RoboCup Rescue Robot League

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Abstract. The RoboCup Rescue Robot League (RRL) aims to foster the development of rescue robots that can be used after disasters such as earthquakes. These robots help to discover victims in the collapsed structure without endanger the rescue personnel. The RRL has been held since 2000. The experience gained during these competitions has increased the level of maturity of the field, which allowed to deploy robots after real disasters, e.g. at the Fukushima Daiichi nuclear disaster. This article provides an overview on the competition and its history. It also highlights the current state of the art, the current challenges and the way ahead.

1 Competition Overview

After a natural or man-made disaster, the first task for the responders is to find and rescue survivors in the collapsed buildings. Even though technologies such as microphone arrays or search cameras help the responders, it is still a dangerous task: the stricken building might collapse completely and bury the rescue team in case of an aftershock. Search and Rescue robots can help to reduce this risk during these Urban Search and Rescue (USAR) missions. The idea is to send these robots into the rubble pile, and let them search for victims using their sensors such as cameras or heat sensors and report to the rescuers once they have found a person.

The RoboCup Rescue Robot League (RRL) competition aims to foster development in this field [1]. The arenas in this competition resemble partly collapsed buildings, with obstacles consisting of standardised and prototypical apparatuses from the DHS[1]-NIST[2]-ASTM[3] International Standard Test Methods for Response Robots [2]. The robots perform 20 min missions in the test arena,

[1] US Department of Homeland Security.
[2] National Institute of Standards and Technology, US Department of Commerce.
[3] Formerly the American Society for Testing and Materials.

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in which they try to find as many simulated victims as possible. The complexity of the terrain increases in the different parts of the arena (see Fig. 1): In the yellow part of the arena (which has to be cleared by autonomous robots which do not rely on radio communication) continuous ramps challenge the sensors of the robot, but they do not challenge its mobility. In the orange part, the ramps are not continuous any more and the robot has to go over smaller unstructured objects such as sand and gravel. Finally, in the red part obstacles such as partly blocked stairs and pipe steps (which simulate extremely slippery curb stone edges) have to be climbed to approach a simulated victim. This part also includes the Symmetric Stepfield [3], a standardised pattern of wooden blocks that resembles the structure of a rubble pile. The easier yellow part of the arena must be cleared by autonomous robots, while in the more difficult parts mainly remote controlled robots are used. Here the challenges are mobility, manipulation, user interfaces for good situational awareness, reliable wireless communications and autonomous assistive features.

Fig. 1. Overview of a RoboCup rescue arena, composed of standardized test elements, organized in a maze. This image depicts a typical International Championship arena (in this case from the 2012 competition in Mexico City)(Color figure online).

The robot scores points for each victim it can find. The simulated victims can be detected by different signs of life, which are all simulated: the visual appearance (shape, color, and movement), the body heat, the sound and the CO_2 emission. The more information can be discovered for a victim, the more points the robot gets. Another important information is where the victim is located. This is not easy to determine, since in an indoor building classical localization approaches such as GPS do not work. A detailed map of the building along with a precise victim location yields extra points.

Beyond the detection of victims, rescue robots can be used to supply items to the victims, such as water bottles, two-way radios or medicine. If the robot is able to supply objects to the victim, it is awarded extra points. Usually, a robot arm (also called a manipulator) is used for the delivery. This manipulator can also be used to open doors by pressing the door handle or to clear the path of the robot from obstacles.

In contrast to the other RoboCup related activities, such as RoboCup soccer, scenarios in rescue do not include adversarial agents but instead inherently demand solutions for unpredictable, unstructured, complex and unknown environments. The goal of the RoboCup Rescue competitions is to compare the performance of different solutions for coordinating and controlling single or multiple robots performing disaster mitigation in a simulated but realistic environment. Since the circumstances during real USAR missions are challenging and always changing [4], benchmarks based on challenges such as the RoboCup Rescue competition can be used for assessing the capabilities of the robots. The competitions are held regularly as a part of the yearly RoboCup World Championship. Regional competitions are held in RoboCup Opens in the United States, Germany, Japan, Iran, Thailand and China. The RoboCup Opens are organized by the regional committees, whereas the international competitions are organized by league organizing committees. The rules are determined by the technical committee whose members are elected annually.

The objective of the RRL is to promote the development of intelligent, highly mobile, dexterous robots that can improve the safety and effectiveness of emergency responders performing hazardous tasks. As a league, we demonstrate and compare advances in robot mobility, perception, localization and mapping, mobile manipulation, practical operator interfaces, and assistive autonomous behaviors. We use the annual RoboCup competitions and subsequent field exercises with emergency responders to accomplish the following:

- Increase awareness about the challenges involved in deploying robots for emergency response applications.
- Provide objective performance evaluations based on DHS-NIST-ASTM International Standard Test Methods for Response Robots.
- Introduce Best-In-Class implementations to emergency responders within their own training facilities.
- Support ASTM International Standards Committee on Homeland Security Applications (E54.08.01) [2].

The teams that performed best during the preliminaries and the finals are awarded the first, second and third place. To highlight the achievements in the different sections special awards are given for *Best-in-Class Autonomy*, *Best-in-Class Mobility*, *Best-in-Class Manipulation* and *Best-in-Class Small Unmanned Aerial System*. The Best-in-Class Autonomy award is given to the robot that found the highest number of simulated victims during the competition and that was able to clear the largest part of the arena and produced the most accurate map during a separate Best-in-Class Autonomy mission. The Best-in-Class Mobility award is assigned to the robot that found the highest number of victims in the red arena and was able to handle the highest number of difficult obstacles (such as stairs, incline planes, and pipe steps) in a certain time. The Best-in-Class Manipulation award is given to the robot with the highest number of objects successfully placed into victim boxes and points gained during a special mission where the robot has to move wooden blocks and to handle different types of switches or valves. The Best-in-Class Small Unmanned Aerial System award is assigned to the flying robot that found the most victims flying and showed autonomous behavior such as station keeping during a separate mission.

Beyond the RRL, the RoboCup competition hosts Rescue Simulation Leagues. An overview of all the rescue leagues can be found at [5].

In important aspect of the RRL is that the teams do not compete against each other, but they fight the simulated disaster to finally help first responders to save lives.

2 History of the Rescue Robot League

After the Great Hanshin Earthquake 1996 in Kobe, the Japanese government decided to promote research related to the problems encountered during large scale urban disasters. One of the outcomes of this initiative was the RoboCup Rescue competition. The competition started in 2000 as a part of the AAAI Mobile Robot Competition and Exhibition. In 2001, the rescue robot competition was integrated into RoboCup competition. The USAR scenario offers a great potential for inspiring and driving research in robot systems that work in unstructured environments.

In 2013, more than 20 teams from 12 nations (Austria, Australia, China, Germany, Greece, Iran, Japan, Mexico, Portugal, Thailand, United Kingdom, United States of America) qualified for the RoboCup Rescue world championship held in Eindhoven (Netherlands). In addition, more than 100 teams compete in RoboCup regional competitions that are offered in Thailand, Japan, Iran and Germany. A good performance at the regional competitions qualifies for the world championship. An overview of the historic competitions can be found on the NIST website[4].

2.1 Towards Standardization of the Arena

During the first years of the competition, the arena showed a typical apartment or house interior, strewn with random debris. This was already a mobility challenge for some of the robots which mostly came from tidy research labs. However, it was not easy to reproduce the arena at other locations and get comparable test results. To get more repeatable results, the National Institute of Standards and Technology (NIST) defined a set of standard test elements for response robots. Starting in 2007, a collection of these elements were used to build the RoboCup Rescue Arena. Using these test elements, the difficulty and complexity of the competition arenas could be defined. The test elements are now standardized under the ASTM (American Society for Testing and Materials) body and

[4] http://robotarenas.nist.gov/competitions.htm.

further developed by the ASTM International Standards Committee on Homeland Security Applications, Operational Equipment and Robots (E54.08.01). The standardized test elements are also used to evaluate and compare commercial robots. They also help the customers to define the requirements they have.

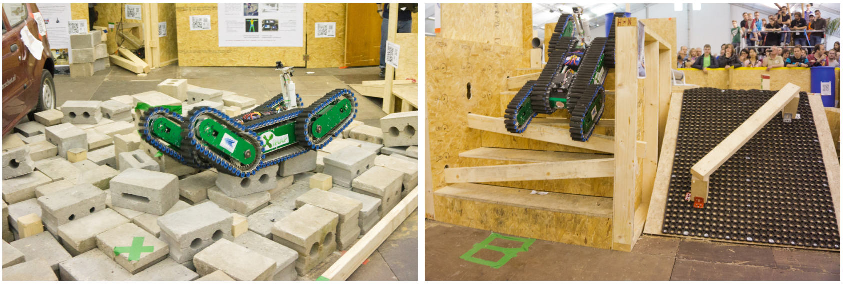
To keep up with the progress of the robots, the test elements are constantly modified. For example, the ramps and stairs became steeper over the last couple of years. The RoboCup Rescue competition is the place where prototypes of these new test element are tested. If they matured, their standardization is discussed at the ASTM committee. Beyond the standardized arena, regional open arenas can be adapted to the typical regional construction methods. For example, the Japan Open features an arena inspired by typical debris present after earthquakes in Japan which involve finer wooden structures.

2.2 Increased Mobility Challenges: From Flat Ground to Blocked Stairs

One of the constant changes over the years is to make the terrain more and more difficult. In indoor environments, the pose of the robot may be measured using wheel encoders. This approach fails if the ground is slippery, e.g. due to water or mud. To simulate this challenge, in 2005 loose paper was added to the arena. To cope with this, teams had to apply sensor fusion in their localization solutions. Wheel encoders are still a common approach for a rough local pose estimation, refined by matching consecutive laser scans or by matching the laser scan against an obstacle map. This approach has matured over time, and many teams do not use wheel based odometry for the pose estimation any more. Localization and mapping solutions can be used today independent from a specific robot – even stand-alone as a hand-held solution.

For years, the ground in the yellow arena was just flat and easy to handle for the autonomous robots. Starting in 2007, small 10 ° ramps were introduced. This was not so much a challenge for the mobility, but the rigidly mounted sensors suddenly sensed fake obstacles: when the robot was tilted due to a ramp, the laser range finder reported a spurious obstacle in front of the robot, which was actually only the floor. These fake obstacles can make autonomous navigation impossible. This forced the teams with autonomy to deal with this problem either by scanning the environment in 3D or by using an active sensing approach, controlling the orientation of the sensors depending of the attitude sensor. Today, the ramps in this easiest part of the arena have a 15 ° slope, and most of the autonomous robots can easily handle them.

Also the terrain in the orange and red part of the arena become more and more difficult. A major step forward was the introduction of Stepfield Terrains [3]. Initially a psuedo-random pattern of wooden blocks that simulate a rubble pile, these were refined into the Symmetric Stepfield terrain and test method over several years of competition. When the stepfields were introduced in 2005, none of the robots could overcome this obstacle reliably. But quickly, the robots evolved, and the stepfields become more difficult over the years. The current version of the wooden stepfield involves obstacles from 10 cm up to 50 cm height.



(a) (b)

Fig. 2. New mobility apparatuses at the RoboCup 2013 in Eindhoven, Netherlands: (a) Stepfield made of concrete blocks. (b) Occluded stair and ramp apparatuses.

An alternative version of the stepfield – used at the 2013 world championship – is built of concrete blocks. The elements are askew and there are gaps between the bricks (see Fig. 2). While originally approached as a challenge to teleoperated mobility, there has also been work on autonomously and semi-autonomously traversing these terrains. Approaches include the use of machine learning and behavioural cloning [6] for mechanically simple platforms and assistive features for controlling high degree of freedom mobility platforms [7]. One lesson from the Fukushima Daiichi nuclear power plant disaster was that stairways cluttered with debris were a major problem to overcome for the robots [8]. This experience was introduced in the stair and ramp test elements, in the form of the Occluded Stair and Ramp. During the final runs in the competition, the rescue robots have to deal with wooden bars blocking these elements as shown in Fig. 2. The robots can either remove the bars with their manipulator or climb over them.

2.3 Advances in Mapping and Autonomy

During the early years, the autonomous robots could apply easy reactive techniques such as wall following to reach and score the victims over flat terrain. With the increased size of the arena, simple navigation techniques were not sufficient any more, and sophisticated exploration strategies become more and more common. Since the arena is unknown to the robot in the beginning, the robot has to build an obstacle map to plan its path efficiently. The quality of these maps improved steadily over the years, see Fig. 3 for two examples. Not only improved mapping algorithms help to get better maps. Also the availability of new sensors helped, such as small laser range finders with larger ranges (e.g. 30 m range instead of 4 m). New, affordable 3D sensors enabled the robots to acquire data from complex environments. These new capabilities have inspired new tests for 3D perception, including 3D versions of the nested Landolt-C visual acuity test artefacts as shown in Fig. 4.

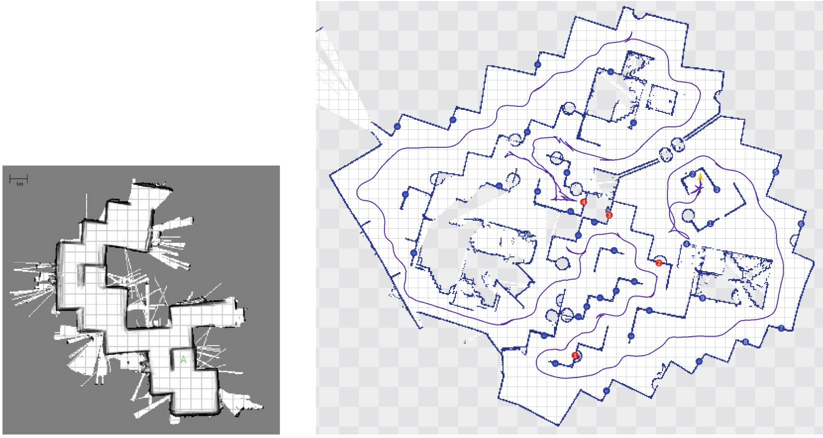


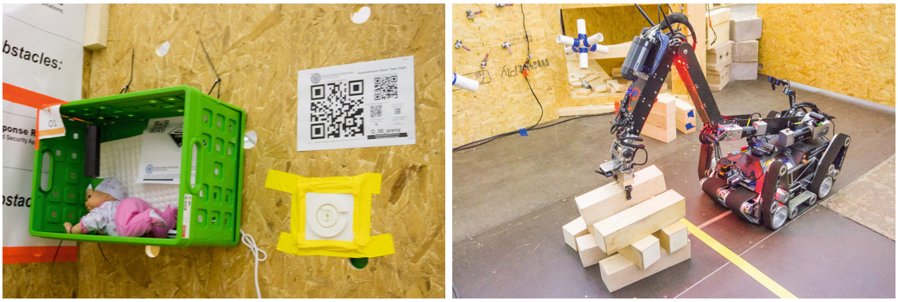
Fig. 3. Improvement of maps generated by autonomous robots during RoboCup Rescue finals over 5 years. Left: 2007 - map of the autonomy winner team Resko from University of Koblenz-Landau (Germany). Right: 2012 - map of the autonomy winner team Hector from TU Darmstadt (Germany). Note that both maps are shown to roughly the same scale.

2.4 Semi-automated Map Scoring

In the early years, the teams could turn in maps of the explored area in arbitrary formats. The Technical Committee (TC) then scored these maps be looking at the area explored by the robot and the accuracy of the map. Points were deducted if the map showed blurry walls or even double walls, which is a result of localization inaccuracies. With an increasing number of teams that produced maps and constantly growing arena sizes, the manual grading become more and more difficult. In 2012, unique visual tags, QR codes, were introduced at the walls of the arena. The robots have to detect and map the tags. For map grading, the number of detected tags conforms with the area covered by the robot. The precision of the localization equals the accuracy of the map. In 2013, different sizes of QR codes were introduced, testing also the accuracy of the sensors. By using these QR codes, map grading became much easier and more reliable. An example for such an QR code can be seen in Fig. 4.

2.5 Manipulation: Placing Objects and Opening Doors

In the initial years of the competition, the goal of the robots was information gathering by passive observation. In recent years, this goal has been extended to that of manipulation of objects in the environment. The initial task was to take wooden blocks and deliver them to the victims. This was extended to delivering operationally significant objects such as water bottles and radios. Most recently, additional challenges have been added including that of dexterously inspecting complex objects, opening doors (including those requiring the robot



(a) (b)

Fig. 4. (a) A victim box (left) containing various signs of life, a QR Code test sheet (upper right) containing QR codes of different sizes to test autonomous vision and a nested set of Landolt-C optotypes in relief to test 3D sensing (lower right). (b) A robot stacking blocks in the box crib shore configuration.

to simultaneously rotate and pull a door handle) and stacking blocks in a box crib shore configuration as shown in Fig. 4.

2.6 Aerial Robots

Aerial robots are becoming increasingly popular among both the responder community and the general public with a plethora of highly capable, small, low cost vehicles. The league saw aerial robots as early as 2004 with a robotic airship. Powered, heavier-than-air robots such as quadcopters have been incorporated into the competition since 2009. This initially took the form of an aerial arena, equipped with prototypical test methods for aerial response robots and separated from the main arena by a safety net. In more recent competitions, the main arena as a whole has been covered with a safety net that aims to both shield spectators from the aerial robots as well as to introduce overhead obstacles that the aerial robots must avoid. Aerial robots are treated similarly to other robots in the competition and have demonstrated their ability to build maps and identify victims. While they do not have to tackle the terrain challenges that face ground robots, they must tackle other issues such as low overhead and side clearances, complex structures in the immediate vicinity of victims and air currents.

3 Today's Competition Structure and Challenges

Because of the standardized test elements, the progress of the league can be seen over the years. When the random stepfields were introduced in 2005, none of the robots was able to cross them reliably. Today, driving through the stepfields is state of the art for the remote controlled robots. During the same time, the fully autonomous robots had to learn how to handle uneven terrain, because their section of the arena is not flat any more, but filled with continuous or crossed ramps. This challenging floor does increase the complexity of the path planning and requires an active sensing approach with stabilized distance and victim sensors. Nevertheless the quality of the generated maps increased over the years, and mapping the whole arena is not state art. An example of a very precise map is given in Fig. 3. The newer map on the right not only shows the obstacles in the arena, but also contains the victim locations and other landmarks (QR codes) found autonomously by the robots' vision system automatically. The maps are scored by looking at the completeness of the exploration (using the number of QR codes found) and at the accuracy of the recorded landmark locations. The scientific output of the league includes solutions for online SLAM solutions [9,10] and solutions for efficient exploration strategies [11]. The performance of these approaches was demonstrated and tested in practice during several RoboCup competitions.

3.1 Re-usable Software Modules

Due to the complexity of the problems addressed in the competition, the barrier for the entry of new teams is high. Therefore, one of the current challenges of the league is to make the successful software modules available for new teams. To this end, the league has established an open source standard software solution based on ROS for the RRL. This standard software solution makes excellent solutions broadly reusable thus enables new teams to reach quickly to the world class performance level. This way, each team only needs to focus on their own topics of interest, such as mapping, exploration or victim detection[5]. Code sharing in the league is done on voluntary basis. However, sharing good contributions is often honored with special awards such as the innovation award or the HARTING Open-Source Award at the German Open, which were both awarded in the past to the team Hector Darmstadt (Germany) for their major contribution to the software repository.

3.2 Rescue Robots in the Field

The obstacles that the robots must overcome in the competition consist of test method apparatuses. These are in turn developed by taking real world response robot operational scenarios and distilling them into elemental tests. Thus robots that perform well in the competition also answer critical real world needs. This was graphically demonstrated during the immediate aftermath of the Great East Japan Earthquake. Visibility into the reactor buildings at the Fukushima Daiichi Nuclear Power Station was critical and while several commercial robots were able to gain entry, the stairs proved too steep to climb. The robot that succeeded in climbing to the upper floors of the reactor buildings was a modified Quince robot, shown in Fig. 5. This robot was developed and refined over successive years, within the RoboCup RRL, by the International Rescue System Institute

[5] The current status of the common software framework for RoboCup Rescue initiative is documented in the ROS wiki at http://www.ros.org/wiki/robocup_rescue.

(Japan), a consortium of Japanese universities lead by Tohoku University [12]. Developments from the RRL are frequently demonstrated to first responders and robot manufacturers during a Response Robot Evaluation Exercises. These presentations help to show the state of the art in rescue robotics, and inspired new products, such as mapping capabilities for commercial robots.

3.3 Academic Summer Schools

The goal of the league is to advance the state of technologies for search and rescue. While the competitions are a vital tool for fostering collaboration between teams, actual collaboration during the competition can be difficult. The League runs academic summer schools in the second half of the year, where Best-in-Class performers from the league and wider research community can share their capabilities with the rest of the league and representatives of responder organisations. These events started in 2004, hosted by the University of Rome "La Sapienza" and held at the Istituto Superiore Antincendi (firefighter training academy) in Rome. Since then they have been hosted by Mahidol University in Thailand, the University of Koblenz-Landau in Germany, the Technical University of Graz in Austria, Linköping University in Sweden, Robolit LLC in Turkey and Curtin University in Australia [13].

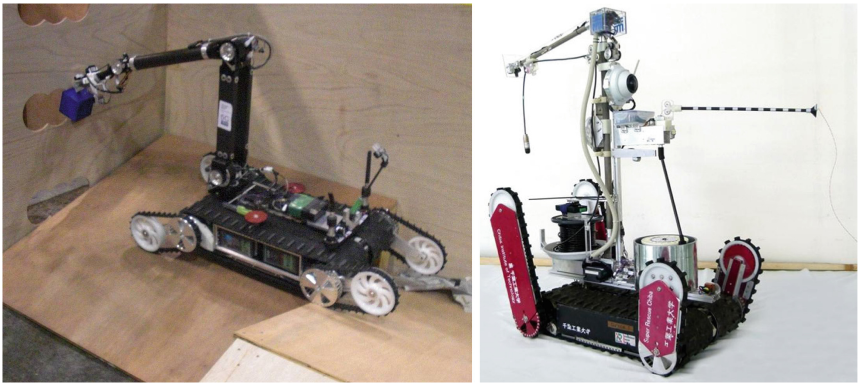


Fig. 5. The Quince robot in competition in Singapore in 2010 (left) and equipped to sample radiation and water levels in the Fukushima Daiichi Nuclear Power Station (right, courtesy of CIT, Tohoku University, IRS and NEDO).

3.4 The DARPA Robotics Challenge

The DARPA[6] Robotics Challenge (DRC)[7] is a related competition that shares many of the same goals and principles as the RRL. NIST also plays a leading

[6] US Defence Advanced Research Projects Agency.
[7] http://www.theroboticschallenge.org/.

role in developing the challenges for the DRC and there are competitors in the DRC who also participated actively in the RRL. The DRC and RRL are complimentary competitions that differ in scope and emphasis. The DRC has much harder tasks that demand significantly greater levels of autonomy, mobility, dexterity, reliability and system integration. The RRL, in contrast, focuses on more incremental improvements that allow all teams to demonstrate their capabilities, including those who only specialise in a particular capability. The cost of entry in terms of personnel and resources is also significantly lower in the RRL. The relationship between the competitions allows for synergies between the two competitions. For example, the process of developing the challenges for the DRC involved evaluating different options within the RRL. Similarly, it is anticipated that many of the capabilities and tools developed for the DRC, including the DRC Simulator, will be adopted by teams within the RRL.

4 Future Goals of the League

The RRL continues to evolve in order to guide teams towards answering gaps in the capabilities of deployed systems. Developed hand-in-hand with the DHS-NIST-ASTM International Standard Test Methods for Response Robots, the challenges of the competition continue to be grounded in the needs of emergency responders across a wide variety of applications. Particular areas of focus for future attention include increasing assistive and full autonomy throughout the arena, improved human-system interaction especially for mobility, navigation and manipulation, the introduction of environmental effects such as fog and smoke, co-operation between robots and fully automated scoring and evaluation.

4.1 Autonomy

Advances in 3D depth perception enable the robots to capture the environment in greater detail. However, most autonomous robots use this knowledge so far to just stay out of difficult terrain. In the future, the robots will be required to deal with more difficult terrain autonomously, by increasing the complexity of the yellow arena.

4.2 Human-System Interaction

One of the greatest challenges in response robotics is in the interface between the robotic system and the human operator. For several years now the League has presented a technical award for Innovative User Interfaces. This has in the past been awarded for such innovations as wearable user interfaces and interfaces that support semi-autonomous operation. In the future, the League seeks to encourage the further development of improved user interfaces for advanced mobility, navigation and manipulation. Examples of such innovations include automatic movement of high degree of freedom mobility bases, such as those equipped with flippers, to address different mobility obstacles [7], improved ways of presenting real time map data to the operator in order to maintain situational awareness and innovative ways of allowing operators to control high degree of freedom manipulators to perform dexterous inspection and manipulation in confined spaces.

4.3 Fog and Smoke

A common characteristic of some response environments is the presence of fog and smoke. The competition is in the early stages of introducing these characteristics, with simulated smoke, in the form of clouds of water vapour, denoting potential incipient fires that are of interest to the robots. In the future, this may be extended to include fog and smoke that are intended to also interfere with the robots' sensing and requiring additional sensors, such as infrared and sonar, to overcome.

4.4 Co-operation Between Robots

The competition allows already the use of multiple robots during the mission, as long as they are controlled by a single operator. A common practice of the teams is to send in two robots: one autonomous and one remote-controlled. To search the arena more efficiently, the number of autonomous robots – working together as a team – should be increased. From a scientific point of view this would push the research on robot teams, working together in unstructured environments.

4.5 Automated Scoring

So far, the scoring of the robot's performance relies on a judge who keeps track of the result on a paper sheet. In the future, this process will be further automated. Ideally, the robot sends the discovered data directly to a judge box, which compares the data with the ground truth data and assigns points automatically.

The next competition will be in July 2014 in Brazil, followed in 2015 by a competition in Thailand. More information is available on the RoboCup website[8].

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