Survey of Rescue Competitions and Proposal of New Standard Task from Ordinary Tasks

Masaru Shimizu[1(✉)] and Tomoichi Takahashi[2]

[1] Chukyo University, Nagoya, Japan
shimizu@sist.chukyo-u.ac.jp
[2] Meijo University, Nagoya, Japan
ttaka@meijo-u.ac.jp

Abstract. This study surveys rescue robot competitions and tracks the changes in the RoboCup Rescue League. The real robot league has been changed because of requests from real disasters; however, the virtual robot league competition basically remains the same as it was in the beginning.

In terms of some elements, the virtual robot league competition has capabilities of reproducing real situations for rescue robot evaluations when compared to the real robot league.

We propose herein a new competition task to mimic actual situations. We used a tank array model as the stage of the competition task after the Fukushima nuclear power plant.

1 Introduction

Since the Great East Japan Earthquake of 2011, robots have been used to explore the interior of the Fukushima Daiichi Nuclear Plant (FDNP). The situations encountered at the FDNP in 2011 and after the September 11 attack on the World Trade Center (WTC) proved to be far more challenging than anything anticipated before these disasters. In the tunnel ceiling collapse accident at Sasago tunnel in 2012 in Japan, the disaster area consisted of certain long and curved narrow spaces.

At the FDNP, robots are expected to be used for a variety of tasks for several decades as the nuclear facilities are decommissioned [3]. These tasks include clearing debris, monitoring and mapping the inside and outside of buildings, setting up instruments, shielding and decontaminating, as well as transporting materials, construction pipes, and equipment. The tasks require robot mobility, perception ability, autonomous ability, multi-robot ability, networking ability, maneuvering ability, and safe behavior ability. Therefore, it will be necessary to design new mechanisms and develop sensing algorithms to satisfy the mid- and long-term schedules for decommissioning the FDNP [29].

The use of robots in emergency, ordinary situations and during reconstruction periods not only require mobility of the robot but also other abilities to complete

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tasks. For example, these robots could be used to inspect water contaminated with radioactive material, such as those stored in the tanks outside the FDNP [27]. It is necessary to evaluate the abilities of robots to develop better robots. Robot competitions play the role of leaders in developing evaluation methods regarding the abilities of robots.

The RoboCup Rescue Real Robot League (RRRL) and the Rescue Virtual Robot League (RVRL) both possess proper robot evaluation items. S. Carpin et al. discussed the usage of a simulation platform in the urban search and rescue task in 2006 [4,6,7]. In the case of the RVRL, using simulation technology, robotic programs, algorithms, and robot behavior can be evaluated before physically constructing the robot. Each league should use its optimum characteristics and fulfill the role expected from disasters that occur.

The robotic tasks at the FDNP include ordinary investigation tasks, such as checking the leak of contaminated water in the tank array area. The task requires rescue robots with three-dimensional mobility, such as a multicopter, an autonomy ability in an unstable Wi-Fi environment, and a multi-robot ability as cooperative by themselves.

We survey the RVRL historical progress, current status, and problems and propose a new competition task based on the scenario of the tank array checking water leaking ordinary investigation task in the FDNP with the tank array, multicopters, ground vehicle robots, and reproduced Wi-Fi behavior. Section 2 describes a survey of the RVRL and rescue competitions and various test methods for evaluating the abilities of response robots. Section 3 describes a proposal for a new competition task based on a realistic ordinary investigation task at the FDNP. Section 4 describes the proposed new competition field. Section 5 discusses the future competition task for the evaluation of robots and a summary of the study.

2 Survey of Rescue Tasks

2.1 Competitions of Rescue Robots

New robots, devices, programs, and algorithms should be evaluated as soon as possible. After developing a robot, the developers evaluate the ability of the robot in terms of mobility, dexterity, sensing, mapping, and other functions required as a response robot. Already various test methods exist that can be used for evaluating the abilities of each individual robot. The tests comprise the following: mobility tests, wireless communication tests, manipulation tests, human-system interaction tests, and sensing tests. Mobility tests include flat surfaces as well as pitching and rolling ramps, steps, inclines, gaps, stairs, and landings. Sensor tests determine the quality of the video. A previous version of the Quince robot, which participated in the RoboCup Japan Open Rescue Real Robot competition, was actually applied at the FDNP; its use exploring the disaster zone allowed a real-life demonstration of its capabilities [31].

Table 1. History of rescue robot competition and test field

Year	Title of competition	Target: Operation	Target: Robot Type	Evaluation	Real /Simulation	Background case
1998	RoboSub	rescue	sea	mobility	real	
2000	RoboCup (Rescue)	rescue	land/air	mobility /mapping /dexterity	real	Hanshin-Awaji earthquake (1995)
2006	ELROB		land/air	mobility	real	
2008	Rowboat		sea	mobility	real	
2012	ICARUS	rescue	land/sea /air	mobility	real	Earthquakes in l'Aquila, Haiti
2013	DARPA (Robotics Challenge)	rescue	land	mobility /mapping /dexterity	real /simulation	Fukushima nuclear disaster
2013	euRathlon	rescue	land/sea /air	mobility /mapping	real	Fukushima nuclear disaster
2014	ARGOS challenge	survey	land	mobility /mapping /dexterity	real	Future plant disaster
2015	JVRC	survey /rescue	land	mobility /mapping /dexterity	simulation	Sasago falling tunnel ceilings accident
2018	WRS (Tunnel)	survey /rescue	land/air	mobility /mapping /dexterity	simulation	Sasago falling tunnel ceilings accident
2018	DARPA (Subterranean Challenge)	survey /rescue	land/air	mobility /mapping /dexterity	simulation	

Table 1 shows a list of robot competitions [2,9–15,17–19,21–25]. Several competitions were organized after certain large disasters. In these competitions, dedicated competition fields were constructed to evaluate response robots. Thus, each competition field incorporates certain real disaster situations. New competitions have new metrical items owing to new disaster situations.

The investigation tasks consist of routine operations, which are simpler than those undertaken by the Quince robot inside the FDNP in 2011 in a larger area. Several tanks were constructed at the FDNP to store contaminated water for the purpose of cooling nuclear fuel. The tanks were arranged systematically in a 100 m wide area, and each tank measures 10 m in height and 12 m in diameter. The robots designed for these tasks require verification. When developing sensors and robots for search and rescue operations in disaster zones, testing the robots in such environments can aid in determining and improving their performance.

When using tele-operation type response robots, stable Wi-Fi connectivity is essential, in addition to other capabilities such as mobility function. A response robot that moves outside of a Wi-Fi connectable area is uncontrollable, and in the worst case the operator loses it. A response robot with a recovery program, which directs the lost response robot to a Wi-Fi connectable area, requires time for the automatic recovery behavior. The system including the response robots requires a simulator that can estimate the Wi-Fi connectable areas to determine the effective locations of Wi-Fi base stations, which are limited in a disaster area and/or a large destroyed facility such as the FDNP.

Thus, a simulator is an appropriate tool that can be used to observe problems when using a response robot with unstable Wi-Fi connectivity. This approach avoids the difficulties of testing in the real field. The RVRL should use more realistic situations with the Wi-Fi networking.

2.2 Standard Test Methods in Robot Competitions

Table 2 shows the relationships between robot competitions and its metrical items:

- Mob. (Mobility): the performance to move on the uneven surface or to climb a ladder.
- Per. (Perception ability): the performance to recognize hazard tags, QR-Codes, and texts in the environment around the robot.
- Aut. (Autonomous ability): the performance to work and produce 3D maps in Wi-Fi blackout areas without human aid.
- Mul. (Multi-robot ability): the performance to work with multiple robots in large size fields and separated fields.
- Net. (Networking ability): the performance to maintain and form the communication link in unstable Wi-Fi areas and Wi-Fi blackout areas.
- Man. (Maneuvering ability): the performance to manipulate, manage, and carry objects.
- Saf. (Safe behavior ability): the performance to move safely and maintain safe behavior with respect to victims and objects in the environment.

Every metrical item is reproduced with a style of robot competitions. For example, National Institute of Standards and Technology (NIST) released Standard Test Methods (STM) for evaluating response robots [1,16]. STM is used as the

Table 2. Competitions and metrical items

Competitions	Metrical items						
	Mob.	Per.	Aut.	Mul.	Net.	Man.	Saf.
RoboCup (RRRL)	✓	✓	✓	✓	✓	✓	✓
RoboCup (RVRL)	✓	✓	✓	✓	✓		
DARPA	✓	✓	✓			✓	
ARGOS challenge	✓	✓	✓	✓	✓	✓	✓
JVRC	✓	✓				✓	
WRS	✓	✓	✓	✓	✓	✓	
DARPA (SubT)	✓	✓	✓	✓	✓		

field for evaluation of mobility in the RRRL. A competition that is closed to real situations possesses considerable amount of metric items. Seven metrical items are merged from robot competitions; every robot competition exhibits several abilities such as autonomy ability, perception ability, networking ability, mobility, maneuvering ability, and multi-robot performance. The RRRL and ARGOS challenges contain all metrical items.

2.3 Issues of RoboCup Rescue League

Table 3 shows the historical comparisons of the competition content of the RRRL and the RVRL. In the RRRL, the number of metrical items is increasing gradually, and the types of inspection items are also increasing. In the RVRL, the number of metrical items is increasing, and the types of inspection items are not increasing. The RRRL has been evolving at the core of evaluation of rescue robots; the RVRL has been stopping evolution. The RVRL does not contain any critical metrical items that the RRRL already contains. However, the RVRL can prepare some of the metrical elements readily compared with the RRRL.

Table 3. Historical comparisons between rescue real robot league and virtual robot league

Year	Real Robot League		Virtual Robot League	
	Size&Ability	Photos	Size&Ability	Photos
2002 ~	10 m x 10 m Mobility Perception Multi-robot Autonomy Safe behavior		(NOT STARTED)	(NOT STARTED)
2008 ~	15 m x 15 m Mobility Perception Multi-robot Autonomy Networking Safe behavior		100 m x 100 m Perception Multi-robot Autonomy	
2012 ~	30 m x 30 m Mobility Perception Multi-robot Autonomy Networking Maneuvering Safe behavior		200 m x 200 m Perception Multi-robot Autonomy Networking	

The RVRL and the RRRL exhibit the same objective, however, they do not share concepts and schemes with each other. For example, the RVRL should be a tool that the RRRL participating team requires to use for robot development with respect to new autonomous programs, perception algorithms, and mapping systems. The RVRL should use metrical elements that are difficult to prepare at the RRRL and are effective for robot development in the competition. For example, large and realistic situation field models that came from the FDNP and natural Wi-Fi behavior can be realized using already existing simulation items.

In 2009, the wireless communication server (WSS) was introduced to simulate robot behaviors, where the robots receive the Wi-Fi [5]. The WSS was not used at recent competitions in 2016 and 2017.

3 New Standard Task from Ordinary Tasks

3.1 Use of Wi-Fi in Networking Ability Evaluation

In Fukushima, robots were employed to perform emergency tasks immediately after the 2011 earthquake. At present, robots continue to perform ordinary tasks such as daily investigation jobs. To perform these ordinary tasks, the robots should move freely within a large area. For robot evaluation in the context of these ordinary tasks, the size of the evaluation field should be known, and a controlled unstable Wi-Fi connection status is required.

Quince robots were used to inspect the inside of the FDNP. Because of the Wi-Fi disability in the FDNP facilities, Quince robots were used in tandem [3].

In Table 2, the networking ability was indicated as an item of robot evaluation. Robot behavior stability is evaluated with regard to disconnection of its Wi-Fi connection. In the real response robot working field, the Wi-Fi status has the capability of being unstable in connection [8,25,28]. To reproduce the natural Wi-Fi behavior, the real robot evaluation field should possess a large sized field that has over 100 m in the radius from the Wi-Fi base station to disconnect the Wi-Fi. Therefore, the condition of Wi-Fi disconnection has been managed in an imaginary manner by defining it in the competition rules at a part of the competition area.

The strength of a natural Wi-Fi radio wave exhibits band fluctuation, even when the Wi-Fi base stations and robots do not move. Further, the movement of humans and robots inside a Wi-Fi area increases the band fluctuation of the Wi-Fi radio waves. Fluctuations of the Wi-Fi radio waves within the diffraction area can induce Wi-Fi disconnection in the outer diffraction areas. Thus, to maintain stable Wi-Fi connectivity throughout the Wi-Fi diffraction area, a safety margin is required in the outer diffraction area.

3.2 Proposal of New Ordinary Investigation Task

Based on the reported robotic tasks performed at the FDNP, we propose an ordinary investigation task in the large area with high and low places by controlling of the Wi-Fi connection status along with an environmental model that is close to the real scenario at the FDNP, the shape of which can affect the Wi-Fi connection status.

Simulations can be used effectively to evaluate robot performance, as evident from Table 1. In particular, certain real metrical elements that are difficult to prepare and control can be reproduced in a simulation. In addition, a town-size field can be prepared considerably readily in a simulator than in a real-world environment. Controllable environmental phenomena are useful for robot evaluation. Simulations such as that used in the Virtual Robot segment of the RoboCup Rescue competition provides platforms where response robots and algorithms can be tested with respect to the disaster zones where they are intended to operate [20]. Thus, a simulator is a useful tool for identifying problems with response robots under conditions of unstable Wi-Fi connectivity. Therefore, in this study, a new simulated standard task with Wi-Fi behavior similar to the natural case is proposed.

The proposed simulation platform is designed considering multicopters, which exhibit the following characteristics:

- Multicopters can move through a larger area in less time compared with ground vehicles.
- Multicopters can move not only horizontally, but also vertically.
- The Wi-Fi-connectable area is invisible.
- The shape of the Wi-Fi-connectable area or Wi-Fi diablo area is difficult to image.

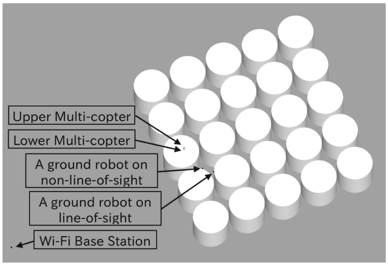
The real sample situation at the FDNP involves arrays of large tanks storing contaminated water. These tank arrays constitute an unstable Wi-Fi connectivity area. Daily investigative tasks using robots require a stable Wi-Fi connection, and automatization of these daily investigations performed by robots requires a lightweight estimation method to calculate the Wi-Fi connectable areas.

4 A New Ordinary Investigation Task Simulation Field

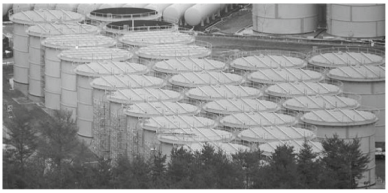
4.1 Background of Proposal

At FDNP, robots have been expected to perform ordinary daily investigation tasks. In this proposal, we focus on the multicopter, which is regarded as a standard robot in the RVRL. The multicopter is one of the most suitable robots for ordinary investigation tasks. In an emergency, the multicopter is used as a response robot under restricted conditions of Wi-Fi behavior is not reproduced, these robots can explore the entire model test environment. In contrast, in our proposed simulation platform that reproduces natural Wi-Fi behavior, robots can explore only the Wi-Fi-connectable area.

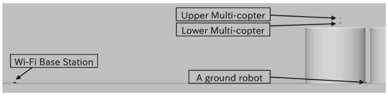
In the proposed competitive field, a tank array field such as that encountered in the FDNP was used. The following conditions were implemented in the proposed simulation platform:



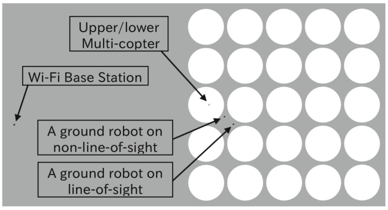
(a) An overview of sample simulation platform.



(b) A real tank array([30]).



(c) A side close-up view of sample simulation platform.



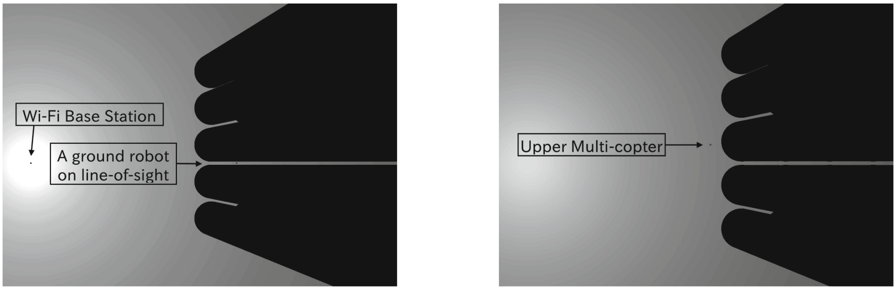
(d) A top overview of sample simulation platform.

Fig. 1. An overview of sample simulation platform and original tank array scene

- A 5×5 tank array was considered as the test environment.
- Each tank possessed 12 m diameter and 11 m height, similar to those of the real tank array.
- The distance between the tanks was 1 m, as in the real tank array.
- Two multicopters and two ground robots were considered as the test robots.
- Radio wave power attenuated via distance and shadowing via buildings was used to model the Wi-Fi behavior.
- To incorporate the attenuation phenomena of the radio wave power, as affected by distance, the distance was considered as 90 m from the center of the tank array.

Figure 1 presents a sample simulation platform image and an actual tank array image [30]. In detail, Fig. 1(a) shows an overview of the sample simulation platform designed using the above conditions. A Wi-Fi base station is located to the left of the image, two multicopters can be found at the center of the image, and two ground robots are positioned to the right of the multicopters. Figure 1(b) is an image of the actual tank array in the FDNP [30]. This array spans an extremely large area, and an elevated position is required to perform the daily investigation tasks. Thus, a multicopter is an appropriate robot for positioning at the station. Note that the multicopter operator must have access to operate the multicopter properly. Figure 1(c) and (d) show side and top views of the sample simulation platform, respectively.

Figure 2 shows two images of the simulated received signal strengths (RSSs) of the Wi-Fi, as received at the horizontal planes of different heights. In the



(a) At 0.3-m-high horizontal plane. (b) At 13-m-high horizontal plane.

Fig. 2. Images of simulated received signal strength of Wi-Fi received at different high horizontal planes

simulation of the RSS-treated diffraction and fluctuation phenomenon of radio waves [26], the former WSS did not treat it. The white color in the figure indicates that the RSS value is high, whereas black means the RSS value is less than -92 dB. The robot cannot connect to the Wi-Fi at a location with an RSS value of less than -92 dB. A Wi-Fi base station is located in the center far left of the image. The black areas in the right half of the image corresponding to the Wi-Fi location shadows of the tanks. (a) shows an image of the simulated Wi-Fi RSS at nearly the ground plane. The Wi-Fi base station can be observed on the left of the image (the black dot in the center of the filled white circle), and a ground robot is visible in the line of sight from the Wi-Fi base station. (b) shows an image of the simulated Wi-Fi RSS at a 13 m-high horizontal plane over the tank. Shadows are moving toward the right of the image in (a), and the upper multicopter can be observed in this image.

From (a)–(b), the outline shape of the Wi-Fi shadowed volume is part of a resting cone, which explains why it was exceedingly difficult to tele-operate the multicopters over and between the tanks. Furthermore, this difficulty explains the usefulness and effectiveness of our proposed Wi-Fi simulation platform for evaluating a multicopter system involving a multicopter operator.

4.2 Sample Tasks for Networking Ability Evaluation

Figure 3 presents an example of the proposed new standard task incorporating the Wi-Fi behavior. A standard task with a course similar to an ordinary investigation task is illustrated. A multicopter robot should begin at the starting point, from "P1" to "P16" in any order, and return to the destination. A list of sample rules is provided below:

- Obtain a scoring point using the grade of accuracy of the generated 3D map.
- Obtain a scoring point by passing near each checkpoint.
- Obtain a scoring point by reporting changes from "P1" to "P16" for before and after the disaster event.
  Change examples: removal of tank surface paint, broken tank edge

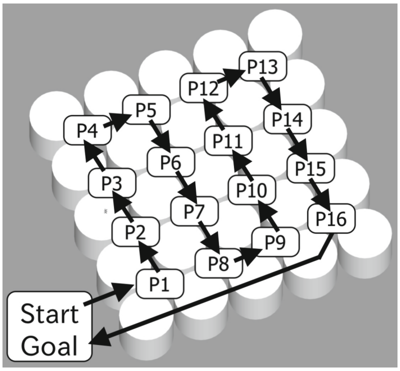


Fig. 3. Image of proposed new standard test method

- Obtain a scoring point by returning to the goal in a relatively short time.
- Double the scoring points by developing and using an autonomous software.
- Lose a scoring point by losing the multicopter robot.

The variety and difficulty grades of the field can be established based on the following weather conditions:

- Fine, rain, and snow.
- Day and night.
- Typhoon (strong wind).

The situations, rules, weather conditions, and environmental models for the simulation platform are changeable. Because the proposed platform is implemented on a simulator, it can be used by anyone and modified readily as required.

5 Summary and Discussion

Simulations are used to design robots and examine the robot's functions before manufacturing real ones. Rescue robots must be confirmed before being used in disaster situations and reconstruction tasks in FDNP that will continue for decades. This study indicates that the RVRL has been a part of the request of the real world and distinctly mentions the points that should be checked in virtual spaces.

We organized necessary tasks with respect to conducting inspections of FDNP as an example of ordinary tasks and proposed new standard tasks with regard to the RoboCup Rescue League. The tasks would be of interest to the teams of the RRRL and the RVRL with regard to the viewpoint of applying their robots in real fields.

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