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The euRathlon 2015 Grand Challenge: the first outdoor multi-domain search and rescue robotics competition— a marine perspective

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PAPER

The euRathlon 2015 Grand Challenge: The First Outdoor Multi-domain Search and Rescue Robotics Competition— A Marine Perspective

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ABSTRACT

The euRathlon project was an FP7-funded Coordination and Support Action (2013–2015). Its main aim was to organize outdoor robotics competitions in realistic search and rescue response scenarios for cooperative land, sea, and air robots. Participant teams were requested to test the intelligence and autonomy of their robots in scenarios inspired by the 2011 Fukushima accident. In the project's third year euRathlon culminated with the organization of the first outdoor multi-domain search and rescue robotics competition in the world: the euRathlon 2015 Grand Challenge. Sea, air, and land robots were asked to cooperate acting as a robotic intervention team in a scenario simulating an industrial area ravaged by a tsunami. The Grand Challenge was held in Piombino, Italy, in the surroundings of the Tor del Sale power plant, from September 17 to 25. To prepare the teams for the Grand Challenge, two competitions, dedicated to land and marine robots, respectively, took place in 2013 and 2014. In all the competitions, a strong effort was made in benchmarking what led to meaningful and reasonable scoring principles. Workshops and educational activities complemented the competitions. In this paper, we will focus on the marine robotics competitions of euRathlon with a particular focus on the Grand Challenge. Both technical achievements and general results are presented. The results in terms of team participation and the fruitful effort in dissemination led to establish euRathlon Grand Challenge as the *de facto* leading search and rescue outdoor robotics competition in Europe.
Keywords: marine robotics, search and rescue, field robotics, competitions, benchmarking

euRathlon Project Overview

Inspired by the 2011 Fukushima accident, euRathlon (euRathlon, 2016) was an outdoor robotics Coordination and Support Action (2013–2015) project funded by the European Union (FP7 EU project coordinated by Prof. Alan Winfield, University of the West of England) with a focus on realistic cooperative search and rescue response scenarios for land, sea, and air robots. The main aim of euRathlon was to propose teams from academia and industry real-world, multi-domain challenges testing the intelligence and autonomy of outdoor robots in demanding mock disaster-response scenarios inspired by the 2011 Fukushima accident (Fukushima Accident, 2015).

The objectives of euRathlon can be summarized as follows:

- Advance the state of the art of multi-robot cooperation and coordination by challenging the participant teams with real-world complex tasks in dynamic environments.
- Promote a creative and excellent environment involving interdisciplinary and interdomain interactions among researchers. Researchers from different robotics communities that usually do not interactions need to work together to achieve common goals.
- Create ties between young engineers/researchers and the organizations/companies involved in robotics to create an effective synergy.

- Create research, industry, and user-recognized benchmarks for robot performance measurement and comparison.
- Disseminate robotics among the public grabbing the imagination of new generations of future researchers.

Motivation

The roots of this project come from the ELROB competition (Schneider et al., 2015) (for the land domain), the Student Autonomous Underwater Vehicle Challenge-Europe (SAUC-E) (for the marine domain) (Ferri et al., 2015), and the Workshop in Research Development and Education on Unmanned Aerial Systems (for aerial robots).

Robotics competitions are becoming more and more popular in the robotics community for different reasons. They represent a key factor for the European robotics community for the education of young researchers/engineers. Encouraging young people today to participate in Science, Technology, Engineering, and Mathematics (STEM) programs is of critical importance to the development of the high-tech workforce of tomorrow (Lundquist & Djapic, 2012; Djapic, 2013). Robotics competitions can be one of the most effective drivers to boost new generations of motivated and creative engineers. There is no better way to educate young and talented people than offering them challenging tasks to be solved in novel and efficient ways. Adding the competition factor to it encourages young engineers to study innovative approaches to problems, thus creating new solutions.

Furthermore, robotics competitions that present challenging tasks to solve such as the DARPA Robotics Challenge (DRC) (2016) add to the educational aspect a strong push to advance the state of the art. These competitions are great opportunities for teams of industrial and academic professionals to create innovative solutions to problems considered still "challenges" by the research community.

The Goal

In 2015, the project's third year, euRathlon culminated with the organization of the first outdoor multi-domain search and rescue robotics competition in the world: the euRathlon Grand Challenge. The event was held from September 17–25, 2015, in Piombino, Italy, in the surroundings of ENEL (Italian national entity for electricity) "Tor del Sale" power plant. The site offered the necessary areas and a credible industrial context. Participant teams were requested to deploy in the field their robotic intervention squad composed of autonomous marine, aerial, and terrestrial robots. To accomplish the Grand Challenge, the robots of the three domains needed to cooperate in order to achieve common objectives in a scenario set up to simulate a nuclear power plant ravaged by a tsunami. Leading up to the final event, the euRathlon consortium organized two single-domain competitions focused on land and sea domains. The land robotics competition took place in Berchtesgaden, Germany (2013) (Winfield, et al., 2014), and the marine competition was held in La Spezia, Italy (2014) (Ferri et al., 2015). These, alongside team-building workshops in Berchtesgaden (2013), Seville, Spain (2014) and Oulu, Finland (2015), paved the way for the 2015 edition. An open process of benchmarking complemented the project leading to derive meaningful and reasonable scoring principles for the multi-domain competitions of euRathlon. The benchmarking was also inspired by the approach taken by the RoCKIn EU project (Amigoni, 2015) The 2015 Grand Challenge was locally organized by the NATO Science and Technology Organisation (STO) Centre for Maritime Research and Experimentation (CMRE) of La Spezia, Italy, locally supported by the Piombino Municipality and ENEL and by the entire euRathlon international consortium. Other than CMRE, the euRathlon consortium was composed of the University of the West of England (UWE), Bristol, United Kingdom (the coordinating partner); Center for Advanced Aerospace Technologies (CATEC), Spain (responsible for the air domain); Fraunhofer Institute for Communication, Information Processing and Ergonomics FKIE, Germany (local organizer of the 2013 land robot competition); Heriot-Watt University, United Kingdom (in charge of scoring and benchmarking); Oceanic Platform of the Canary Islands (PLOCAN)/University of Las Palmas de Gran Canaria (ULPGC), Spain (supporting the logistics for the marine robot competitions); and University of Oulu, Finland (responsible for the workshop organization).

In the next sections, after briefly describing the euRathlon 2014 marine robotics competition, we will present the euRathlon 2015 Grand Challenge with a particular focus on the competitions involving marine robots.

euRathlon 2014 Marine Robotics Competition

CMRE has been pushing the education of marine engineers and scientists through the organization of the Student Autonomous Underwater Vehicle Challenge-Europe (SAUC-E) in its premises, in La Spezia, Italy, since 2010. SAUC-E (first edition dates back to 2006) challenges teams to solve tasks in real-world conditions (e.g., low water visibility). The real-world scenario makes SAUC-E unique in the world since other marine competitions typically use pools (Robosub [AUVSI Foundation, 2016], MATE ROV [Marine Technology Advanced Education, 2016], SAUVC [SAUVC, 2016], etc.). The rich experience of organizing a unique competition led CMRE to participate in the euRathlon project as the local organizer for the 2014 and 2015 competitions.

Thus, the euRathlon 2014 marine robotics competition was also held in CMRE basin (see Figure 1), in La Spezia, from September 29 to October 3, 2014. More details about the competition can be found in Ferri et al. (2014, 2015). The competition was specifically designed to prepare teams for the 2015 Grand Challenge. The cooperation between marine surface vehicles and autonomous underwater vehicles (AUVs) was encouraged and highly rewarded with extra points awarded, and the scenarios were prepared as reduced versions of those of the 2015 Grand Challenge.

Five challenges were proposed by taking inspiration from a Fukushima-like disaster. In each challenge, a team had to participate with an AUV while an autonomous surface vehicle (ASV) could be used as a collaborator to support the underwater operations:

- Long-distance underwater navigation—reaching the disaster area. The AUV had to navigate autonomously for a path of about 1 km. The challenge was held outside the CMRE basin and was completely new and never tried, not even partially, during previous SAUC-E competitions.
- Environmental survey of the accident area (mapping)—understanding the effects of the disaster. The AUV had to follow a wall of the CMRE basin, locate a mid-water buoy with a flashing light, and map the area where mid-water buoys were deployed (see Figure 2).
- Leak localization and structure inspection—localizing a leak of toxic material. The AUV had to follow a plume composed of mid-water buoys. Black numbers were painted on them to indicate the proximity to the source of the leak. The underwater structure (see Figure 2) had to be inspected.
- Underwater manipulation—acting on the plant to close a valve. The AUV had to close a valve positioned on the underwater structure.
- Combined challenge—to accomplish simplified versions of the cited tasks in sequence.

FIGURE 1

The CMRE water basin. Credit: CMRE.

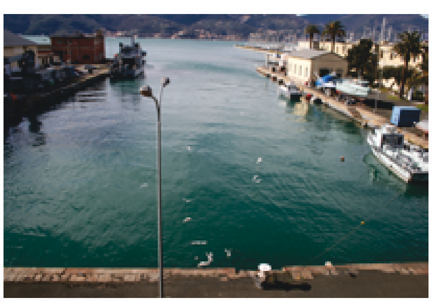


FIGURE 2

(Left) The piping assembly structure. (Right) The mid-water buoys (OPI). Credit: CMRE.

For each challenge, the robots had to perform all the tasks autonomously except for the manipulation, in which tele-operation was allowed. Six teams participated in the competition. Not all the teams participated in every scenario as each challenge had a dedicated day and it was a competition in itself.

The team of the University of Girona, Spain, won four of five challenges while the first prize for environmental survey of the accident area was awarded to the AVALON team, DFKI, Germany. Results from some teams were encouraging, considering the type of missions to be proposed in the Grand Challenge. Good results in long-range navigation and especially in the combined scenario demonstrated that teams were able to credibly attempt the complex tasks composed of concatenated subtasks characterizing the Grand Challenge 2015. It is important to note that some of the challenges were proposed in euRathlon for the very first time. It is also worth noting that all teams used tele-operation in the manipulation task. Autonomous manipulation by using a floating vehicle remains still an open research topic, and both better algorithms and more expensive vehicles (with complex robotic arms) are needed. Most of teams were still coming from universities, and some had elementary gripper systems. For a detailed analysis of the performance of the teams, refer to Petillot et al. (2015).

The euRathlon 2015 "Grand Challenge"

The euRathlon 2015 Grand Challenge was held in Piombino, Italy, September 17–25, 2015, in the area surrounding the Tor del Sale building, and in the ENEL-owned thermal power plant sheltered harbor (see Figure 3). The location offered all the areas needed for the robots, space for hosting participants and the public, and offered a credible industrial context as a background for the competition.

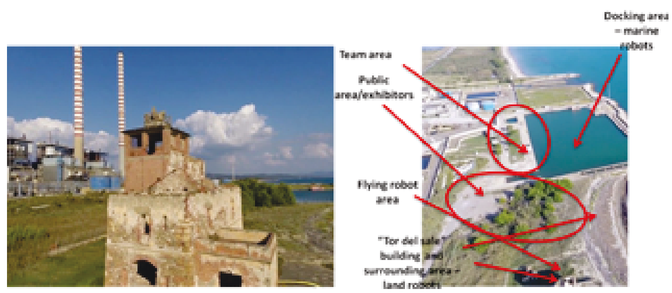
The Grand Challenge (see a schematic in Figure 4) was a multi-domain robotics challenge, with land, air, and sea robots. The general scenario of the Grand Challenge is inspired by the Fukushima 2011 disaster. euRathlon simulates a situation in which a potent earthquake affected the area where a nuclear plant is located. In less than an hour from the initial earthquake, a tsunami strikes the energy plant. A robotic multi-domain team is deployed in the ravaged area to intervene. This scenario was translated into the three missions: localizing two missing workers in the disaster area (simulated with mannequins), surveying the area of disaster to identify dangerous leaks, and finally closing valves inside the Tor del Sale building and underwater to stem the leaks. To accomplish the Grand Challenge, the cooperation between air, land, and marine robots was necessary.

The competition was designed as a 9-day event, in which teams had 3 days of practice before starting to compete. The Grand Challenge was held in the last 2 days of the event. Leading up to it, simpler scenarios were proposed to the teams arranged in increasing order of complexity: single-domain trials in the first 2 days, followed by subchallenges (double-domain).

Multi-disciplinary and multi-institution teams for a total of 134 participant students and engineers met in Piombino to tackle this unique challenge. A total of 16 teams from 10 different countries, with around 40 robots, took part in the event.

FIGURE 3

Competition site location (42°57.253′N, 10°35.993′E) in the surroundings of Tor del Sale ENEL power plant. (Left) View of the Tor del Sale building representing the “reactor building” and the surrounding area. The “machine room,” which had to be reached and explored by the robots, was one of the rooms at the building ground floor. (Right) Aerial view of the competition site. The positions of the areas for robot competition, the team and spectator/exhibitors areas, and the “reactor building” (Tor del Sale building) are shown. Source: euRathlon.



Setting-up the euRathlon “Grand Challenge” Competition Site

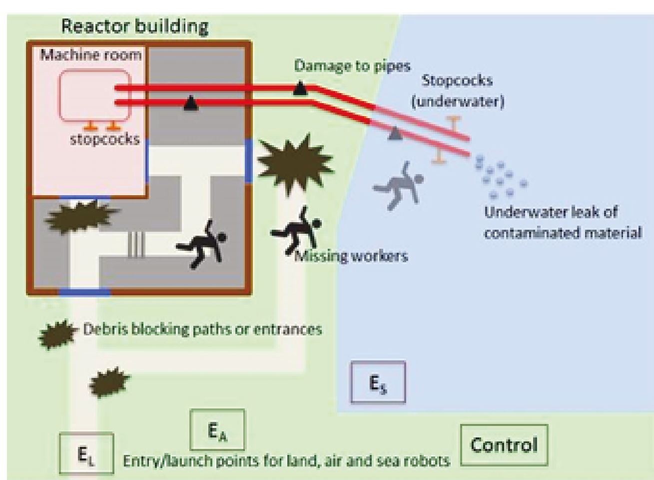
The Tor del Sale area can be viewed in Google Earth at 42°57.253′N, 10° 35.993′E (see Figure 3). The area was setup to simulate a nuclear power plant damaged by a tsunami. The Tor del Sale building (see Figure 3) simulated the “reactor building” and contained the machine room where the land robots had to enter to close the valves.

Setup of Areas to Host Teams and Spectators/Exhibitors

During the design phase, we carefully considered suitable spaces to allow both the teams and the public to attend the event. euRathlon was in fact intended

FIGURE 4

euRathlon 2015 Grand Challenge schematic. The Grand Challenge comprises three missions: find missing workers, survey and monitor the incident area, and stem the leak closing the right stopcock in the building and underwater. Credit: euRathlon.



not only as a robotics competition for specialized participants but also as an event for the general public.

Two distinct areas, one for teams/staff and one for spectators/general public, were identified (see Figure 3 and Figure 5). Access to the team area was restricted to badge holders (staff, specialized visitors, judges, journalists, etc.). The general public could only enter the team area accompanied by a member of the organization in organized visits. The areas were set up to host the high number of participants (134) and visitors (we had 200 visitors among the specialized public plus 1,200 general public over the 9 days) and temporary structures were mounted to create an euRathlon village with all the needed comforts including a bar/cafeteria, WCs, free water fountains, Internet connection, exhibition space (a large tent hosted the exhibitors—the spectator tent), office/organization space, etc. As in previous years, two swimming pools were set for testing the marine robots. Specific areas were dedicated to the general public to watch the robots during their operations (see "Outdoor spectators" area in Figure 5) and real-time video from four cameras placed in the building area were displayed on monitors in the spectator tent.

A detailed blueprint and images of the euRathlon competition site are visible in Figure 5 and Figure 6.

Areas for Robots Competition

The flying and ground robots competed in the beach area and in the surroundings/inside of the building (see Figure 7). The ground and aerial robots started their missions from "Robot start point A" and had to inspect the highlighted area to look for OPIs (object of potential interest) and the building (see Figure 8 and Figure 9). The marine area was divided in two competition arenas (Figure 10). Because of the large number of marine teams, there was the need of having two teams running in parallel during the single-domain trials. Whenever an arena was not used for the competitions, it was made available for practice. In the two domain challenges and Grand Challenge, the two arenas were merged to build a larger competition area. As is depicted in Figure 10, the same objects were present in each arena: two buoys to act as a gate (2.5 m wide) that the robots needed to pass, five mid-water buoys (OPIs), visible in Figure 2, to simulate a plume (leak), pipes, and an underwater structure with the valve to be closed (see Figure 11). Images of the competition area for marine robots are shown in Figure 6. During the event, the teams were continuously supported at sea by two rubber boats of the organization.

The Missions of 2015 Robotics Competitions

The Grand Challenge was composed of three missions:

FIGURE 5

Blueprint of the working area. The tents and several locations are shown: spectator tent (30 × 12 m) containing registration/info desk, exhibitors, bar, TV screens for the spectators, team meeting tent (8 × 12 m), working as a team meeting space and for team meals, staff tent (8 × 12 m), 25 tents (4 × 4) for teams, control stations. The two pools for robot testing and land robot trial area are also visible. Source: euRathlon.

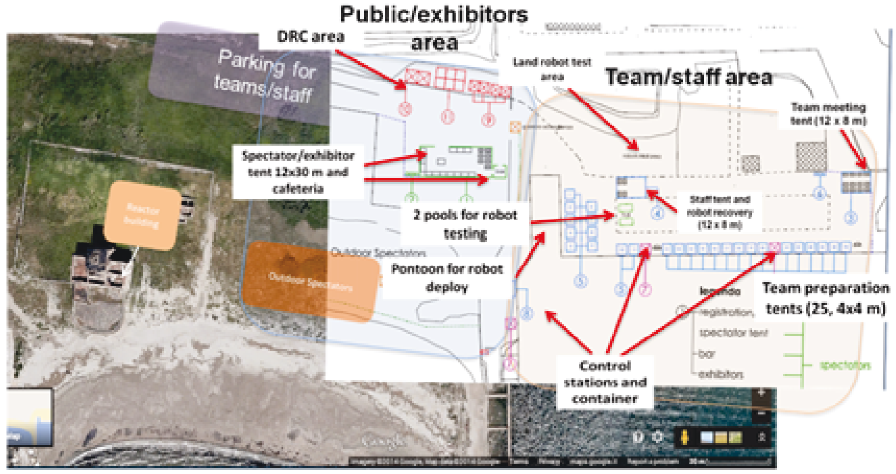
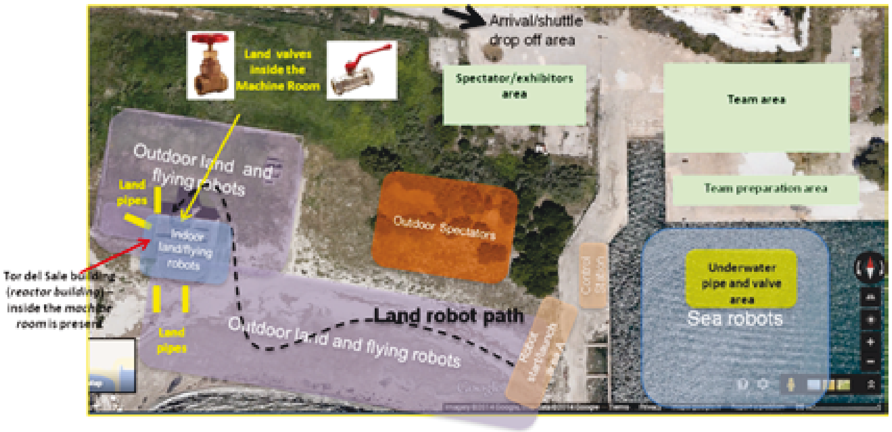


FIGURE 6

(Left) Team tents along the ENEL harbor. (Center) Team ENSTA 1 testing their vehicle in one of the pools. (Right) Competition area for marine robots. Sea scenarios took place in the harbor of the ENEL power plant. Photo credit: euRathlon. Credit: euRathlon (left, right), Andrea Cesarini (center).

FIGURE 7

Ground and air robots had to inspect the highlighted area. Source: Google Earth.



- **Mission A: Search for missing workers.** Robots had to search for two missing workers represented by mannequins dressed in orange suits, which could be inside the building, outside the building, floating on the sea surface near the coast, or trapped underwater. Teams received bonus points if a worker was found during the first 30 min of the Grand Challenge, because in a real scenario the probability of finding a missing person alive decreases rapidly with time. The mannequins outside the water could be found either by aerial or land robots, and cooperation could be used to avoid useless searches.
- **Mission B: Reconnaissance and environmental survey of a building.** Land and/or aerial robots had to inspect the building to evaluate damage (represented by markers) and find a safe path to the machine room where valves were located. This required robots to survey the area; create a map of the building, the outdoor area surrounding it, and the marine area; and locate the OPIs in order to provide situational awareness to the team.
- **Mission C: Pipe inspection and stemming a leak.** Land and/or aerial robots had to locate four pipe sections on land; marine robots (surface or underwater) had to locate another four matching pipes underwater, look for damage to the land pipes and identify a contaminant leak (represented by a marker) in land and underwater, reach the valves in the machine room and underwater, and close the correct valves in a synchronized process.

These missions did not need to be tackled separately and could be accomplished in parallel. Strategy was important, as the teams were free to tackle the mission goals in parallel or in sequence and to choose the order. Within certain limits, teams were also free to choose which types of robots to deploy, as well as how and when to deploy them. The missions are high-level descriptions of the Grand Challenge, and not all the tasks are explicitly mentioned. For instance, while searching for missing workers, the marine robots should also map the area in order to gain more points.

The euRathlon Grand Challenge main goal was task fulfilment, but autonomy and cooperation between domains were also essential for achieving the mission objectives. Although competing robots faced mock scenarios, the environmental conditions and difficulties were intended to be as realistic as reasonably possible—while also safe for competitors and spectators, and the success criteria reflected straightforward end-user priorities such as task completion and minimal manual intervention by operators.

The Grand Challenge was held in the last 2 days of the event (September 24–25) and was successfully met if all the three missions were accomplished within 100 min. The Grand Challenge was designed to encourage and reward cooperation between ground, marine, and aerial robots, while allowing maximum flexibility in participation and

FIGURE 8

(Left) The beach area, theater of land robot operations, with the “Tor del Sale” building in the background. (Center) The building simulating the “reactor building,” which the land robots, supported by UAVs, had to reach and to explore. (Right) Fenced dune area for the public. Credit: Andrea Cesarini (left) and euRathlon.

FIGURE 9

(Left) View of the machine room. The valve and the relative ERICard (CEFIC, 2016) are visible. The blue barrel to be opened and the canister on the right to be placed inside the barrel. (Center) ICARUS land robot enters the building. On the top right, one OPI signaling the correct entrance can be seen. (Right) Bebot land robot climbs the ramp in order to get to the building area. Credit: euRathlon.

innovation; testing not just the robots but also the human-robot teams. As mentioned, leading up to the Grand Challenge single-domain competitions (called trials) and two-domain competitions (called subchallenges) were proposed to the teams from September 20 to September 23. These competitions proposed tasks preparatory for those of the Grand Challenge.

A short description of the competitions involving the marine domain follows. For every domain, two trials were held. In the marine domain, they were Sea Trial S1 and Sea Trial S2, respectively. In each marine trial, a team had to participate with one AUV while an ASV could be used as a collaborator vehicle to support the underwater operations or for mapping the area/locating the missing worker.

- Sea Trial (S1): Navigation and Environmental Survey—Robots were tasked with surveying an area of 15 × 15 m in the basin of the dock. The AUVs had to navigate from the launch point to a validation gate, pass through it, and search for damages on the seabed, marked by submerged orange buoys (see Figure 2).
- Sea Trial (S2): Leak location and valve closing—Marine robots had to locate a leaking underwater pipe and close the valve associated with it (see Figure 11). The leak was represented by a plume of orange buoys and an orange rectangular marker on one of the four yellow pipes. Once the leaking pipe was found, the robot had to follow it to reach the underwater structure where the valve was mounted. Finally, the robot had to close the valve to stop the hypothetical leak.

After the trials, two-domain subchallenges were used to test the collaboration between different domains before having the full three-domain robotic team in action. There were two subchallenges involving the sea domain planned, the Subchallenge Land + Sea (L+S) and the Subchallenge Sea + Air (S+A). The description follows.

- Subchallenge (L+S): Stem the leak —One or two land robots and the marine robots were required to participate in this scenario. In this subchallenge, it was known that the pipes on land close to the shore were not damaged or leaking, so no inspection of them by the land robots was required. Land and sea robots started from the premise that they had already reached the building and the pipes area underwater, respectively. The main tasks were to find the leaking pipes and close the correct valves underwater and on land to stop the leak. Robots had to cooperate to map the area and discover the correct valves. The robots could not close the valves until the two correct parts of the pair were found, as the process of closing them had to be synchronized.

FIGURE 10

Schematic of the marine robot competition area. The two arenas are visible along with the different areas. Credit: euRathlon.

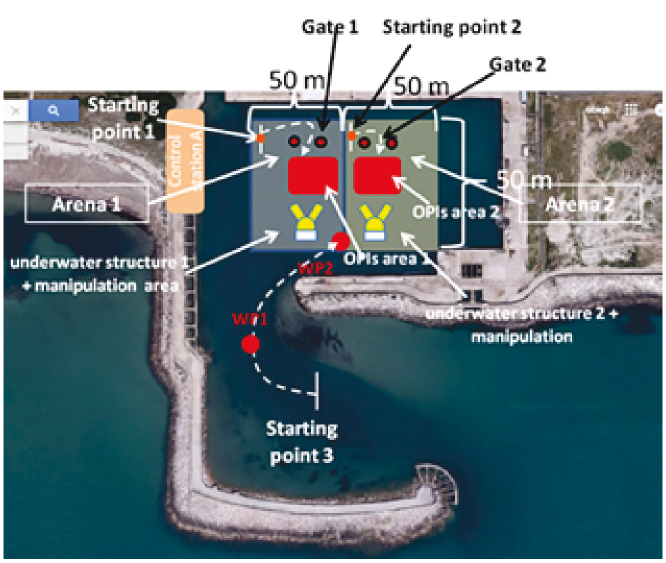
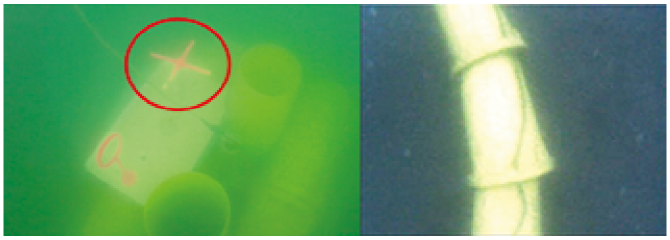


FIGURE 11

(Left) Underwater structure. In particular, the valve to be closed is shown inside the red circle. (Right) Particular of the pipe. Credit: CMRE.



- Subchallenge (S+A): Pipe inspection and search for a worker—Marine robots and one aerial robot were required to participate in this scenario. Aerial robots had to inspect and map the beach area surrounding the building, and sea robots had to inspect and map the harbor area. They had to search for damages and leaks in the four pipe sections on land and the four pipe sections underwater, represented by different markers. Robots also had to look for a missing worker represented by a mannequin dressed in bright orange. The worker could be located on the land outside the building or at the sea (at the surface near the shore or trapped underwater) in a supine or prone position.

Unfortunately, the Subchallenge S+A was canceled due to poor weather conditions that could compromise the aerial robots safety.

The timeline of the several marine-related euRathlon competitions with the associated tasks, technical challenges, and complexity are summarized in Table 1 and Table 2.

The 2015 Participant Teams

Of the 16 teams that participated in the euRathlon 2015, 12 had a marine component. This reflects the interest of the marine robotics community in our competitions. Of the 12 teams, only three had not participated previously in any edition of SAUC-E and/or euRathlon and were new entries in the competition. As in the marine robotics competition of 2014, three of the marine teams received on loan robot kits purchased by the euRathlon consortium (3 SPARUS II AUVs manufactured by the University of Girona (University of Girona, 2016) with 2 Explorer DVL 600 KHz sensors from RD Teledyne). This aimed to increase the interest in marine robotics among the European community and to give the opportunity to teams from other domains to start working and advance in the marine robotics field. Only one team from 2014 kept the vehicle (team Robdos from Spain). Two other teams were awarded with one vehicle: OUBOT (Hungary) and AUGA (Spain). An open call was opened to select the teams. This experience was successful, as the results will show.

The participant teams that had marine robots were as follows:

1. AUGA—Team AUGA is from ACSM (Advanced Crew and Ship Management), a company that participated in the sea trials with one loaned SPARUS II AUVs.
2. AVORA—The AVORA team is from the University of Las Palmas de Gran Canaria, Spain. This team participated in previous versions of SAUC-E.
3. AUV Team TomKyle—AUV Team TomKyle is from the University of Applied Sciences of Kiel, Germany. Second place ex-aequo in SAUC-E 2014.
4. B.R.A.I.N. Robots—B.R.A.I.N. Robots e.V. from Esslingen, Germany, participated in euRathlon 2013 with land robots. It was their first participation in the marine competitions of euRathlon/SAUC-E.
5. ENSTA Bretagne Team 1—One of the two multi-domain teams from the Institute of ENSTA Bretagne, France. ENSTA is the only institution that participated in both euRathlon 2013 and 2014. Regular participant in SAUC-E and first place in SAUC-E 2014.
6. ENSTA Bretagne Team 2—The second of the two multi-domain teams from the Institute of ENSTA Bretagne, France. Regular participant in SAUC-E and second place ex-aequo in SAUC-E 2014.
7. ICARUS—This is the team of the ICARUS EU-FP7 Project (ICARUS, 2016), with partners from Belgium, Germany, Poland, Portugal, and Spain. Some of the partners participated in euRathlon 2013 with land robots.
8. Team Nessie—This team was originated in the Heriot Watt University (United Kingdom) but included also Ph.D. students from ATLAS and DFKI in the framework of the ROBOCADEMY EU-FP7 Project (ROBOCADEMY, 2016). Past awarded participant in SAUC-E.
9. OUBOT—The team from Obuda University (Hungary) participated with one of the loaned SPARUS II AUV.

TABLE 1

Timeline of the euRathlon competitions related exclusively to the sea domain.

	Timeline of euRathlon Competitions		
	euRathlon 2014 Sea Robotics Competition	euRathlon 2015	
		Sea Trial 1	Sea Trial 2
Tasks to be solved	- Long distance underwater navigation - Environmental survey of the accident area - Leak location and structure inspection - Underwater manipulation - Combined challenge (the previous four tasks to be done in a row)	Navigation and Environmental Survey—Robots were tasked with surveying an area of 15 × 15 meters in the basin of the dock. The AUVs had to navigate from the launch point to a validation gate, pass through it and search for damages on the seabed	Leak location and valve closing - Marine robots had to locate a leaking underwater pipe (leak represented by buoys), follow the pipe, reach an underwater structure, and close the valve associated with it.
Technical challenges and increased complexity	Several different marine tasks including hard tasks like manipulation or long range navigation. The combined challenge put together all of them and acts as preparation for the 2015 Grand Challenge.	This trial fuses two of the tasks from 2014 (navigation and environmental survey). It acts as preparation for the Grand Challenge as a longer-distance navigation is required in it. The complexity increases as the arena is wider than in 2014 and two tasks are fused.	This trial fuses other two of the tasks from 2014 (leak localization and valve closing). It acts as preparation for the Grand Challenge as the AUV will do the same (close valve) but synchronized with the land robot. The complexity increases as the arena is wider than in 2014 and two tasks are fused.
Types of robots	AUVs, ASVs (optional)	AUVs, ASVs (optional)	AUVs, ASVs (optional)

10. Robdos Team Underwater Robotics—Robdos is formed by a group of students from the University Polytechnic of Madrid (UPM) and the company Robdos SRL. They participated with one of the loaned SPARUS II both in euRathlon 2014 and 2015. Past participant of SAUC-E.
11. UNIFI Team—UNIFI is the team of the University of Florence (Italy). Past participant awarded of SAUC-E.
12. University of Girona—The team of the University of Girona is formed by students and researchers of the Underwater Vision & Robotics Research Centre (CIRS). The team develops and operates the robot vehicle SPARUS II AUV. Regular participant and awarded team in different editions of SAUC-E and winners of four challenges out of five in euRathlon 2014.

euRathlon 2015 Competition Results

euRathlon 2015 Grand Challenge could only be accomplished by multi-domain teams. However, of the participants, only few (3) were three-domain teams. To allow single or double-domain teams to take part in the final competition, the consortium helped the matching between teams by using an online form filled out by the participants and the website forum. Team matching offered the possibility to smaller research groups to participate, learn, and collaborate with other teams. This strategy was fruitful leading to six multi-domain teams and is validated by the good results achieved by the combined teams. Two of the teams on the podium of the Grand Challenge were matched. The first Grand Challenge prize (10,000 €) was awarded to Team Cobham (Land) matched with the University of Girona (Sea) and ISEP/INESC TEC (Air) (see Figure 12). The team used two unmanned ground vehicles (UGVs), one AUV, and one unmanned aerial vehicle (UAV) to attempt the Grand Challenge. The second place was shared by the ICARUS multi-domain team (two UGVs, one AUV, one ASV, one UAV used) and Bebot-team (Land and Air—one UGV and one UAV) together with AUV Team TomKyle

TABLE 2

Timeline of the euRathlon multi-domain competitions that include the sea domain.

	Timeline of euRathlon Competitions		
	euRathlon 2015		
	Land + Sea Subchallenge	Sea + Air Subchallenge	Grand Challenge
Tasks to be solved	Stem the leak—The main tasks were to find the leaking pipes and close the correct valves underwater and on land. Robots had to cooperate to map the area and discover the correct valves. The process of closing them had to be synchronized.	Pipe inspection and search for a worker—Aerial robots and sea robots had to inspect and map the beach and harbor area. They had to search for damages and leaks in the pipes on land and underwater. Robots also had to look for a missing worker represented by a mannequin.	3 missions: - Search for missing workers - Reconnaissance and environmental survey of a building - Pipe inspection and stemming a leak The missions do not need to be tackled separately. Which robots to use is also to be chosen by the teams (with limits).
Technical challenges and increased complexity	This subchallenge prepares for the Grand Challenge where the synchronization of the valve closing has to be performed too. The technical challenge and added complexity here is communication between the land and marine robots.	This subchallenge prepares for the Grand Challenge as the searching for a missing worker will be performed in it. The technical challenge here is to communicate if the worker has been found (so the other robot can stop searching) and to communicate the leaking pipe. Canceled (bad weather)	The Grand Challenge gathers the subtasks presented in the other trials in three complex missions. The challenge here is not only communication and cooperation but also choose the best strategy (e.g., which robots to deploy and in which order).
Types of robots	UGVs, AUVs, ASVs (optional)	AUVs, ASVs (optional), UAVs	UGVs, AUVs, ASVs (optional), UAVs

(Sea), which deployed one underwater vehicle. ICARUS is an FP7 project (ICARUS, 2016) with many partners, research groups, and robots and therefore complex to integrate, but at the same time with years of experience working together. The Bebot-team had no previous collaboration with the AUV Team Tomkyle, showing how organized and committed teams can collaborate effectively also with few days of practice.

FIGURE 12

Winner of the euRathlon 2015 Grand Challenge: Team Cobham (Land), University of Girona (Sea), and ISEP/INESC TEC (Air). Credit: euRathlon.

Focusing on marine competitions, the Sea + Land Subchallenge podium was Cobham + University of Girona, ICARUS and Bebot-team + AUV Team Tomkyle. In the sea trials, the results were the same for both Sea Trials 1 and 2 with University of Girona winning both, followed by ENSTA Bretagne Team 1 and AUGA. The first and second teams in the ranking have many years of experience in marine robotics competitions, while the third was a newcomer. AUGA team had a loaned SPARUS and outperformed more experienced teams after only a few months of work with the robot. This team had previous experience with ROVs, and this helped them in familiarizing with the SPARUS II AUV. A summary table with the results of the Grand Challenge and all the competitions involving marine robotics can be seen in Table 3.

Team OUBOT had excellent performance considering the short time they had to practice with the loaned SPARUS II. This team succeeded to partially accomplish the trials after only 6 months of practice with their vehicle and without any previous experience in the marine domain. By loaning mature platforms, good teams with little or no experience in marine robotics had the possibility to focus on sensing and navigation. Even if entering the sea domain is complex, committed teams with an effective technical support by the manufacturer were able to accomplish some achievements at sea.

Besides that, OUBOT team also won the award for the rookie team (four thrusters), provided by VideoRay, Inc. This shows the interest that industry can have in supporting competitions such as euRathlon creating ties with brilliant young researchers for future collaboration. The platform that was loaned, the SPARUS II AUV, was manufactured by the University of Girona, a previous (and this year) winner of SAUC-E and euRathlon competitions. SAUC-E and euRathlon helped the University of Girona to validate and test the platform leading to its commercialization. Competitions may also work as a bridge from academic research to commercial applications.

The teams had the opportunity to test their robots in a real scenario and in realistic conditions. This pushed them to the brink of their limits and led to very innovative solutions. For instance, in the land domain, the difficulties of communications inside the building were tackled by using either multiple robots acting as communication relays (e.g., ICARUS had one large UGV transporting a small UGV able to enter the building, SARRUS had two land robots of the same type) or by using deployable wireless repeaters dropped as in the case of Bebot-team by an UGV robot along its way or in the case of ICARUS by an UAV. ICARUS and Bebot-team strategies resulted in a good performance as the second place ex-aequo in the Grand Challenge demonstrates. These examples show how limited communications can seriously impact the operations of robots in real emergency situations since a link with a command and control center cannot be guaranteed. For this reason, the described approaches show how multiple robots, in particular heterogeneous (e.g., ICARUS), can cooperate to adapt the team to the environment to operate in an effective way in a wide and complex harsh area.

Several teams performed direct communication between robots with no intervention of the operators, namely ICARUS, Bebot + AUV Team TomKyle, and Cobham + University of Girona both in the Sea + Land Subchallenge and in the Grand Challenge. However, this is one of the areas that need improvements in the future.

Results show that the keys to success are several.

The first one is the experience of the teams in working under stress (for instance, during project demonstrations or competitions).

Some of the most experienced teams in robotics competitions were in fact among the winners (e.g., Cobham or University of Girona) or had good performance (ENSTA Bretagne 1, TomKyle). ICARUS, although with little experience in robotics competitions (only some of the partners participated before in euRathlon), performed very well. ICARUS is a European multi-partner project, and the consortium has had the opportunity to work together for several years improving the cooperation between the robots and the effectiveness of the

TABLE 3

Summary of results for the competitions involving marine robots.

Places	Grand Challenge	Subchallenge L+S	Sea Trial 1	Sea Trial 2
1st	Cobham (Land) + University of Girona (Sea) + ISEP/INESC TEC (Air)	Cobham (Land) + University of Girona	University of Girona	University of Girona
2nd	ICARUS (ex-aequo) Bebot-team (Land and air) + AUV Team Tomkyle (Sea)—ex-aequo	ICARUS	ENSTA Bretagne 1	ENSTA Bretagne 1
3rd	N/A	Bebot-team (Land) + AUV Team Tomkyle (Sea)	AUGA	AUGA

collaboration between different research groups. AUGA, also a newbie in robotics competitions and new to the field of AUVs, performed well due to their previous large experience with ROVs and the marine domain. OUBOT, with no experience in marine robotics prior to the event, performed quite reasonably due to their strong background in computer vision.

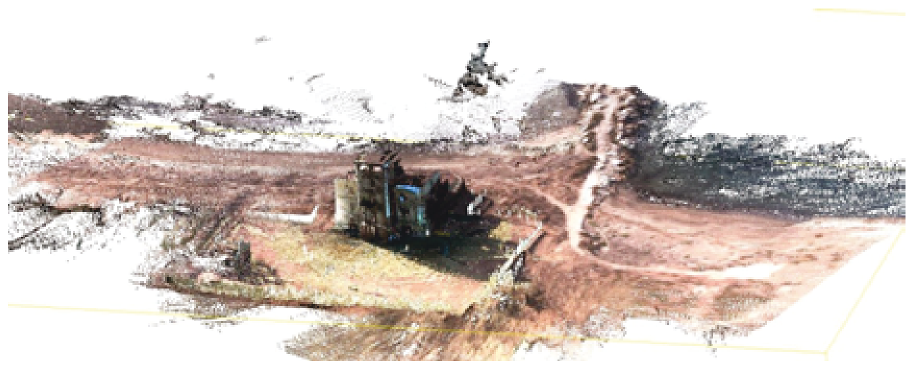
But experience is not the only road to victory as some results of a couple of experienced teams have shown. Another important factor was the innovation of the proposed solutions. Teams that risked innovative approaches achieved good results and solved fundamental issues such as poor communications as shown in the previous paragraph. In the future, we will push the teams for more innovation, and we will reward more the most innovative approaches.

Finally, the human-to-human communications and cooperation has been of the utmost importance. Setting up a multi-partner team on-the-fly is not easy. Only through good management skills and effective communications between the individual single domain teams, a multi-partner team can be successful. In some cases, the size of the team can influence the performance, and large teams inherently have more issues to solve internally in order to get their robots cooperate effectively. In these cases, social and managerial capabilities are essential to solve the unavoidable conflicts that rise in stress situations. It must be noted that the missions of the Grand Challenge were not explicitly defined and the cooperative strategic planning of the several groups composing a team was necessary to accomplish the achievements.

The results of the teams on the podium of the Grand Challenge were satisfactory in terms of accomplished achievements (measure of performance). The first-ranked team achieved almost 82% of the available achievements (completely or partially). The best team from the autonomy perspective was ICARUS (in particular the aerial vehicle). For instance, in the aerial scenario A1, ICARUS got seven of eight achievements. Using different vehicles in different domains not only can allow the sharing of important information but also help in creating improved maps. Figure 13 shows the impressive result obtained by the ICARUS team by fusing the aerial and land robots maps.

FIGURE 13

The fused map obtained by the ground and aerial vehicles of ICARUS team during the Grand Challenge. Credit: ICARUS team.



However, the general performance of the teams demonstrates that there is a need for a greater degree of autonomy to be able for a robotic team to robustly succeed in complex tasks in realistic environments. From our experience, this is true in particular for the land domain where teleoperation (or semi-autonomous modes) are strongly used also by professionals in real-world intervention tasks. The walls of the buildings and debris can in fact severely hamper communications. In that case, only fully autonomous vehicles can survive in the hostile environment.

For what concerns the marine domain in particular, the conditions were harsh with low visibility (<1 m) being the main challenge. Although the area is a protected harbor with shallow waters (~4 m), the visibility was very low due to a storm that occurred a few days before the event. Even though the objects to identify were bright orange, in some cases they could be hardly seen as visible in Figure 14.

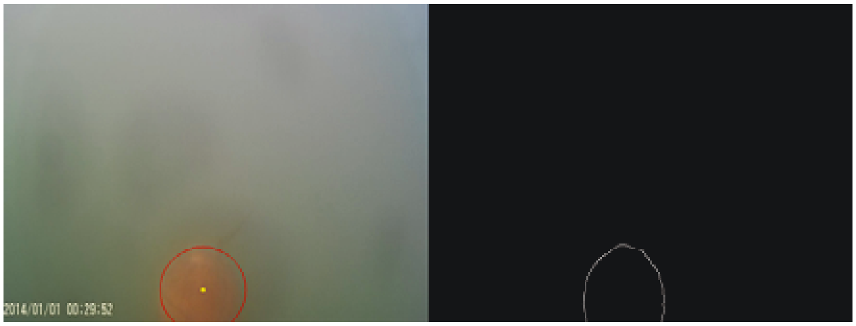
Nonetheless, the teams managed to perform the tasks under such difficult conditions by achieving many of the proposed goals. As an example, the object detection and recognition of the buoys by the OUBOT team is shown in Figure 14. Figure 15 presents an outstanding 3D reconstruction of the mannequin by the University of Girona.

Quantitative Results

To rank the teams, a scoring system was designed by dividing the proposed missions in subtasks. These were translated in achievements, whose accomplishment was judged by either a binary (e.g. entering the building) or a real number between 0 and 1 (e.g., quality of the map). The achievement accomplishments were then mapped into points by also taking into consideration the autonomy

FIGURE 14

On the left, one of the orange buoys (OPI) that simulated the plume. Results of the object recognition algorithm by OUBOT team in conditions of low visibility. Credit: OUBOT.



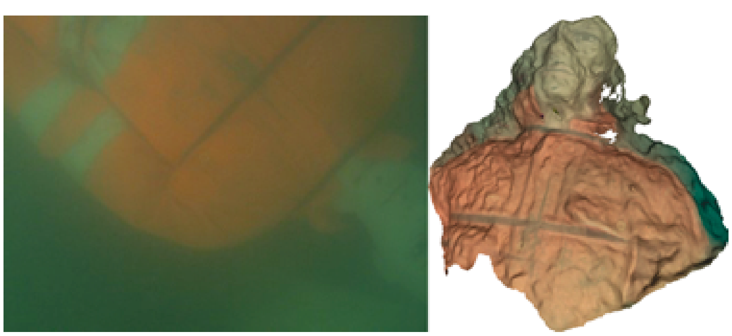
degree of the vehicles. This scoring system is directly related to the benchmarking methodology and inspired by the Task Benchmarking of RoCKIn project (Amigoni, 2015).

The winning team for the marine trials (University of Girona) managed to accomplish over 85% of the proposed achievements proposed in the two trials completely or partially. The robots operated in a fully autonomous way in all the tasks, except for the manipulation in which teleoperation was allowed. The scoring of the first three ranked teams of Sea Trial 2 is shown in Table 4 as a quantitative example. For more details about the results, see euRathlon (2016). The scoring mechanism takes into account the key and optional achievements. Each achievement gives up to 1 point (either binary or real value) and is weighted in the sum producing the A/OA values. Examples of achievements in Trail S2 are "AUV passes the gate"-binary, "AUV reaches the pipe area"-binary, "AUV builds a map of the area"-real value. Autonomy class awards the degree of autonomy with which a certain achievement is accomplished (1 fully autonomous, 0.5 semiautonomous, 0 teleoperated). Key penalties (e.g., leave the operating area) decreases the final score.

A summary of the number of teams achieving at least 50% of the proposed accomplishments per each marine domain-related scenario can be found in Table 5. It is worth noting that the winner in each of these scenarios had a relatively good performance with over 85% in both sea trials and over 80% for the Grand Challenge. In the Sea + Land Subchallenge, the winner had a worse performance but still managed to accomplish at least two thirds of the achievements.

FIGURE 15

On the left, the mannequin placed underwater. On the right, the 3D reconstruction of the mannequin. Credit: University of Girona.



euRathlon 2015: More Than a Competition—An International Robotics Event for the General Public

euRathlon 2015 has not only been a complex and challenging robotics competition involving more than 100 young and brilliant researchers, but it has also been an international robotics event for the technical and general public. It was both a unique opportunity to get together different robotics communities and to engage the general public with several activities running in parallel to the competition program. The strong dissemination effort and the international level of the competition attracted the interest of professional organizations and robotics companies, which supported the event with money and in-kind prizes. This strong support not only allowed us to increase the money available for prizes but also created opportunities for exhibitions and high-level events running in parallel to the competition itself. This in turn contributed to attract public, media attention and other sponsors leading to a virtuous circle, which boosted the dimensions and impact that the euRathlon 2015 Grand Challenge had in the general public and national/international robotics communities.

IEEE Oceanic Engineering Society (OES) played an essential role as Platinum Sponsor contributing for the awards of the competitions. IEEE OES also supported the competition

TABLE 4

Results of the Sea Trial 2: Leak location and valve closing.

Teams	UDG	ENSTA 1	AUGA
Achievement (A)	10	4	4
Optional Achievement (OA)	3	2	1
Autonomy Class (AC)	10	2	2
Key Penalty (KP)	0	0	0
Penalties (P)	0	0	0
T (Time)	55	60	60
Overall results			
SCORE = A + OA + 0.5 * AC + V − KP	18	7	6
Rank	**1st**	**2nd**	**3rd**

by providing judges. Their participation demonstrates the recognition that euRathlon 2015 gained in the robotics community, particularly in the marine domain. The EvoLogics (EvoLogics, 2016) company was a Silver sponsor and attended the event with an exhibition booth and a demo of their Sonobot surface vehicle (EvoLogics, 2016) in the harbor. Texas Instruments, SBG Systems, and VideoRay, Inc., contributed as Silver sponsors to the prizes on a smaller scale. SBG Systems also attended as an exhibitor. Many local companies sponsored or supported the event in different ways (see euRathlon, 2016, for a comprehensive list of supporters and sponsors). IEEE Robotics and Automation Society (RAS) also recognized the event by providing in-kind awards for the Best Autonomy Award and Best Multi-Robot Cooperation Award. Several representatives attended the event, taking the opportunity to meet and evaluate the teams and the proposed innovative approaches.

In total, there were 12 exhibitors at Tor del Sale hosted in booths inside the spectator tent. More than half of them were of (or included) the marine domain: IEEE OES, EvoLogics GmbH, ISME-Interuniversity Center of Integrated Systems for the Marine Environment, an Italian Research Consortium, ROBOCADEMY project, an FP7 EU project, the ICARUS FP7 EU project, the Institute of Biorobotics from the ScuolaSuperiore-Sant'Anna, Pisa, with their Marine section and the companies Applicon-Nexse/WSENSE that are active in underwater acoustics and networks. NIST (National Institute of Standards and Technology) was also present at the competition and considered it a good opportunity to study benchmarking for the different domains. The technical demos, exhibition space, and the opportunity to meet other members of the community attracted over 300 robotics experts between participants, staff, judges, and international guests.

Among them were Mr. Shinji Kawatsuma of the Japan Atomic Energy Agency (JAEA) and Dr. Larry Jackel, head of the logistics of DRC 2015. Professor René Garello, President of IEEE OES, was present and awarded the winners of marine trials. Professor Satoshi Tadokoro, the IEEE RAS President-Elect, awarded the IEEE RAS TC Best Autonomy Award and Best Multi-Robot Cooperation Award. Dr. Nick Chotiros, Associate Director of the Office of Naval Research Global (ONRG), was part of the judging team. As in the past years, ONRG supported the competition by providing personnel.

Besides the exhibitor companies and institutes, which increased the interest for the specialized public, satellite events were organized focusing more on the general public. A series of conferences on robotics at the Piombino Castle were held in the evenings of the 20th and 21st. A demo of the Robot-Era project (urban robots for the elderly assistance) (Robot-Era, 2016) was conducted by Scuola Superiore Sant'Anna in Piombino downtown on the 22nd. Two robots that participated in the DRC in June 2015 in Pomona, California, WALK-MAN (from IIT, Italy) and HUBO (from KAIST, South Korea), the winner of DRC 2015, in an absolute

TABLE 5

Number of teams with at least 50% of achievements accomplished and percentage of achievements fulfilled by the winner in each sea-related trial.

Scenarios	Sea Trial 1	Sea Trial 2	Sea + Land Subchallenge	Grand Challenge
Number of teams with at least 50%	3	3	3	3
% of achievements accomplished by the winner	86%	89%	67%	82%

premiere in Europe, performed a very crowded demo at Tor del Sale site (see Figure 16). The DRC, 2016) is the world's leading competition of humanoid robots, with the aim to develop robots capable of assisting humans in responding to natural and man-made disasters. All these events contributed to disseminate robotics among the nonspecialized public and in particular to the younger participants.

In total, around 1,200 people attended the public program, including several large parties of school students who visited the competition, from elementary to high school groups. euRathlon 2015 Grand Challenge attracted also a great interest from the international news media, national TV, and local and national newspapers with over 120 media spots in total (including six TV videos and a post on IEEE Spectrum online).

FIGURE 17

Group photo of euRathlon 2015 participants. Credit: euRathlon.

Conclusion

The euRathlon 2015 Grand Challenge was a great success and, thanks to the large participation of teams, to the specialized and general public, and to the impact on media, established itself as the *de facto* leading outdoor search and rescue robotics competition in Europe.

The competitions have shown that the robots today are effective in tackling single-domain tasks in realistic outdoor scenarios. Nonetheless, we are still far from full autonomy. This is particularly true in the land domain and in autonomous multi-robot cooperation. In the land domain, we have seen the highest use of teleoperation. Teleoperation is still the preferred solution also by professional teams.

In the future, search and rescue robotics systems need to increase the level of autonomy to effectively exploit multi-robot cooperation and the synergies the different types of robots can offer. Autonomy is in fact necessary to overcome situations common in disaster response intervention. For instance, when poor communications are present, only autonomous robots can continue their missions.

Focusing on the marine competitions, the best teams' robots were able to accomplish most of the proposed tasks even in low-visibility conditions. The robots were able to detect and map part of the OPIs and to navigate in the area. Markers on the pipes

FIGURE 16

From top-left in clockwise order. People attending the DRC demo. Cobham robot performing NIST tasks. DRC-HUBO robot from Team KAIST.WALK-MAN robot closing a valve during the exhibition. Credit: euRathlon.

were extremely hard to detect by means of optical sensors. Because low visibility is usually expected in areas after natural disasters, future research should focus on improving acoustic sensors to allow robots to acquire better situational awareness essential to accomplish the mission. All the underwater tasks were faced autonomously except for the manipulation, in which robots were teleoperated. Manipulation with a floating vehicle is still an open research topic especially in the low-visibility conditions of the harbor area.

One of the important results of euRathlon 2015, and of the euRathlon project in a broader sense, was the cross-fertilization among the different robotics communities. This cross-fertilization creates new links between researchers leading to new projects and collaborative efforts. The 9 days of the competition saw the gathering for the first time of researchers with different backgrounds aiming to solve the same problems seen from different perspectives. euRathlon 2015 pushed teams to move from considering single robots as the solution to challenges to more complex human-robotic, multi-actor systems. The cooperation among robots and humans was essential to succeed in the missions. Only with this kind of human-robotic integrated systems, we will be able to intervene successfully in real disaster areas in the near future as the Fukushima 2011 accident has demonstrated.

euRathlon 2015 was not only a great competition but also a robotics event that proved to be a great attraction in the scientific community and in the general public, showcasing the best of European robotics for the rest of the world. Several researchers came from the United States, representing important institutions (DRC, IEEE OES, IEEE RAS, and NIST), and also from Asia (Japan Atomic Energy Agency and Korean Advanced Institute of Science and Technology), making it a real global event.

The visit of 1,200 persons over the 9 days, including school parties, shows the importance that the event assumed in disseminating robotics among people and especially among the youngsters who proved to be very interested in the competition.

The logistical organization of such an event is complex. Besides setting up the areas for a robotics competition, a large effort is needed to create the temporary infrastructure to host the teams and visitors. Furthermore, finding a suitable location for this kind of competition was difficult. We needed a site with a sheltered marine area with a nearby space for land and aerial robot operations. In the area, we also needed a ruined building with the possibility to host the robot operations. Finally, we had to get the permissions for flying and marine robot operations from the competent authorities.

In the future, it is essential to guarantee continuity in proposing a euRathlon-like competition to allow teams to grow and continue to build an interconnected robotics community. Another competition for land, sea, and air robots will take place during September 2017, integrated in the RockEU2 H2020 European project. This project also includes indoor robotics competitions and several actions to strengthen the European robotics community. The aim is to create a European Robotics League comprising the flagship European robotics competitions. For more information regarding all the events of the euRathlon project (competitions, workshops, demos and parallel activities), the reader can consult euRathlon-Videos (2016).

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Title

The euRathlon 2015 Grand Challenge: the first outdoor multi-domain search and rescue robotics competition— a marine perspective

Abstract

The euRathlon project was an FP7-funded Coordination and Support Action (2013–2015). Its main aim was to organize outdoor robotics competitions in realistic search and rescue response scenarios for cooperative land, sea, and air robots. Participant teams were requested to test the intelligence and autonomy of their robots in scenarios inspired by the 2011 Fukushima accident. In the project's third year euRathlon culminated with the organization of the first outdoor multi-domain search and rescue robotics competition in the world: the euRathlon 2015 Grand Challenge. Sea, air, and land robots were asked to cooperate acting as a robotic intervention team in a scenario simulating an industrial area ravaged by a tsunami. The Grand Challenge was held in Piombino, Italy, in the surroundings of the Tor del Sale power plant, from September 17 to 25. To prepare the teams for the Grand Challenge, two competitions, dedicated to land and marine robots, respectively, took place in 2013 and 2014. In all the competitions, a strong effort was made in benchmarking what led to meaningful and reasonable scoring principles. Workshops and educational activities complemented the competitions. In this paper, we will focus on the marine robotics competitions of euRathlon with a particular focus on the Grand Challenge. Both technical achievements and general results are presented. The results in terms of team participation and the fruitful effort in dissemination led to establish euRathlon Grand Challenge as the de facto leading search and rescue outdoor robotics competition in Europe.

Keywords

Marine robotics, search and rescue, field robotics, competitions, benchmarking

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