
  - Subtask undertaken: Text
  - Key decision message and event message (e.g. the detection of an OPI has to be recorded here): Text
  - Time: UTC time. Should be a series of Time corresponding to a series of events, e.g. the subtask starts, the subtask ends, start to close a valve, finish closing the valve, etc. The Time can be used as one of the measurements for Functionality Benchmarking.

  Each team will produce a log file with the mission data. The data must be provided to the referees within 60 min of Task Benchmarks from the end of the team's time- slot. The log file(s) has/have to clearly show the actions of the robot(s) during the tasks.

- **Map Information:** this must include the following information and formats:
  - The map file: (KML format – Keyhole Markup Language). KMZ files with a kmz extension
  - Abstract Level information: OPIs, Features. This should be integrated in the kmz file
  - 2D/3D map in raster or vector format with geo-reference information for high bandwidth data.

- **Object Recognition Information:** this information must be stored in KML format and include the following:
  - Target ID: Text/Number
  - Target position (Latitude, Longitude, Depth)
  - Target image: image files (JPEG, PNG, BMP, PPM).

- **Robot communication data:** The log of the messages exchanged (with timing information) has to be provided. The teams must provide the Technical Committee a brief description of the communication protocol used until to the day before of the run.

All the information (map, navigation, mission status) must be stored in a single KML file if possible.

All data requirements have to be met. Submitted data which do not comply with the formats specified will not be accepted.

All data submitted will be used for the Functionality Benchmarking and as shared data as planned for the ERL Emergency Robots competition.

6.5.5 Procedures and Rules TBM-4

Robots will start from their starting points near the building and the underwater pipe area. The objects that have variations will be moved from the original position to a different position. See also Section 6.1 for information on general procedures.

The underwater robot must navigate in a straight line and after a rotation of 90 degrees has to cross the gate without touching the buoys (a total distance of about 15 m has to be covered up to the gate), reach the underwater pipes area (optionally assisted by a surface robot), the plume and find the pipe that is leaking underwater. It also must build a map of the pipes area. Once it finds the leaking pipe it must report it to the control station or the land robot.

Ground robots must inspect and build a map of the land pipes area, find the pipe that is leaking on land and report it to the control station or the underwater robot.
A ground robot must enter the building and find an unobstructed path to the machine room. This path must be shown on the map of the building. Once inside the machine room, it will have to look for the valve reported by the underwater robot.

The underwater robot will look for the valve reported by the land robot.

The ground robot and the underwater robot must close the correct valves in a synchronised process (the underwater process must be recorded by the on board camera of the underwater robot).

The robots must find the OPIs that mark pipe leaks, valves, etc,. When an OPI is found, images must be acquired and the positions of the OPIs with respect to the map(s) built must also be provided. No recovery of OPIs is required.

The metric map will not be evaluated specifically in the Task Benchmark. However, a poor quality metric map or an out-of-date map can affect the evaluation of the position of the objects selected for the task or the path the robot has to follow. The metric map must contain the information requested and be legible by an end-user/external person.

The Task Benchmark ends when the robots when the robots accomplished all the requested achievements or when reaching the time limit (**Time limit: 45 min**) whatever occurs first. No manual intervention is allowed to save files on the USB stick during the run.

The first collection of data must be provided to the Technical Committee when the team's time-slot just finishes, this data will allow referees to check if a task has been performed autonomously or not. Teams must provide the processed data for benchmarking purposes (i.e. 2D/3D maps, etc.) to the referees **within 60 min** of the end of the team's time-slot.

6.5.6 Acquisition of Benchmarking Data TBM-4

During this Task Benchmarks, the Internal Data defined in Section 6.5.4 will be collected for the following Functionality Benchmarks:

- FBM-3: Object Recognition (Sea).

6.5.7 Scoring and Ranking TBM-4

The set A of achievements (in no specific order) for this task are:

Set A1: Outdoors

- From the starting point of the building, a ground robot reaches WP5 L within a precision of 3m avoiding obstacles along the route.
- A ground robot reaches WP6 L within a precision of 3m with autonomous navigation, avoiding obstacles along the route.
- The robots recognise the damages outside the building (1 achievement for damage – each damage can only be scored once).
- The ground robot(s) build(s) an outdoor map of the land pipes area.
- A ground robot detects the leak marker on the pipe.
- A ground robot reports which pipe is leaking on land.
- A ground robot recognises the number on the leaking pipe on land.
- Robots localise the unobstructed entrance in real-time in automatic way.

Set A2: Indoors

- A ground robot enters inside the building through the unblocked entrance.
- A ground robot finds a safe and unobstructed path to the machine room. (The safe path - collision free from obstacles and structures - from the building entrance to the machine room must be showed on the map).
- The ground robot(s) build a geometric indoor map of the building (Area1). (Use the best map or a combination of ground robots maps).
- The ground robot(s) build a geometric indoor map of the building (Area2). (Use the best map or a combination of ground robots maps).
- A ground robot recognises the machine room sign in real-time in automatic way.
- A ground robot enters the machine room.
- The ground robot recognises the ID of the correct set of valves in the machine room.
- The ground robot closes the correct valve. The robot must close one valve of the set autonomously and the other one manually. The process must be recorded by the on board camera of the robot.

Set A3: Underwater

- The underwater robot provides acoustic and optical images of the gate.
- The underwater robot passes through the gate without touching it.
- The underwater robot passes through the gate within the first 30 minutes from the start of the run.
- The underwater robot detects the five plume buoys in real time. Images are needed.
- The underwater robot recognises the number on the five plume buoys.
- The underwater robot produces a geometric map of the plume (Area: B1+B2). Father area from the piping assembly.
- The underwater robot produces a geometric map of the plume (Area: B3+B4+B5). Closer area to the pipping assembly.
- The underwater robot inspects the 4 pipes underwater.
- The underwater robot detects the leak marker on the pipe in real time.

- The underwater robot reports which is the number of the leaking pipe by its geometric position.
- The underwater robot recognises and provides images of the black number stamped on the leaking pipe.
- Following the leaking pipe up to the assembly structure, the underwater robot provides an image mosaic of the first half of the leaking pipe.
- Following the leaking pipe up to the assembly structure, the underwater robot provides an image mosaic of the second half of the leaking pipe.
- The underwater robot provides a 3D reconstruction of the manipulation console where the correct underwater valve is.
- The underwater robot closes the correct valve with a rotation of the first 45 degrees. The process must be recorded by the on board camera of the robot.
- The underwater robot closes the correct valve with a rotation of the last 45 degrees (the process must be recorded by the on board camera of the robot).

Set A4: Cooperation

- The underwater robot communicates through a surface robot or directly to the ground robot the found leaking pipe.
- The ground robot receives and decodes the message with the correct leaking pipe sent by directly by the underwater or through the surface robot.
- The ground robot communicates the correct land leaking pipe to the underwater robot (directly or through the surface robot).
- The underwater robot receives and decodes the message with the correct land leaking pipe sent by the ground robot or the surface robot.
- The ground robot and the underwater robot close the correct valves in a synchronised process.

Set A5: General

- The ground robots return to the landing area all the tasks have been done.
- The underwater robot surfaces in a controlled way once all the tasks have been done.
- Benchmarking data is delivered appropriately (time and format)
- The ground robot(s) transmits live position and images/video to the control station during the run.
- The marine robot(s) transmits live position and images/video to the control station during the run or the manipulation task.

The set **PB of penalised behaviour** for this task are:

- The robot needs manual intervention (e.g. a robot gets stuck). Zero intervention is permitted for marine robot and up to a maximum of two interventions are permitted for land robot. Note: when the maximum number of interventions reaches the allowed maximum, the run is considered terminated and a new run is restarted.
- A ground robot leaves the operating area.
- The ground robot hits the obstacles.
- A ground/marine robot needs to change batteries or to be refuelled. Up to a maximum of only one change during the run.
- The underwater robot surfaces at any point (where GPS fix can be obtained) and re-submerges. When it reaches a maximum of two times, the run is terminated and the team must restart a new

run. A surface to prepare the robot for the underwater manipulation is allowed without penalisation.

Additional penalised behaviours may be identified and added to this list if deemed necessary.

The set **DB of disqualifying behaviours** for this task are:

- A robot damages competition arena.
- A robot does not conform to safety regulations for the competition.
- A robot impacts the sensitive dune area.
- A robot enters any of the upper floors of the building.
- A marine robot is tele-operated (except for safety reasons agreed by the technical committee and the manipulation task).
- A robot closes a wrong valve underwater.
- A robot closes more than one wrong valve on land.

Additional disqualifying behaviours may be identified and added to this list if deemed necessary. These sets will be completed in later rule revisions.

7. Functionality Benchmarks

In the current competition plan the Functionality Benchmarks scenarios are not designed separately to evaluate individual functionalities. Instead, they are implemented in the Task Benchmarks, so the data required for the Functionality Benchmarks will be collected during the task benchmark runs mentioned in each case. The Functionality Benchmarks will be the post-processed after the competition.

In the following sections we will define the Functionality Benchmarks for ERL Emergency Robots based on these four aspects:

- FBM-1: 2D Mapping (Land + Air)
- FBM-2: Object Recognition (Land + Air)
- FBM-3: Object Recognition (Sea)
- FBM-4: Vertical Wall Mapping (Air)

7.1 FBM-1: 2D Mapping Functionality (Land + Air)

7.1.1 Functionality Description FBM-1

This functionality benchmark measures a robot's ability to explore (cover) the 2D search and rescue area and, while doing so, visit a number of waypoints. This FBM applies to aerial and ground robots only. It will be calculated from data collected in the combined air and land robot challenge, TBM-2: Survey the building and search for missing workers.

7.1.2 Feature Variation FBM-1

The variation space for this Functionality Benchmark is as described in TBM-2.

7.1.3 Input Provided FBM-1

Teams will be provided with GPS coordinates of the waypoints, together with the boundaries of the search areas (indoor and outdoor) during the competition. See the figure below for an example with 6 waypoints (WP1 … WP6) and 4 points (C1 … C4) marking the corners of the walled search area in front of the Torre del Sale building.

Figure 29. Example of waypoints and point (Photo credit: euRathlon)

7.1.4 Expected Robot Behaviour or Output FBM-1

The robots will navigate through the 2D search and rescue area, via the waypoints provided, searching for Objects of Potential Interest (OPIs) (see also FBM-2).

Each team must provide a set of files saved on the USB stick given to teams before task TBM-2. The USB stick will be formatted with NTFS file system and all the files must be saved in a folder with the name of the team.

The following information must be provided:

Vehicle Navigation (Coverage) Data: this must be in KML (Keyhole Markup Language) format and has the following requirements

- The data sampling frequency: 1 Hz, i.e. a data sample every one second.
- Time: UTC time
- Position: Latitude, Longitude (in decimal degrees)
- Heading: (in degrees)
- Altitude: Air Domain only (in meters)

Waypoint Data: this must be in KML format[2] - as a KML <placemark> - and include the following:

- Waypoint ID: text (i.e. WP1, WP2 etc)
- Waypoint position (Latitude, Longitude)

Object Recognition Information: this information must be in KML format - as a KML <placemark> - and include the following:

- Object type: text (types as specified in Appendix 1)
- Object position (Latitude, Longitude)
- Object image: image files (JPEG, PNG, BMP, PPM).

Each team will produce a log file with the mission data. The log file(s) must clearly show the actions of robots during the task.

Note: Maps will be accepted in different formats. Files must be provided in accessible formats, either image files or 3D maps accessible through open software such as MeshLab or CloudCompare, which support a large number of formats and are usually not unfamiliar to ROS users. However, for benchmark purposes we would appreciate that the teams try to submit the map in KML format. A KML tutorial can be found in the following link: https://developers.google.com/kml/documentation/kml_tut

All data requirements have to be met (see data exception regarding maps format). Submitted data which do not comply with the formats specified will not be accepted.

The data must be provided to the referees 60 minutes from the end of the team's time- slot.

7.1.5 Procedures and Rules FBM-1

As Functionality Benchmarks are calculated from data collected during the Task Benchmarks (TBM-2), the applied procedures and rules for FBM-1 are the same as TBM-2: *(Air+Land) Survey the building and search for missing workers*.

[2] See KML tutorial https://developers.google.com/kml/documentation/kml_tut

7.1.6 Acquisition of Benchmarking Data FBM-1

During the execution of the functionality benchmark, the internal data will be collected:

- The GPS coordinates of the waypoints actually visited by the robot(s), and
- The path(s) followed by robot(s) showing the actual coverage of the search area.

After the task benchmark is completed, and within the time limit specified in the TBM, the teams must deliver the waypoint and coverage data outlined to the organisers, as a KML file that can be loaded into Google Earth.

7.1.7 Scoring and Ranking FBM-1

The 2D map coverage functionality benchmark is defined as follows. The FBM combines two values, map coverage and accuracy:

- **Map Coverage (MC):** This is simply the % of the expected map coverage actually covered by the robot. Map coverage cannot exceed 100%.

- **Accuracy:** we make use of the Root-Mean-Square Error (RMSE)[3] between real (ground truth) x, y positions and the robot's estimated x, y positions of the same features (i.e. waypoints). This is measured in m, and it is a real value metric – the lower the better.

  The Error is the (Euclidian) distance between two waypoints *e*.

  $p_i = (x_i, y_i)$

  $p_i' = (x'_i, y'_i)$

  The error (Euclidian distance) between p_i and p'_i, is

  $$e_i^2 = (x_i - x'_i)^2 + (y_i - y'_i)^2 \quad (1)$$

  Thus if we have 3 points, p_1, p_2 and p_3:

  $$RMSE = SQRT((e_1^2 + e_2^2 + e_3^2) / 3) \quad (2)$$

Example (Team A):
Suppose we have 3 features (i.e. waypoints) in the map, and the known (x, y) positions, with reference to a fixed origin or datum point, for these features are, $p_1 = (1, 1)$; $p_2 = (2, 4)$ and $p_3 = (4, 4)$, all in metres. Then the robot, using the same fixed origin, maps the terrain and locates the same three features – perhaps using SLAM or a related approach. The robot's position estimates for these features will be p'. Suppose that $p'_1 = (0.9, 1.1)$, $p'_2 = (2.05, 3.8)$ and $p'_3 = (4.1, 3.95)$.

The Root Mean Square Error is calculated using (1) and (2) above, giving an *RMSE* = 0.158m (see table below).

[3] See https://en.wikipedia.org/wiki/Root-mean-square_deviation

Root Mean Square Error					
	Ground truth p_i		Estimates p_i'		Euclidian distance
i	x	y	x	y	e_i
1	1	1	0.9	1.1	0.14
2	2	4	2.05	3.8	0.2
3	4	4	4.1	3.95	0.11
				RMSE	**0.15m**

Note that prior to calculation of the RMSE error values $e_i > MaxError$ are capped to *MaxError* and error values $e_i < MinError$ are set to zero. In 2015 euRathlon competition, on which this FBM is based, *MaxError* was set at 15m and *MinError* at 2m, thus any *e* values < 2m were rounded down to zero.

The RMSE is then normalised as follows:

MI = (MaxRMSE – RMSE) / MaxRMSE (3)

This function normalises *MI* between [0…1]. The value of *MaxRMSE* is based on the maximum value of *RMSE* of all teams competing. In the 2015 euRathlon competition, on which this FBM is based, *MaxRMSE* was set at 6.124 (rounded up to 3 places of decimals).

The 2D coverage FBM-1 in the range [0…1] will be computed using the mean of the metric index *MI* (equation 3) and the Map Coverage *MC*.

FBM1 = (MI + MC) / 2 (4)

For example, assume that *MaxRMSE* is 4 meters and the map coverage is 75% for team A, the team would score a map coverage FBM-1 of (0.96+0.75)/2 = 0.85.

Teams will be ranked within FBM-1 based on the numerical values calculated by equation 4. In the event that two teams score the same FBM-1, the team with the highest normalised RMSE score *MI* will be ranked highest.

7.2 FBM-2: Object Recognition Functionality (Land + Air)

7.2.1 Functionality Description FBM-2

This functionality benchmark has the objective of assessing the capabilities of ground and aerial robots in processing sensor data in order to recognise objects. All objects presented to the robots in this functionality benchmark are items that might be found in an outdoor and indoor disaster response environment. The benchmark requires that robots detect Objects of Potential Interest (OPIs) and identify the type of each object found. This FBM applies to aerial and ground robots only. It will be calculated from data collected in the combined air and land robot challenge, TBM-2: Survey the building and search for missing workers.

7.2.2 Feature Variation FBM-2

The variation space for this Functionality Benchmark is represented by the set of objects to be found in TBM-2, which are described in Appendix I. These objects will not be moved during the TBM.

7.2.3 Input Provided FBM-2

The input provided to teams is the set of all OPIs used within the competition. These are described in Appendix 1. Note that for FBM-2 the underwater OPIs are not applicable.

7.2.4 Expected Robot Behaviour or Output FBM-2

The robots perceive the presence of the specific objects of interest in the environment by making use of its sensors. The Object Recognition here includes object **detection** (the presence of an object) and **recognition** that identifies the type of the object (e.g. a missing worker, pipe, valve, ERIcard etc). The Object Recognition functionality also needs to provide location information of the object, and an image, although this additional information is not needed for the quantitative benchmark but only as confirmation that the correct objects have been found. The location of each object found must be marked on the same KML file provided for FBM-1, together with evidence that the OPI has been recognised (i.e. an image).

Each team must provide a set of files saved on the USB stick given to teams before task TBM-2. The USB stick will be formatted with NTFS file system and all the files must be saved in a folder with the name of the team.

The following information must be provided:

Vehicle Navigation (Coverage) Data: this must be in KML (Keyhole Markup Language) format and has the following requirements

- The data sampling frequency: 1 Hz, i.e. a data sample every one second.
- Time: UTC time
- Position: Latitude, Longitude (in decimal degrees)
- Heading: (in degrees)
- Altitude: Air Domain only (in meters)

Waypoint Data: this must be in KML format[4] - as a KML <placemark> - and include the following:

- Waypoint ID: text (i.e. WP1, WP2 etc)
- Waypoint position (Latitude, Longitude)

Object Recognition Information: this information must be in KML format - as a KML <placemark> - and include the following:

- Object type: text (types as specified in Appendix 1)
- Object position (Latitude, Longitude)
- Object image: image files (JPEG, PNG, BMP, PPM).

[4] See KML tutorial https://developers.google.com/kml/documentation/kml_tut

Note: Maps will be accepted in different formats. Files must be provided in accessible formats, either image files or 3D maps accessible through open software such as MeshLab or CloudCompare, which support a large number of formats and are usually not unfamiliar to ROS users. However, for benchmark purposes we would appreciate that the teams try to submit the map in KML format. A KML tutorial can be found in the following link: https://developers.google.com/kml/documentation/kml_tut

All data requirements have to be met (see data exception regarding maps format). Submitted data which do not comply with the formats specified will not be accepted.

Each team will produce a log file with the mission data. The log file(s) must clearly show the actions of robots during the task.

The data must be provided to the referees 60 minutes from the end of the team's time- slot.

7.2.5 Procedures and Rules FBM-2

As Functionality Benchmarks are calculated from data collected in the Task Benchmarks, the applied procedures and rules are the ones of the Task Benchmark TBM-2: *(Air+Land) Survey the building and search for missing workers.*

7.2.6 Acquisition of Benchmarking Data FBM-2

After the task benchmark is completed, and within the time limit specified in the TBM, the internal data will be collected:

- The location (GPS coordinates) of each OPIs found
- The type of each OPI found (types as defined in Appendix 1), and
- An image (or equivalent scan) of the OPI as confirmation that the OPI was found.

7.2.7 Scoring and Ranking FBM-2

The output of the FBM is (1) object detected and (2) the type of the object.

Inspired from domains of Pattern Recognition and Information Retrieval, several metrics will be used[5]:

- **Precision and Recall:** Precision is measured as the percentage of correctly recognized objects against all recognized objects which include correct ones and incorrect ones. The Recall (also known as sensitivity) is measured as the percentage of correctly recognized objects against all objects that could be detected in the scene.

  For example, suppose there are 2 missing workers, 4 pipes and 4 ERIcards (8 OPIs in total). If 3 objects are recognized but of these only 2 are correctly recognized, the precision will be 2 / 3 = 66.66%, and the recall will be 2 / 8 = 25%.

[5] See http://en.wikipedia.org/wiki/F1_score

Precision can be seen as a measure of exactness or quality, whereas recall is a measure of completeness or quantity.

- **F-measure:** Both precision and recall are real-valued, the higher the better, but to properly benchmark object recognition we need to consider them together. We use a combined measure, the traditional F-measure or balanced F-score .

The general form of F measure is

$$F_\beta = \left(1 + \beta^2\right) \cdot \frac{precision \cdot recall}{\beta^2 \cdot precision + recall} \quad (5)$$

where β is a non-negative real value.

The traditional F-measure or balanced F-score (F_1 score) is the harmonic mean of precision and recall.

The F_1 measure will be used here, i.e. $\beta = 1$.

For the example given above the F_1 measure would be (from equation 5) 2*(0.66 * 0.25)/(0.66 + 0.25) = 0.36. This is the value of the Object Recognition FBM-2.

Teams will be ranked within FBM-2 based on the numerical values calculated by equation 5. In the event that there is a tie between two teams that score the same FBM-2, the position data for OPIs will be taken into account – the team with the lowest RMSE position error will be ranked highest.

7.3 FBM-3: Object Recognition Functionality (Sea)

7.3.1 Functionality Description FBM-3

This functionality benchmark (FBM) has the objective of assessing the capabilities of an underwater robot (only data from marine robots will be considered in this FBM) in processing sensor data in order to extract information about observed objects. Specifically, the objects to be recognised in this FBM are the orange buoys (see Appendix I) simulating the leak of pollutant chemical. Each buoy is identified by a black number, from 1 to 5.

Each buoy is a particular instance of the buoy class. The benchmark requires that the robot detects the buoys and identifies them, based on the black number and their location.

The data required for this functionality benchmark will be collected from any of the following Task Benchmarks:

- TMB-1: (Air + Land +Sea) The Grand Challenge
- TBM-3: (Sea + Air) Pipe inspection and search for missing workers
- TBM-4: (Land + Sea) Stem the leak

7.3.2 Feature Variation FBM-3

5 orange buoys (described in Appendix I) will be present in each run. The position of the buoys may be varied from one TBM to another, but will not be changed during the task benchmark.

7.3.3 Input Provided FBM-3

The present objects in this FBM will be instances of the buoy class. 5 instances will be present in an area to be surveyed (~20 m x 20 m). The area will be given to the teams in the previous days of the competition in the form of 4 GPS coordinates corresponding to the corners of the area.

Each buoy is identified by a black distinctive number (H between 100 mm and 150 mm, reproduced twice or thrice along the equatorial plane). Numbers will go from 1 to 5, with the smaller number positioned farther from the pipe assembly structure. The number identifies the object instance unique ID. Teams need to recognise the number and localise the object correctly to label them.

Object ID= [object class, object instance]

Object class	Object instance
Buoy	1
Buoy	2
Buoy	3
Buoy	4
Buoy	5

7.3.4 Expected Robot Behaviour or Output FBM-3

The acoustic and/or optical imaging sensors of the underwater robot must gather the data.

In this FBM, only the data collected by an underwater robot will be considered.

The robot must provide the object ID (Object class, Object instance) of the detected buoys. The robot must also provide the position of the objects. The imagery of the object must be acquired by the robot. The provided log of the robot must show together with the robot navigation data, the timing at which the detection has been carried out with the object ID and position.

The team must provide a set of files saved in the USB stick given to the teams before the task. The USB stick will be formatted with NTFS file system and all the files must be saved in a folder with the name of the team.

The following information must be provided:

Object Recognition Information: this information must be stored in KML format and include the following:

- Object ID: Class/Instance

- Object position (Latitude, Longitude, Depth)
- Object image: image files (JPEG, PNG, BMP, PPM).

Vehicle Navigation Data: this must be in KML (Keyhole Markup Language) format and has the following requirements

- The data sampling frequency: 1 Hz, i.e. a data sample every one second.
- Time: UTC time
- Position: Latitude, Longitude (in decimal degrees)
- Heading: (in degrees)
- Depth: Sea Domain only (in meters)

Mission Status Data: This gives the information related to the status of the mission undertaken must be in KML format with the following requirements:

- Subtask undertaken: Text
- Key decision message and event message (e.g. the detection of the OPI has to be recorded here): Text
- Time: UTC time. Should be a series of Time corresponding to a series of events, e.g. the subtask starts, the subtask ends, start to close a valve, finish closing the valve, etc.

Each team will produce a log file with the mission data. The log file(s) must clearly show the actions of the underwater robot during the task.

The data must be provided to the referees 60 minutes from the end of the team's time- slot.

Map Information: map only produced by an underwater robot of the area to be surveyed containing the buoys; this must include the following information and formats:

- The map file: (KML format – Keyhole Markup Language). KMZ files with a kmz extension
- Abstract Level information: OPIs. This should be integrated in the kmz file.

Note: Maps will be accepted in different formats. Files must be provided in accessible formats, either image files or 3D maps accessible through open software such as MeshLab or CloudCompare, which support a large number of formats and are usually not unfamiliar to ROS users. However, for benchmark purposes we would appreciate that the teams try to submit the map in KML format. A KML tutorial can be found in the following link: https://developers.google.com/kml/documentation/kml_tut

All data requirements have to be met (see data exception regarding maps format). Submitted data which do not comply with the formats specified will not be accepted.

7.3.5 Procedures and Rules FBM-3

As Functionality Benchmarks are implemented in the Task Benchmarks, the applied procedures and rules are the ones of the Task Benchmark. The FBM performance will be computed on each TBM. The best performance will be the one considered for the final FBM ranking.

7.3.6 Acquisition of Benchmarking Data FBM-3

During the execution of the benchmark, the Internal Data will be collected:

- Number and ID of detected buoys
- Imaging of the detected buoys (acoustic and/or optical)
- Position of the detected buoys
- Robot navigation log
- Robot log showing the executed detection

7.3.7 Scoring and Ranking FBM-3

Evaluation of the performance of a robot according to this functionality benchmark is based on:

1. The number of correctly identified (CI) objects via the black distinctive number (instances of buoy class with relative number – recognised ID).

2. The number of correctly classified (CC) objects (instances of buoy class without the detection of the black number – the team must provide evidence from imaging, navigation log and object position related to the classified object).

3. Position error (PE) for all correctly identified/classified objects. The position error will be calculated based on the Euclidean distance error between the detection and the ground truth.

The previous criteria are in order of importance, since this functionality benchmark is primarily focused on object recognition.

The formula used for scoring the FBM is: SCORE=2.5*CI+CC.
The ties are broken by using the position error for all the identified/classified objects. The average of the best two position errors for the detected objects (i.e. the minimum and second minimum) will be considered.

7.4 FBM-4: Vertical Wall Mapping Functionality (Air)

7.4.1 Functionality Description FBM-4

This functionality benchmark has the objective of assessing the capabilities of aerial robots in extracting specific information about the damaged building. The data will be collected during the (Land+Sea+Air) The Grand Challenge Task Benchmark.

Aerial robots must inspect and map a vertical wall of the building in which interesting structures are present, in order to obtain valuable information for the emergency response team. In this context, a map is defined as "any digital representation of the environment suitable for performing other functionalities" such as localisation, path planning or object recognition. Depending on the specific robot platform under test, mapping requires a more or less extended exploration of the environment.

The emergency response team is interested in obtaining high valuable information of the damaged building from the outside, to assess further inspections to be performed by other response teams. The teams will be required to explore a specific wall of the damaged building. The wall to be explored will be determined by the organisers during the competition days and will be the same wall for all the teams. After the exploration, teams must provide a 2D or 3D map of the designated wall along with several metric measurements, which must be calculated from such map. The requested metric measurements are the size of the entrance door, the size of the window in the first floor, and the distance from the bottom side of the window in the first floor with respect to the ground.

Figure 30. Damaged building to be inspected (Photo credit: euRathlon)

Figure 31. Three possibilities for wall inspection, the one to be inspected will be decided during the competition days (Photo credit: euRathlon).

7.4.2 Feature Variation FBM-4

There is no variation for this Functionality Benchmark since the wall to inspect will be the same for all the teams, and the requested metric measurements will not change.

7.4.3 Input Provided FBM-4

The teams will be provided during the competition days with a satellite view of the damaged building indicating the wall to be vertically inspected.

Figure 32. Example of designation of the wall to be inspected (Photo credit: euRathlon).

7.4.4 Expected Robot Behaviour or Output FBM-4

The teams must command the aerial robot to go to the designated wall and gather data in order to obtain the requested information. The aerial robot should carry out a mission to acquire the necessary sensor information to build the map. The aerial robot must keep a minimum safety distance of 5 meters from the wall. Impacts against the wall will be penalised. After the data acquisition is completed, the aerial robot must return to the designated landing area.

The map must be built using sensor information, and it is mandatory that the requested metric measurements that the teams calculate are derived or extracted from such map (not from human inspection of the building). If the provided map is 2D, an appropriate scale factor must be also specified to derive the metric measurements. If the map is 3D, there is no need for specifying a scale factor.

The output provided by the teams is a set of files that must be saved in a USB stick given to the teams before the task. The USB stick will be formatted with NTFS file system and all the files must be saved in a folder with the name of the team.

The following information will be evaluated for this Functionality Benchmark:

- File with the name 'vertical_map' containing the built map of the designated vertical wall. If the map is 2D, an image in a standard format must be provided (e.g. JPEG, PNG…), and a scale factor must be specified within the same image or inside a text file with the same filename as the map image ('vertical_map.txt'). If the map is 3D, the file type must be readily accessible using open tools such as MeshLab or CloudCompare.
- Text file with the name 'vertical_wall.txt' containing the five requested measurements in millimetres, each one in a different text line (width of the entrance door, height of the entrance door, width of the window in the first floor, height of the window in the first floor, and distance from the bottom side of the window in the first floor with respect to the ground).

7.4.5 Procedures and Rules FBM-4

As Functionality Benchmarks are implemented in the Task Benchmarks, the applied procedures and rules are the ones of the Task Benchmark: (Land+Sea+Air) The Grand Challenge.

The aerial robot must perform the operation within the authorised flight volumes in the competition area. The aerial robot must keep a minimum safety distance of 5 m from the wall. Impacts against the wall will be penalised.

7.4.6 Acquisition of Benchmarking Data FBM-4

After the task benchmark is completed, and within the time limit specified in the TBM, the teams must deliver the organisers the following data to be used for this FBM:

- a 2D or 3D map of the designated vertical wall,
- the width and height of the entrance door,
- the width and height of the window in the first floor, and
- the distance from the bottom side of the window in the first floor with respect to the ground.

7.4.7 Scoring and Ranking FBM-4

For each team, an accuracy metric will be used to score the performance of this functionality. We propose the Root-Mean-Square Error (RMSE) between real (ground truth) distances and the robot's estimated measurements. This is measured in mm, and it is a real value metric – the lower the better.

We require the teams to obtain the following information:

- width and height of the entrance door,
- width and height of the window in the first floor, and
- distance from the bottom side of the window in the first floor with respect to the ground.

If we have these five ground truth distances d_i and the five estimated distances $\hat{d}_i$ for evaluation, the RMSE is calculated as follows, and rounded so it does not have decimals:

$$RMSE = \sqrt{\frac{1}{5}\sum_{i=1}^{5}\left(d_i - \hat{d}_i\right)^2}$$

For this error, a metric $Index$ is calculated so the score is between 0 and 1. This is performed by using a maximum admissible error $MaxError$, so that

$$Index = \begin{cases} \frac{MaxError - RMSE}{MaxError} & if\ RMSE < MaxError \\ 0 & if\ RMSE \geq MaxError \end{cases}$$

The value of MaxError will be determined based on competitor's performances.

Teams will be ranked based on this $Index$, from highest to lowest. Ties are broken by observing which team obtained less error in the estimated size of the entrance door (width error + height error), then in the estimated size of the window in the first floor (width error + height error), and finally in the estimated distance from the bottom side of the window in the first floor with respect to the ground.

Example:
Suppose the ground truth values and the estimated measurements from one team are the ones indicated in the following table:

Measurements	**Ground truth values (mm)**	**Team's estimated values (mm)**
Width of the entrance door	d_1=2034	$\hat{d}_1$=2156
Height of the entrance door	d_2=2506	$\hat{d}_2$=2387

Width of the window in the first floor	d_3=1243	$\hat{d}_3$=1492
Height of the window in the first floor	d_4=1688	$\hat{d}_4$=1517
Distance from the bottom side of the window in the first floor to the ground	d_5=6342	$\hat{d}_5$=6791

Thus, for the example above, the RMSE will be 254 mm.

Errors between values (mm)	Squared errors	Averaged sum of squared errors
-122	14884	64377,6
119	14161	
-249	62001	**RMSE**
171	29241	253,7274128
-449	201601	

From this error, the final metric $Index$ is calculated by establishing a maximum admissible error $MaxError$. If for example this maximum error is set to 500 mm,

$$Index = \frac{MaxError - RMSE}{MaxError} = 0.49$$

8. Contact information

Official information concerning rules, interpretations, and information about the competition can be found on ERL Emergency website http://www.robotics-league.eu or you can contact us at erl.emergency@robotics-league.eu

Appendix I: Objects of Potential Interest (OPI)

This appendix describes the Objects of Potential Interest (OPI) that have to be found in the ERL Emergency Robots Task Benchmarks. It also includes a summary of the OPIs as help.

The list of OPIs regarding to the Task Benchmarks are:

1. Blocked and unblocked entrances

Cards of different colours (similar to those shown in Figure 33) will be used as markers for the blocked and unblocked entrances to the reactor building. They will be A3 in size and will be located close to the entrance they refer to. In order to find the blocked and unblocked entrances to the reactor building, robots will have to find these markers and provide evidence to the referees. The green marker includes an Augmented Reality code. The code represented in the figure is only representative. The exact code will be given prior to the competition.

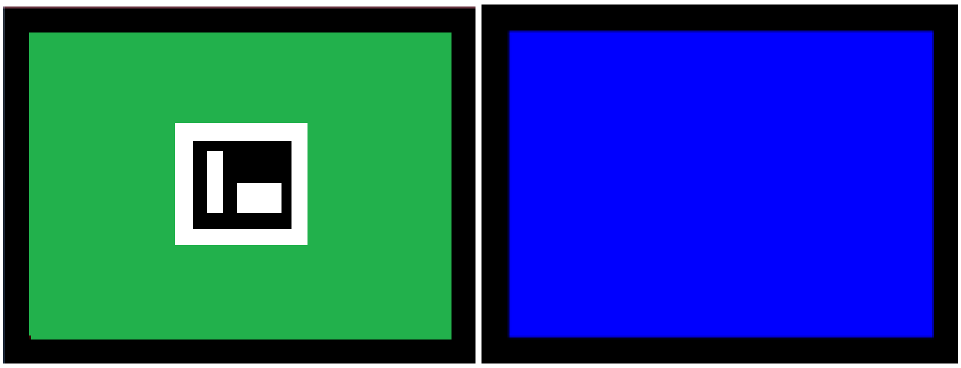


Figure 33. Markers for unblocked (left) and blocked (right) entrances.

2. Damages on land pipes and building

Red markers cards similar to those shown in Figure 34 will be used to represent structural damages in the building (if found inside the building). And also will be used to represent damages on the land pipes (if found in the land pipe area). They will be A3 in size and can be located both outside and inside the building.

Figure 34. Marker for damages on the pipes and also structural damages in the building.

3. Machine room

A card sign similar to that shown in Figure 35 will be used to indicate the teams which is the machine room. This card will be located close to the machine room entrance and will be at least 40 x 40 cm in size. In order to find the machine room, robots will have to find this marker and provide evidence to the judges.

Figure 35. Machine room sign.

4. Missing worker

Mannequins wearing bright-colour work clothes will be used to represent the missing workers. An example is shown in Figure 36.

Figure 36. Mannequin representing a missing worker. Photo: euRathlon

5. First-Aid Kit

The first-aid kit will be a comercial one with dimensions smaller than 30x30x30 cm and weight less than 1Kg. It will be made from a material that will not break if dropped to the floor. The kit will also have a handle or handling system (made of soft or hard material). It is possible for teams to design their own handling system to be applied or adjusted to the object. There will be two first-aid kits, one for each worker found on land.

The first-aid kit that the organisation will most likely use is a “Reliance Medical Green Scandi Copenhagen First Aid Bag”. http://www.reliancemedical.co.uk/product/helsinki-bag/

Figure 37. First-Aid kit. Photo: Reliance Medical

6. Plume and Gate

The marine OPIs will be soft reflective (both acoustically and optically) approximately spherical objects (see Figure 38) and they will be located at mid-water (between 0.5 m and 1.5 m altitude from the bottom). They will be tethered to the ground by a light rope. For what concerns the dimensions, they will fit in spheres with OD between 0.25 m to 0.5 m. OPIs will be orange in colour with a black distinctive number (with a height between 100 mm and 150 mm, reproduced twice or thrice along the equatorial plane). The number of the OPIs will be provided to the teams before the Competition (a maximum of 5 OPIs will be placed in the area for simulating the plume and mapping tasks). The gate will be constituted by two of these OPIs without any number.

We suggest that teams assume that the buoys will be visible only from a close (1-2 m) distance but these conditions constantly change according to the weather (lighting conditions, sea state, water turbidity…).

Figure 38. Image of the buoy without a number (gate) and with a number (plume). The OD of the sphere is 30 cm.

7. Pipes and Leaks

During the competitions, there are several tasks related with pipe inspection The following pipes are located in the operation area:

Figure 39. Pipes and valves locations (for land and for underwater robots).

On land:

On land, 2 pipes are positioned on the shore and 2 pipes coming out from the building (for a total of 4 pipes) as shown in Figure 39. Each pipe is associated to an ID number, from 1 to 4 and these numbers are painted in black colour on the pipe. For details about how these pipe sections look like see Figure 41 and Figure 42. The pipes will have red markers such as in Figure 34 to represent damages and a blue marker with a symbol to represent a leak (see Figure 40). The symbol may vary and will be given prior to the competition.

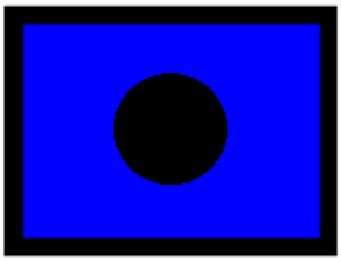


Figure 40. Marker representing a leak on a pipe.

Underwater:

There will be two piping assembly structures underwater. These piping assemblies consist of cylindrical shapes, yellow in colour, OD=0.5 m by LG=1.5 m (shown in Figure 41). The structure, composed of yellow pipes, has the following dimensions: 2 m (front area) x 3 m x 1.8 m (height).arranged to form a 3D structure. The assembly will be placed on the bottom and will not be moved during the competition (but its position will be unknown until the time-slot of the first participant team). A map with the positions and IDs of the pipes and of the valves located underwater will be given to the teams.

Departing from each of the piping assemblies, two pipes at least 3 m long will be present (see Figure 42).Each of these pipes will be identified by an ID number (from 1 to 4) painted in black colour on the pipe surface. This ID number indicates to which of the land pipes the underwater pipe is logically connected. A red marker marks the leaking pipe as seen in Figure 43

Figure 41. Piping assembly structure.. The structure, composed of yellow pipes, has the following dimensions: 2 m (front area) x 3 m x 1.8 m (height).

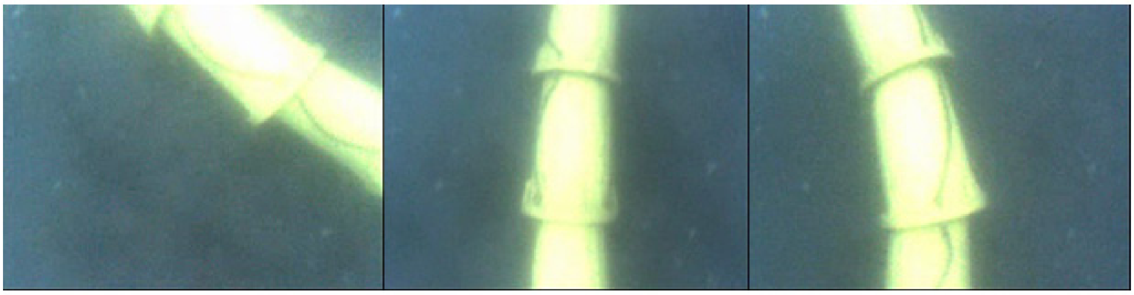


Figure 42. Pipe composed of yellow cylinders (OD=0.5 m). Two pipes will be positioned starting from the piping assembly. The pipes will be at least 3 m long.

Figure 43. Marker to represent a leaking pipe underwater.

8. Valves

During the competitions, there are some tasks related to robotic manipulation of valves.

On land:

As specified in the scenarios document, inside the machine room there are 4 valves and each of them corresponds to one of the 4 pipes on land. Each valve will be represented by a set of two different types of valves (one gate valve and one lever valve, as shown in Figure 44. So physically, there will be 4 sets of two valves (8 valves in total). There will be achievements associated to closing the gate valve and to closing the lever valve.

Figure 44. Set of valves. (Left) Gate valve, (Right) Lever valve

The association between the pipe leaking underwater and the correct valve in the machine room will be indicated by ID numbers. The valves on the machine room will be identify by ERICards (similar to that shown in Figure 45) positioned on the wall behind the valves. Each one of the four ERICards will be associated with one underwater pipe (i.e. underwater pipe number 4 will be associated with an ERICard like the one shown in Figure 45). The association between underwater pipe numbers and ERICards images will be given to teams. This way the ID number on the pipe leaking underwater will indicate the valve in the machine room. For example, if the pipe leaking underwater is number 4, the land robot will have to look for the ERICard associated to number 4 and close the valve (the gate valve and the lever valve).

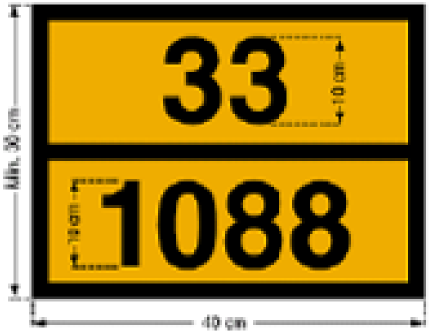


Figure 45. Example of an ERICard that will be positioned on the wall behind each valve.

<u>Underwater:</u>

There will be two piping assembly structures underwater. These piping assemblies consist of cylindrical shapes, yellow in colour, OD=0.5 m by LG=1.5 m (shown in Figure 41), arranged to form a 3D structure. The assembly will be placed on the bottom and will not be moved during the competition (but its position will be unknown until the time-slot of the first participant team). A map with the positions and IDs of the pipes and of the valves located underwater will be given to the teams.

Departing from each of the piping assemblies, two pipes at least 3 m long will be present (see Figure 42).Each of these pipes will be identified by an ID number (from 1 to 4) painted in black colour on the pipe surface. This ID number indicates to which of the land pipes the underwater pipe is logically connected.

The AUV will have to follow the correct pipe number indicated by the land robot and reach the correct valve. The manipulation console where the cross-shaped underwater valve is placed is like the one shown in Figure 46 and Figure 47 (*Note that the ring-shape device on the picture won't be used*)

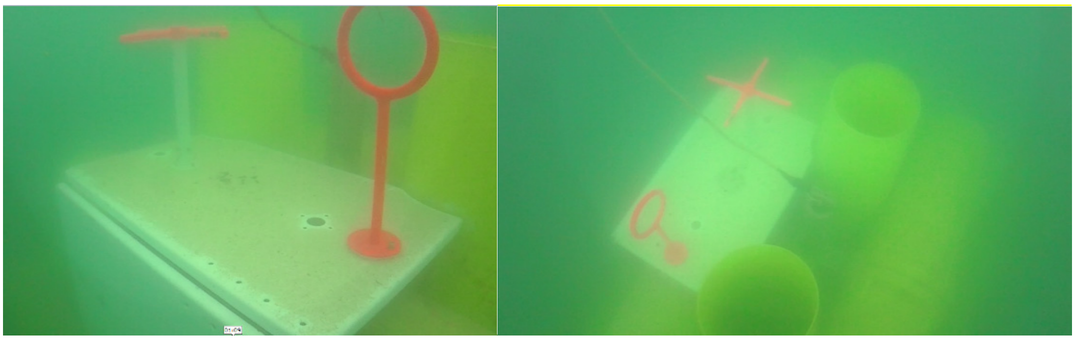


Figure 46. Manipulation console with the cross-shaped lever.

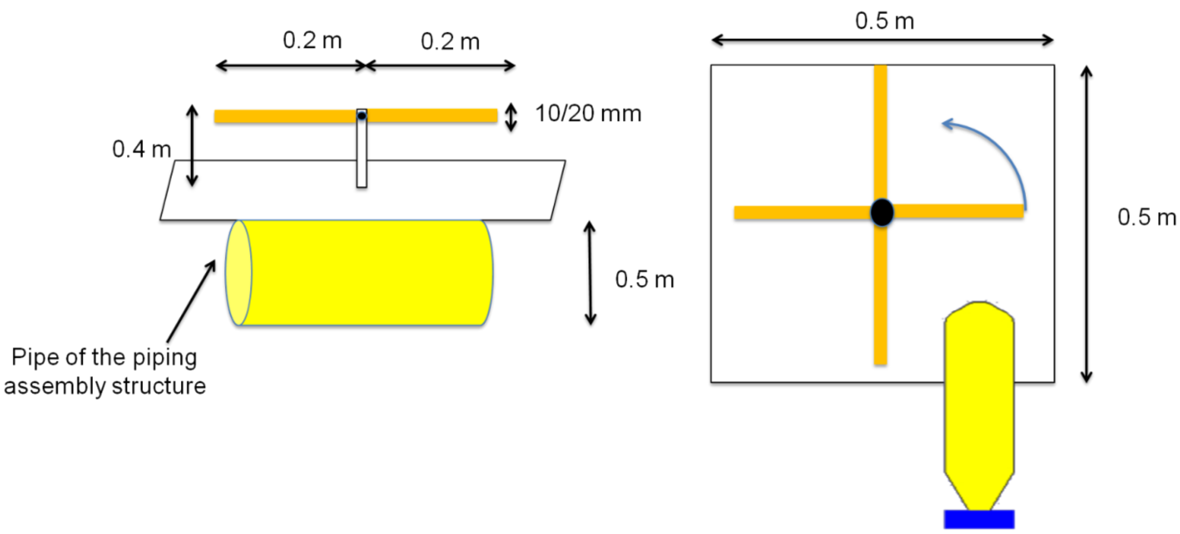


Figure 47. (Left) Front view of the cross-shaped lever. The lever is linked to a vertical shaft supported by the horizontal plane of the console. The horizontal plane is fixed to one pipe of the underwater piping assembly structure. (Right) Frontal view of the lever.

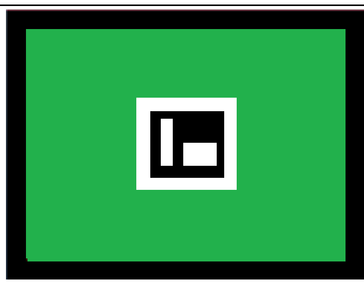
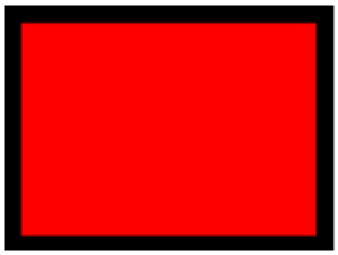
9. Obstacles

Obstacles representing debris in the land area of the competition will be created by grouping objects already present in the area (e.g. rocks, trunks) and/or wooden /cardboard boxes.

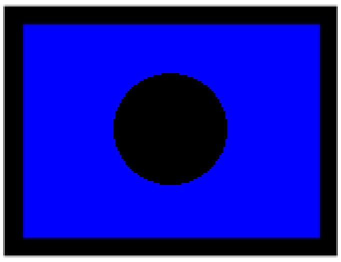
SUMMARY OF OPIs

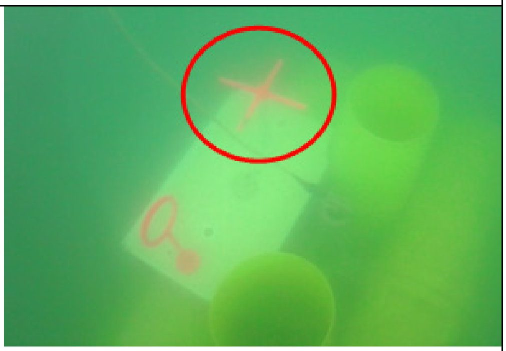
TBM-1: The Grand Challenge (Land+Sea+Air) Task Benchmark
TBM-2: Survey the building and search for missing workers (Land + Air) Task Benchmark
TBM-3: Pipe inspection and search for missing workers (Sea + Air) Task Benchmark
TBM-4: Stem the leak (Land + Sea) Task Benchmark

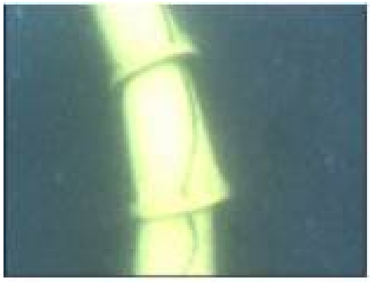
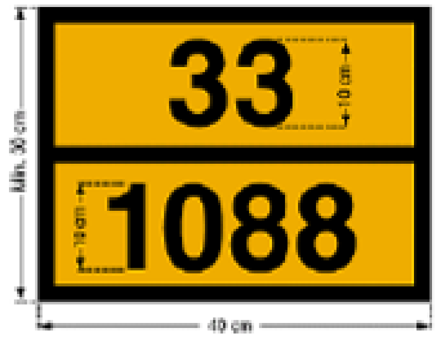
FBM-1: 2D Mapping (Land + Air) Functionality
FBM-2: Object Recognition (Land + Air) Functionality
FBM-3: Object Recognition (Sea) Functionality
FBM-4: Vertical Wall Mapping (Air) Functionality

OPI	Task Benchmark	Description	Picture
Blocked entrance	TBM-1 TBM-2 FBM-1 FBM-2	An A3 blue card with black border will be attached to a wall close to an entrance to indicate that it is blocked.	
Unblocked entrance	TBM-1 TBM-2 FBM-1 FBM-2	An A3 green card with black border and an AR code will be attached to a wall close to an entrance to indicate that it is unblocked.	
Damages on a land pipe or the building (indoor or outdoor).	TBM-1 TBM-2 TBM-3 TBM-4 FBM-1 FBM-2	An A3 red card with black border will be attached to: 1) The outer and inner walls of the building to represent damages. 2) A land pipe to represent damages.	

Leak on an underwater pipe.	TBM-1 TBM-2 TBM-3 TBM-4 FBM-1 FBM-2	A leak on an underwater pipe.	
Machine room entrance	TBM-1 TBM-2 TBM-4 FBM-1 FBM-2	A card sign will be used to indicate the machine room. This card will be located close to the machine room entrance and will be at least 40 x 40 cm in size.	
Missing worker	TBM-1 TBM-2 TBM-3 FBM-1 FBM-2 FBM-3	Missing workers will be represented by mannequins wearing bright-colour work clothes.	

First-aid Kit	TBM-1 TBM-2 TBM-3	The first-aid kit will be a comercial one with dimensions smaller than 30x30x30 cm and weight less than 1Kg. It will be made from a material that will not break if dropped to the floor. The kit will also have a handle or handling system (made of soft or hard material). It is possible for teams to design their own handling system to be applied or adjusted to the object.	
Leak on a land pipe	TBM-1 TBM-2 TBM-3 TBM-4 FBM-1 FBM-2	An A3 blue card with black border and a sign will be attached to a pipe to indicate that a land pipe is leaking.	
Plume	TBM-1 TBM-3 TBM-4 FBM-3	The plume will be marked using several approximately spherical buoys. Their diameter will be between 0.25 m to 0.5 m. They will be located at mid-water (between 0.5 m and 1.5 m altitude from the bottom). They will be tethered to the ground by a light rope. Numbers written on the buoy will distinguish them. The number of the buoys that constitutes the plume will be provided to the teams before the competition (~ 5 buoys can be expected).	

Gates	TBM-1 TBM-3 TBM-4 FBM-3	The sea gate will be marked using two (both acoustically and optically) approximately spherical buoys. Their diameter will be between 0.25 m to 0.5 m. They will be located at mid-water (between 0.5 m and 1.5 m altitude from the bottom). They will be tethered to the ground by a light rope. The sea gate buoys will not have numbers and are located in a different area than the plume ones.	
Valves underwater	TBM-1 TBM-4	One valve will be attached to the piping assembly structure. It will be a cross-shape valve whose dimensions are shown in Figure 20.	
Pipe assembly	TBM-1 TBM-3 TBM-4	The piping assembly structures that will be located underwater will consist of yellow cylindrical pipe sections arranged to form a 3D structure. They will have a diameter about 0.5 m and a length of about 1.5 m. The assemblies will be placed on the bottom and will not be moved during the competition. The dimensions of the whole structure are: 2 m (front area) x 3 m x 1.8 m (height).	

Underwater pipes	TBM-1 TBM-3 TBM-4	The underwater pipes will have a diameter about 0.5 m and a length of at least 3 m. They will be connected to the piping assembly structure.	
Valves in the machine room	TBM-1 TBM-4	At the machine room, 4 sets of two valves (1 lever valve + 1 gate valve) represent the 4 valves in the machine room.	
ID number of the valves in the machine room	TBM-1 TBM-4	The ID number of the valves in the machine room will be identified by ERICards positioned on the wall behind the valves.	
Underwater debris	TBM-1 TBM-3 TBM-4	Objects representing debris in the underwater area. They will be common objects that could be washed away by a tsunami.	