STUDY ON ENVIRONMENT REPRODUCTION METHOD IN RESCUE ROBOT EVALUATION SIMULATION PLATFORM

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Contents

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Concept of this study

As we can use high-performance computer hardware and high-performance simulation software with high-performance physical calculation libraries, we should be able to utilize simulations with additional kinds of robot performance-evaluation scenes. Currently, various simulation platforms for robots are available, including Gazebo, Choreonoid, MORSE, and OpenHRP [3–9].Some robotics simulators have been used in famous robotics competitions. For example, Gazebo was used in the DARPA Robotics Challenge [10,11] and RoboCup Rescue Virtual Robot League [12,13]. Choreonoid was used in Japan Virtual Robotics Challenge [14,15]. To evaluate and measure the robot performance under certain environmental factors, additional components are necessary in order to use an original robotics simulator as a robotics evaluation simulation platform. The aim of this study is to propose the new components required to utilize a simulation platform for robot-performance evaluation, including the following aspects:

1. Proposal of new simulated environmental factors required for performance evaluation of rescue robots.

2. Proposal of a robot evaluation simulation platform involving the proposed simulated environmental factors.

3. Discussion of the effectiveness of the proposed simulated environment factors for evaluation of the performance of rescue robots.

This study presents some implementation examples and their experimental results.

1.2 Background of this study

It is urgent to develop response robots that can be utilized not only in wide-area natural disasters and accidents but also in disaster sites.

Table 1: A list of recent some disasters, disasters made large no-entry area.

Year	Location	Incident(s)
1986	Chernobyl, Soviet Union	Nuclear accident, No-entry town
1995	Hanshin-Awaji, Japan	Earthquake, Housing collapse, huge area fire
1999	Tokaimura, Japan	Radiation accident, No-entry facility
2001	World Trade Center, USA	Huge building collapse
2004	Mihama, Japan	Radiation accident, No-entry facility
2011	Tohoku, Japan	Earthquake, Tsunami, Nuclear accident
2012	Sasago, Japan	Tunnel ceiling collapse

Table 1 lists some disasters in recent years in which there were large areas where people could not enter. This is a reason to use response robots. Furthermore, response robots are needed to prevent secondary disasters. Response robots have been developing with disasters. The development of response robots needs methods to evaluate the functions that will be used in a disaster. Recently, the standardization of response robot evaluation methods has being required. For example, National Institute of Standards and Technology (NIST) of the United States and the American Society for Testing and Materials (ASTM) have released a series of Standard Test Methods(STM) for response robots consists of various test methods for evaluating the mobility, the dexterity, the mapping ability and the other useful effective features of robots [16–18].

STM is made up of various kinds of single STM modules. STM modules are developed after experiences of evaluating and scoring response robots in past competitions. Almost all STM modules that we can use currently are for testing in the mobility, the negotiation ability, the dexterity, the sensing ability, the mapping ability involving the exploration. Figure 1 shows some examples of STM. Figure 1 (a) mimics unstable terrain in continuous up-down terrain to evaluate the mobility. Figure 1 (b) gives a narrow space with movable obstacles, robots have to push the obstacles over to go through the narrow space without breaking the obstacles for evaluating negotiation ability of the robot. Locations of movable obstacles are adjustable to create proper clearance between the robot and the obstacles for various size of robots. Figure 1 (c) shows a stepped terrain that mimics the blocked obstacles like rocks for evaluating the mobility of the robots. Figure 1 (d) shows a stair for evaluating the mobility of the robots. The stair has several horizontal bar-shaped obstacles sometimes. Figure 1 (e) gives screwed cap and pipe with a QR-code for evaluating dexterity and sensing ability of robot camera with arm. At first, the robot must turn the cap in counter-clock-wise and remove the cap. And at last, the robot must recognize the QR-code inside of the pipe. Figure 1 (f) mimics a maze with continuous up-down terrain and characteristic shaped wall to evaluate mapping ability of the robot. Figure 1 (g) gives valves with various directions and heights for evaluating dexterity of the robot. The robot must turn valves both directions over 1 turn. Figure 1 (h) shows a STM field made up of several kinds of STM modules. Each STM module was designed to be combinable.

In additional point, in Table 2, Wi-Fi was indicated as an item of robot evaluation. A robot behavior stability is evaluated in case of disconnecting it's Wi-Fi connection. In real robot evaluation field, a huge size field that has over 100 m radius from Wi-Fi base station to disconnect the Wi-Fi. Therefor, the condition of Wi-Fi disconnection has been handled imaginary by defining in the competition rule at a part of competition area.

Usually, the test methods require a location, initial costs, and maintenance costs. Thus, robot evaluation imposes a heavy burden on developers. Moreover, the robot development procedure is changing. For that reason, simulation is being used for robot performance evaluation in robot development. Owing to the improved performance of computers, the utilization of simulation methods has diversified. Physical behaviors of robots can now be reproduced by simulation. In previous simulations, only accurate calculation results were expected. In the current simulations, methods that emphasize realistic display in real time have been established with the support of GPUs. As robots usually have many movable parts, robotics simulators perform heavy calculations in the simulation model by using complex 3D CAD data from the original robot blue prints. To evaluate the robot, instead of simulating everything, the test method should reproduce the behaviors of those effective and essential factors of the environment that have direct relationship with the test. Therefore, in this study, some methods for reproducing the behavior of the environmental elements necessary for robot evaluation have been proposed. The robot evaluation environmental behaviors that should be reproduced can frequently be found in robot competitions. Table 2 includes some past rescue robot competitions [11, 13–16, 19–33].

For example, the RoboCup and DARPA Robotics Challenge included competitions using both real and virtual robots, with almost the same content in each of them.

In competitions using virtual robots, it is often seen that natural phenomena that are difficult to reproduce with the current simulation technology are replaced with an equivalent. For robot performance evaluation, it is necessary not to replace the natural phenomena required for the evaluation with something equivalent, but to reproduce the behavior of these phenomena. Table 3 lists environmental factors in real robot evaluations. Those environmental factors should be programmed in the simulation platform to keep the behavior as natural as possible.

Thus, the behavior of a phenomenon may be reproduced so that a sensor or program of the virtual robot or an operator controlling the virtual robot can react naturally. Therefore, it is necessary to investigate what kinds of robot-performance evaluations exist, and what kinds of phenomena are required for specific robot performance evaluations.

1.3 Classification of the simulation used in this study

In many cases, simulations are used to facilitate accurate reproduction and prediction of a specific phenomenon based on precise numerical calculations. For the proposed application, accuracy is more important than calculation speed because real-time information is not necessarily required.

Table 2: History of rescue robot competition and test field.

Year	Title of competition	Target		Field	Background case
		Operation	Robot		
1997	Disaster City	rescue training	land/air	Standardi-zed Real Test Field	Oklahoma City Bombing (1995)
1998	RoboSub	rescue	sea		
2000	RoboCup Rescue (Real Robot)	rescue	land/air	Real Field	Hanshin-Awaji Earth-quake(1995)
2005	Robotics Test	facility	field/facility	Real Field	Real Disasters
2006	RoboCup Rescue (Virtual Robot)	rescue	field/facility /land/air	Simulation	Real Disasters
2006	ELROB		land/air		
2008	Roboboat		sea		
2011	Guardian Centers	rescue training	land/sea/air	Real Field	
2012	ICARUS	rescue	land/sea/air		Earthquakes in l'Aquila, Haiti
2013	DARPA	rescue	land	Real /Simulation	Fukushima nuclear disaster
2013	euRathlon	rescue	land/sea/air		Fukushima nuclear disaster
2014	ARGOS challenge	survey	land	Real Field	
2015	JVRC	mainten-ance /rescue	land	Simulation	Sasago Tunnel Ceiling Accident
2018	WRS	mainten-ance /rescue	land/air	Simulation	Tunnel Accident , Plant mainte-nance and response

Based on IEEE International Symposium on Safety Security and Rescue Robotics(SSRR) 2017 ShanghaiTech University, pp.76

Table 3: Elements in robot evaluation field.

Elements	Robot	Field	Situation
Rough terrain	ground	land	rescue / home
Brightness in environment	ground / aerial / under water	every where	rescue / home / autonomous vehicle
Town or City size field	autonomous vehicle	land	rescue / autonomous vehicle
Dynamic changeable environment	ground / aerial / under water	every where	rescue / home
Wi-Fi	ground /aerial	land / midair	rescue / home / maintenance
Sound	ground / aerial / under water	every where	rescue / home / maintenance
Vibration	ground / aerial / under water	every where	rescue / home / maintenance
Touch feeling on a surface	ground	land	rescue / home / maintenance
Air flow	aerial	land / midair	rescue / maintenance
Water flow	rescue	land	rescue
Water pool	under water	sea / lake / pond	rescue / maintenance
Gas	ground/aerial	land / midair	rescue / home / maintenance
Heat	ground / aerial /under water	every where	rescue / home / maintenance

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The simulation should also reproduce the behavior of the phenomenon under investigation. For example, real-time performance may be required for a control algorithm of an autonomous robot in a specified environment, when a reaction of the robot operator is performed according to a predetermined evaluation standard. In this application, it is necessary to reproduce the behavior of the environmental element rather than to accurately reproduce the actual environment with high-precision numerical modeling based on a large number of calculations.

In this study, the latter type simulation is treated.

1.4 Related Works

Many robot-performance evaluations can be seen in rescue robot competitions. This section introduces two competitions that used simulation platforms. Those competitions are the primary sources of this study as the author was a member of the respective technical committees.

1.4.1 Simulated evaluation tasks in RoboCup Rescue Leagues

RoboCup is a worldwide robot competition [34,35]. RoboCup has a rescue league for rescue robots. [36, 37]. The rescue league comprises the rescue robot league (RRL) and rescue simulation league (RSL) [21,38–40]. The RSL consists of the rescue virtual robot league (RVRL) and rescue agent simulation league [13, 41, 41–59]. The RVRL is a virtualized RRL, and it is one of the starting points of this study [60–64].

The performance evaluation items of the rescue robot are the rough-terrain movement ability, automatic map-generation ability, and victim-search ability. Both the real and virtual robot leagues evaluate the same items, but the evaluation method is different depending on the characteristics of each league. Figure 2 represents a sample of same field in the real and the virtual. The virtualized field of Figure 2 (b) must have enough difficulty for evaluation of the rescue robot mobility, then it can be use in RVRL. Some evaluation methods cannot be realized depending on the characteristics of the league. In the real robot league, the ability to move through rough terrains with debris of complicated shape, to generate maps automatically, to search victims by sound and thermal images, and to evaluate the victim state using a camera are being evaluated. In the virtual robot league, we are only evaluating the abilities of rough-terrain movement with debris of simple shape, automatic map creation, and judgement of victim state by camera. The evaluations of the autonomous mobility with several kilometers of wide-area search capability, height search capability of several tens of meters, and radio wave forced interruption area are done only at the virtual robot league. Figure 3 indicates a field model for the 3rd preliminary game in RVRL 2017 [1]. In Figure 3, the area size was 220 m x 200 m, an airport facility was shown. A team had four robots, but one robot operator could run their robots. At least, high accuracy mapping system and autonomous robot controlling system were required.

1.4.2 Simulated evaluation tasks in Japan Virtual Robotics Challenge

The Japan Virtual Robotics Challenge was held in October 2015 [14, 15], mainly comprising humanoid type robots but also crawler type ones. Tasks of JVRC was evaluations for the mobility and the dexterity. It included several works to do with the arms.

Figure 4 shows three sample tasks with robot arms [2]. Figure 4 (a) (b) (c) (d) represent tasks of removing a L shaped object, task of removing an angled rod from a hole, task of handling a hose and Task of hammering test, respectively. A hammering test uses a hammer and ear for the work, and thus, requires not only arm but also sound. In robot operation for hammering sound inspection, it is necessary to control the moving direction of the hammer so that the impact surfaces face each other at the moment of impact. The necessary phenomena to be reproduced for this robot performance evaluation are the generation of sound by hammering and its propagation. The simulation platform of JVRC could not reproduce an impact sound by the direction of moving hammer head. In JVRC, an equivalent task was used for hammering test. It used a combination a pipe model and a QR-code instead of a hammer and generating impacting sound.

1.5 Advantages of robot evaluation in simulation platforms

The use of simulations for robot-performance evaluation offers the following advantages, which contribute to shorten the development cycle and generate high robot output:

1. It is safe to conduct evaluations under marginal or extreme conditions.
2. Evaluations outside the safety margin, which cannot normally be realized, can now be implemented.
3. The evaluations of the robot behavior safety, sensor-processing algorithm, and autonomous behavioral algorithm can be done at the robot concept-design stage, before prototype production.
4. The evaluation platforms are easy to share, maintain, and reuse; the capability of sharing is important in standardization of the usual evaluation methods.

1.6 Overview of paper

Figure 6 shows the composition of this paper. And Figure 7 indicates the relationship of between the elements of robot evaluation and the chapters of this paper. Chapters 2, 3, 4 and 5 include examples of individual simulation method of evaluation elements.

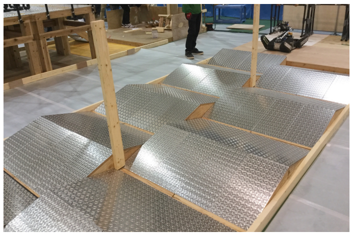
Followings are intoroductions of each chapter. Chapter 2 presents a sample exercise simulation field for robot operators, in which a robot operator team could have team exercise time in a simulation platform. The simulation platform is equipped with a new proposed scenario-based active environment.

Chapter 3 includes a formularization method to generate obstacles with differential difficulty. Through simultaneous localization and mapping (SLAM), a better map is generated, depending on the terrain, without corrected range information [65–67]. The experiments in this chapter show different degrees of accuracy between the map images generated with obstacles of different difficulty.

Chapter 4 describes a simulated fluctuating Wi-Fi radio behavior and a sample simulation platform with Wi-Fi environment. In this chapter, two experiments demonstrate the effectiveness of the proposed method.

Chapter 5 shows a proposal of a sound reproduce method with a sample simulation platform for hammering test by robot. Hammering test is a inspection task not only after disaster but also ordinary maintenance task before disaster.

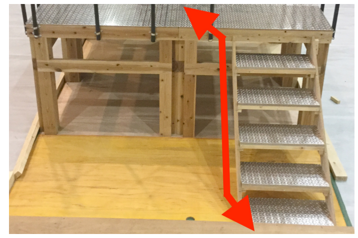
Chapter 6 presents the conclusion of this study. Summary and future works are shown.



(a) STM for the mobility (on continuous ramp).

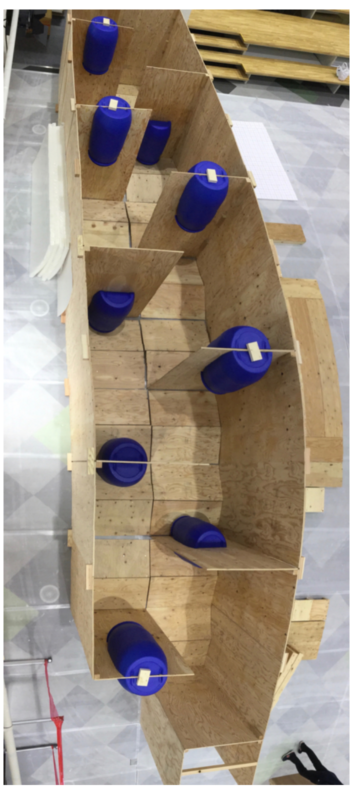
(b) STM for negotiation ability.

(c) STM for the mobility (on stepped terrain).

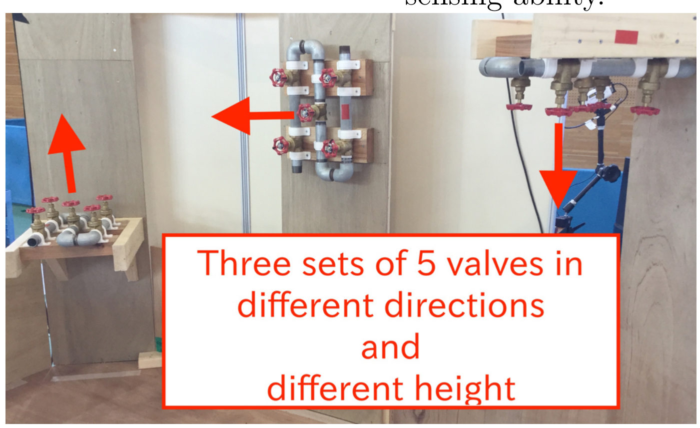


(d) STM for the mobility (with stair).

(e) STM for dexterity and sensing ability.



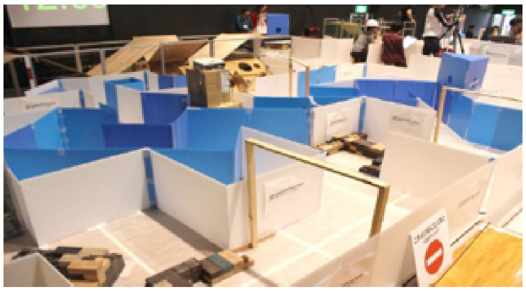
(f) STM for mapping ability.



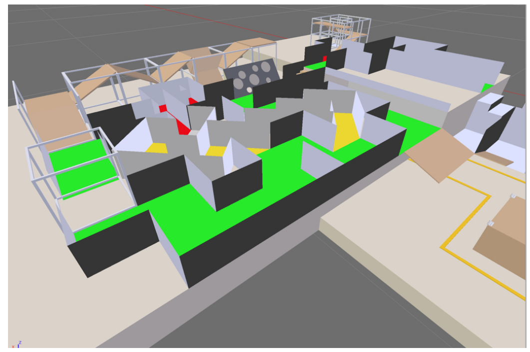
(g) STM for dexterity.

(h) A test field made up of several kinds of STM modules.

Figure 1: Example of STM for rescue robot evaluation.



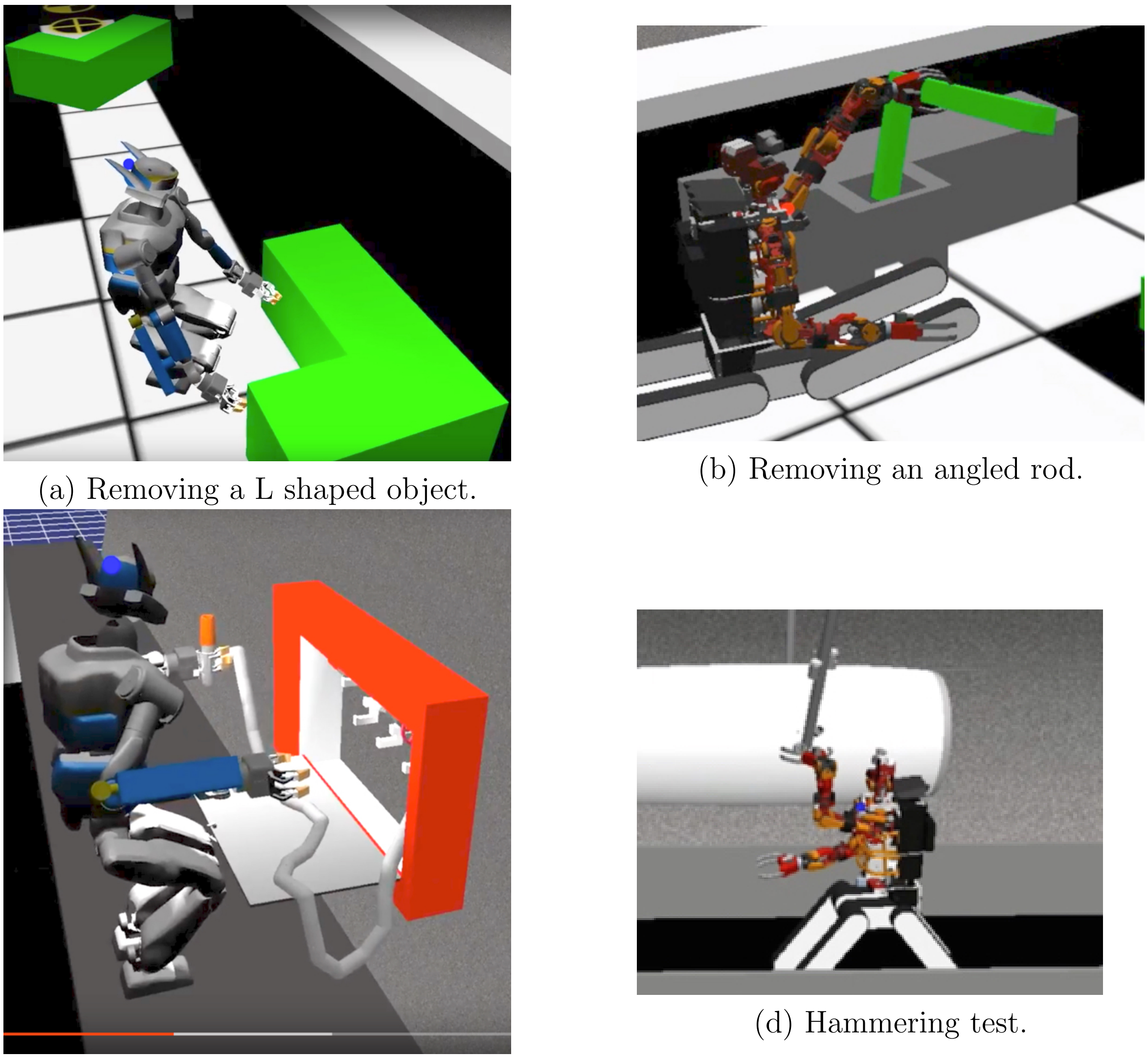
(a) A sample field of RRL.



(b) A virtualized same field.

Figure 2: Sample same fields of real and virtual in RoboCup Rescue Leagues.

Figure 3: A sample large field (size : 220 m x 200 m) from RoboCup 2017 RVRL [1].



(a) Removing a L shaped object.

(b) Removing an angled rod.

(c) Handling a hose.

(d) Hammering test.

Figure 4: JVRC tasks using arms [2].

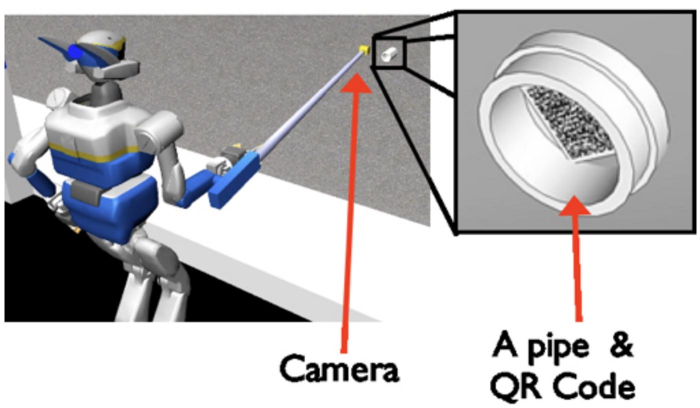


Figure 5: An equivalent hammering task was used in JVRC [2].

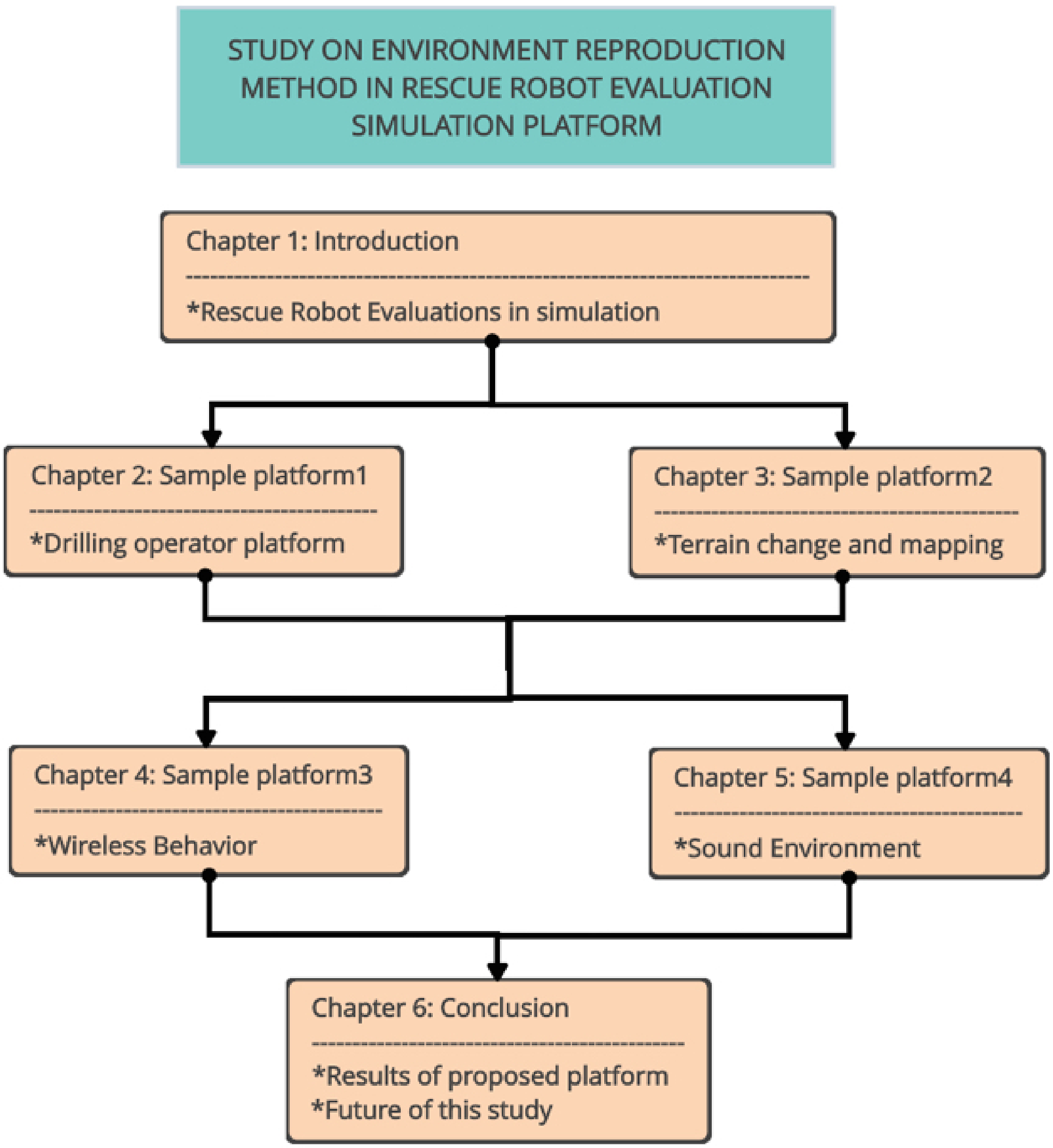


Figure 6: The composition of this paper.

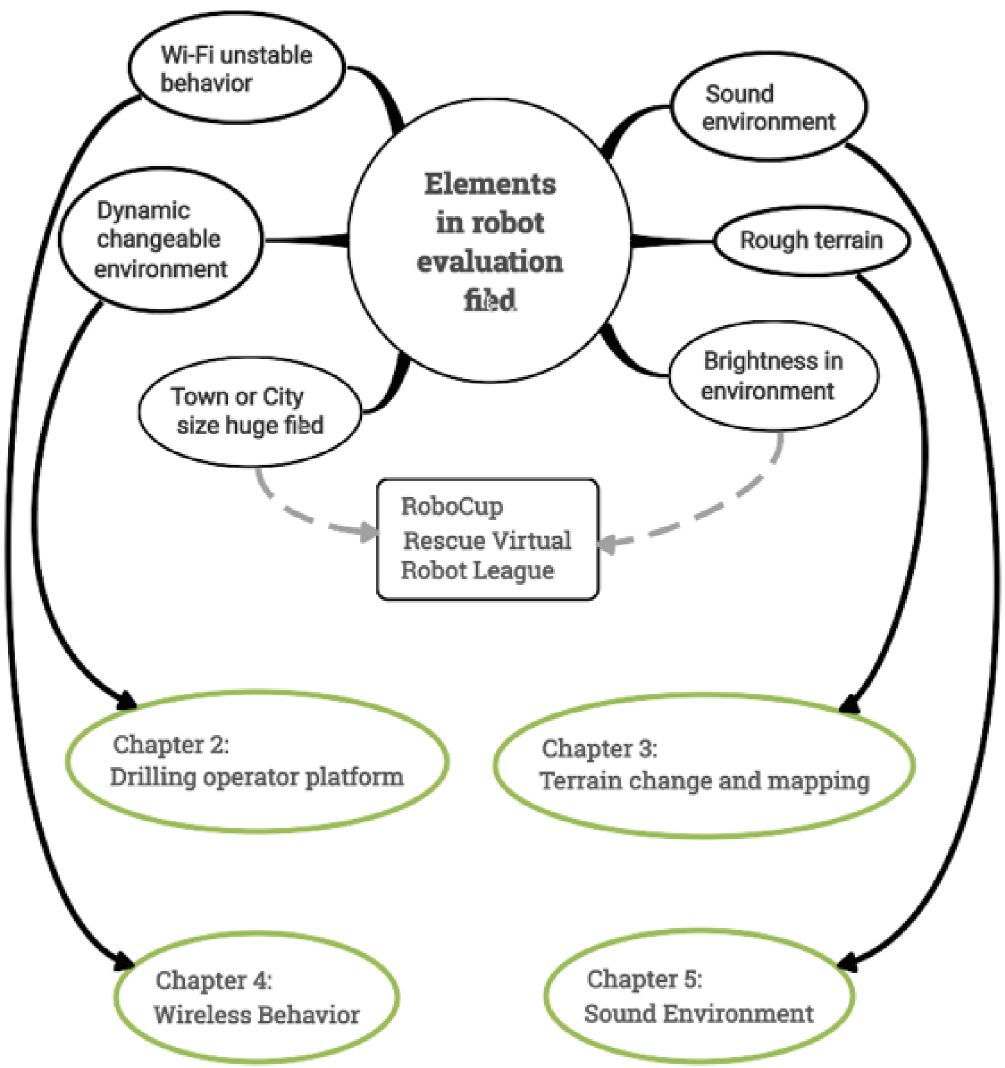


Figure 7: The relationship of between the elements of robot evaluation and the chapters of this paper.

Chapter 2 Training Platform for Rescue Robot Operation and Pair Operations of Multi-Robots

2.1 Overview of this chapter

In this chapter, a report on the situation at Fukushima is introduced and two lessons that were learned involving are presented: 1) multi robot operation and 2) robot operation by workers. Workers with no prior experience with robots operated multi-robots in dynamically changing environments. On the following two themes are focused in multi-robot operations: 1) communication between operators and 2) pairing of operators. An experiment using a rescue robot operation-training platform based on USARSim is shown, and the results of the experiment are discussed. It can be believed that these verify that the training platform is useful for rescue robot operation.

2.2 Introduction of this chapter

Since the September 11th attack on the World Trade Center, rescue robots have been widely accepted as one of the rescue tools at disasters sites where human rescuers cannot enter. Such a situation occurred again at the Fukushima Daiichi Nuclear Plant (FDNP) in Japan after the Great East Japan Earthquake on March 11, 2011. The interiors of buildings were destroyed by the earthquake and the resulting tsunami, and some areas were highly contaminated by radiation. The condition of the equipment in the buildings to make recovery plans must be checked. Several types of robots were used to determine the status inside buildings where it was impossible for humans to enter.

According to Tokyo Electric Power Company (TEPCO), robots have been used at various situations with different aims at FDNP [68].

- At June 30, 2011: Warrior robot cleaned 1st floor of the building of Unit 3 using a vacuum cleaner [69].
- At October 21, 2011: Quince robot measured radiation and temperature of 1st and 5th floor in the reactor building of Unit 2 [70].
- At November 5, 2011: Warrior robot removed obstacles inside in the building of Unit 3 and measured radiation dose [71].
- At May 24, 2012: Quince robot surveyed 1st floor of the building of Unit 3, and discovered that a room door was blown away [72].

And an operator at FDNP noted some very important and useful points in his blog [73].

1. It is difficult to operate panels or controls while wearing five pairs of gloves or seeing the user interface from behind a bulky mask,
2. Emergency robots shouldn't be stand-alone machines, they work best in pairs or teams,
3. There are very few people in the world who are able to operate robots as agilely, after training.

Rescue robots are supposed to be designed for use in unstable and dynamically changing environments. The situations encountered at FDNP were not ones that had been experienced before and they have changed as the recovery efforts have made. The robots have not been designed to do tasks in such situations, but also the human operators have not been trained to operate the robots doing the tasks.

Searching for victims and exploration to determine the conditions at a disaster site are important operations. It is desirable to review the operation plans and drill robot operators to ensure that the robot can perform the necessary missions for such operations. A training platform has being developed for rescue robot operations based on USARSim(Unified System for Automation and Robot Simulation), which that has been used in the RoboCup Rescue Virtual League and other contests [74].

In this chapter, an event generation function is proposed for the training platform and pair operations is showed for multi-robots under unstable and dynamically changing environments. Section 2.3 describes the background and related works and the proposed simulation platform is introduced in Section 2.4. This platform provides a dynamically changing environment and training fields where disaster events repeatedly occur, which are necessary for checking rescue operations and training robot operators. Section 2.5 presents the results of the experiments and a summary is provided in Section 2.6.

2.3 Background and Related Works

Rescue robots have been widely accepted since disasters such as the September 11th attack on the World Trade Center in 2001. RoboCup Rescue competitions began in 2000 [37]. This competition aims to promote the research and development of rescue robots, and the rules and fields were designed based on real situations that occurred during the Hanshin Awaji great earthquake in 1995 and other disasters after that. The RoboCup Rescue activities contributed to rescue and search operations in Fukushima Daiichi. A robot that was developed for RoboCup Rescue was used to explore the inside of buildings at Fukushima [75] [70].

Real and virtual robot competitions have been held to achieve the aim of RoboCup. In the virtual robot competition, USARSim has been used as a platform. USARSim is configured based on the Unreal Tournament game engine and provides a high-fidelity simulation of robots by creating 3D environments and emulating wireless communications and other sensors, which make the simulation more realistic.

The experiences at Fukushima Daiichi presented various themes for the development of rescue robots. The followings two lessons are focused upon:

1. Multi-robot operations:

   iRobot Case: According to the blog, two robots were used as a pair [73]. Therefore, if there was a problem with one of them, the other was there for support

Quince Case: The mission of the robots was to explore and measure the radiation inside buildings where radio waves could not reach them. One of the robots carried as cable and was operated using this wired connection. It also worked as an access point for the other robot, which allowed it greater freedom of movement to measure the radiation. [75] [70].

2. Robot operation by workers:
   The operators were workers of FDNP. They were familiar with the sit structures and know where each of the numerous cables and pipes was located. Thus, they were be able to discern the complete environment from the limited images captured by the cameras mounted on the front of the robot. However, they did not have experience in operating the robots. They had to be taught and drilled in the robot operations on sites at FDNP.

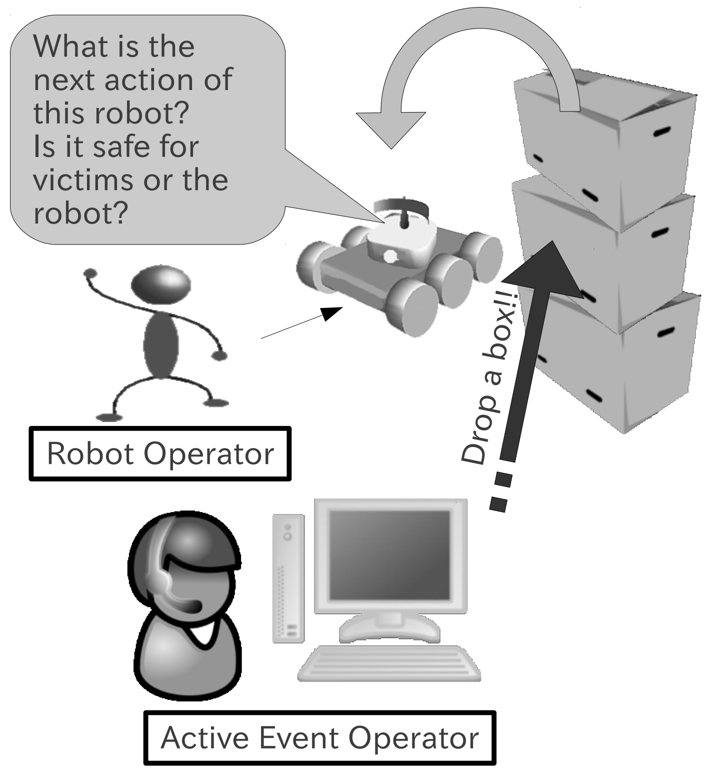
It can be believed that similar situations could occur in the future, after suffering from unexpected disasters. Therefore, a simulation platform was proposed for designing/developing rescue robots, along with drills for robot operations [74]. By using the platform for training the robot operators, it was showed that the performance of the operators was increased by doing drills, which ranged from mastering necessary robot operations to operations in destroyed environments.

In this chapter, a mechanism that simulates events including collapses and noisy environments is introduced. It is also showed by experiments that even when the same pair of men operates the multi-robots, which one operates the first robot or leads the mission is important in the cooperation. A standard for operator selection is also discussed.

2.4 The Proposed Robot Training Platform

2.4.1 Performance Test Scenario

Figure 8 shows a framework for the drilling rescue robot operators using the following outlines for drills. Robot operators are asked to operate the robot to pass nearby boxes without colliding with them. The robot operators become accustomed to basic



Adapted from Advanced Robotics, Vol.27, No.5, pp.386

Figure 8: Framework for performance test simulations. With this simulator, robot developers can evaluate the behaviors of their robot under active events.

operations, but are also trained to deal with unexpected situations. An active event operator causes some unexpected situations for the robot operator at anytime. The active event operator can make some scenarios for active events. The active scenario will be run step by step at programmed timing in the scenario.

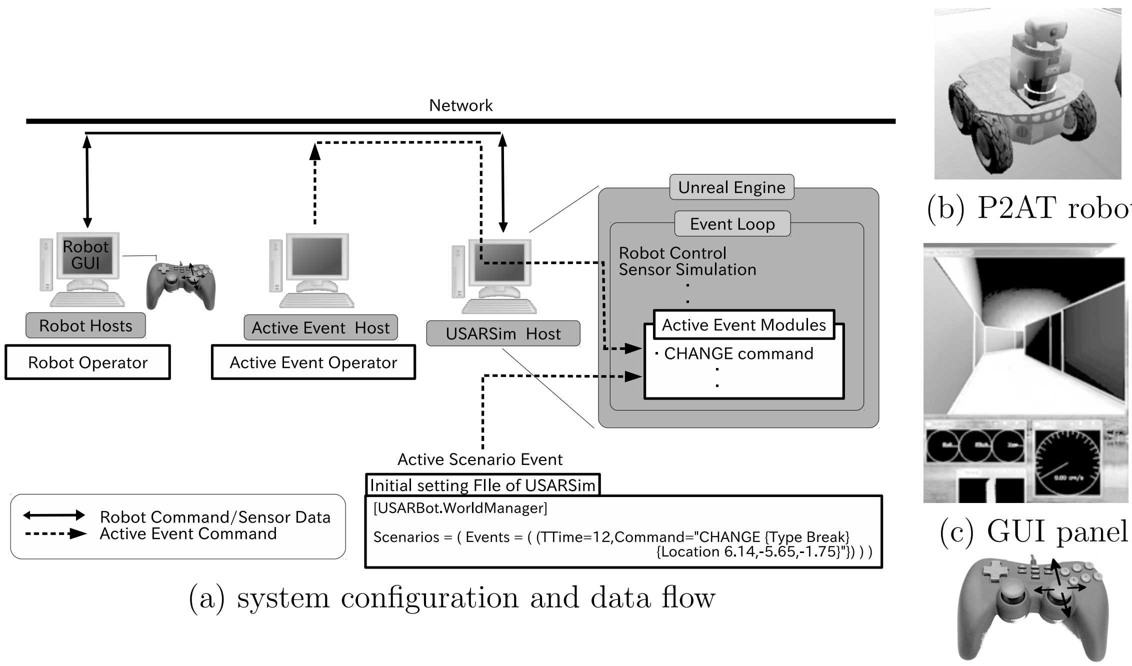
1. The operator moves the robots by viewing images that are sent from a camera mounted on the robot.

2. The operator may make mistakes because of noise in the camera images or unexpected and sudden movements such as the robot slipping or jumping.

3. Poor robot operation causes a collision with boxes, causing the box at the top

to fall to the floor.

4. The fallen box becomes an obstacle that prevents the robot from exploring certain areas.



(a) system configuration and data flow

(b) P2AT robot

(c) GUI panel

(d) joystick

Adapted from Advanced Robotics, Vol.27, No.5, pp.387

Figure 9: Configuration of performance platform system: diagram of command and data flow of USARSim enhanced active events.

2.4.2 System and Test Field

Figure 9 shows the configuration of the training system [76]. A P2AT robot is modeled as a rescue robot. It has a camera, 3D acceleration sensor, range finder, and dead reckoning system. In the proposed platform, the robot is operated using a GUI interface and joystick. Figure 9 (a) explain the relationship between USARSim and the robot operator's host and the active event operator's host. The operator of the robot sends commands for the robot from the robot host to USARSim by the network. And the operator receives the camera image, sensor informations from USARSim.

The active event operator sends commands for the active event to USARSim. This system needs network to connect every softwares; USARSim, a client software for GUI with a joystick to operate the robot, a terminal software to control the active event. Each software can run on separate PCs or on one PC together. In this chapter, all softwares run on one PC. Figure 9 (c) shows the GUI panels for the robot operations. The upper part displays images that are taken by a camera mounted on the robot. Indicators are laid-out at the lower part. These indicators show the roll, pitch, and yaw for the robot's tilting angle, along with a range image from the range scanner and the speed of the robot. The operator looks at the images that are captured by a camera mounted on the front of the robot. The robot is controlled using joystick, where the movements of the joystick are sent to USARSim as commands via client programs. USARSim simulates the motions of robots and the changes in environments. White rectangles represent the active event module.

Figure 10 shows a test field. It is modeled after an exploration task in FDNP [70]. Quince robot went from 1st floor to 5th floor by going U shaped stairs, narrow space, and bypassing obstacles. The test field is designed to have elements to drill the robot operations that are needed in such exploration tasks.

The robot moves around this course in a clockwise direction. Figure 10 (a) and (b) shows landing and slopes. Each slope angle is 11.3°, and the length is 4.4 m. The highest place is at a height of 1.9 m. Figure 10 (d) shows a collapsing wall and unstable floor (top view). The wall in this area is set in order to prevent the robot from falling, however the wall acts as an obstacle to robot movement.

2.4.3 Event Scenario Mechanisms

Dynamically changing environments are one of the requirements for training robot operators. An event action mechanism that changes the conditions of the simulation at every step is added to USARSim. Using this mechanism, a disaster sequence can be simulated in the training.

Some active events are accompanied by sounds. USARSim has a sound function in the environment simulation module. This sound function is activated by some active events, and a sound is played. A USARSim user can set the sound parameters (the type of sound, volume, play time) connected with an event when the user wants a sound.

The following is an example of an event scenario (the left bottom box of Fig. 9). This command results in the collapse of walls 12 s after the robot starts. Figure 10 (d) shows the result of this scenario command.

```
Scenarios= (Events= ((Time= 12, Command= "CHANGE {Type Break} {Location 6.14, -5.65, -1.74}")) )
```

2.5 Experiment for multi-robot operations

2.5.1 Overview of pair operations environments

Figure 11 (a) and (b) show robot cooperations at slopes and the operations respectively. The course is the same as the one described in Section 2.4.2 except that there is no textured wall on either side of the slope. The wall prevents robot operations from slipping from the slope and the texture (Figure 10 (b)) is demonstrated to be effective for robot operation [74]. When the robot moves up the slope, the camera images mounted on the robot do not change in a case of no wall. So the operator cannot notice when the robot arrives at the landing.

The multi-robot operation described in the blog cited in Subsection 2.3 is a practical solution. When the operators see no changes in the images from their own cameras, they look at the images from the other robot to confirm the status of their own robots. On the other hand, the camera images of the robot give the upper part of the robot, when the second robot is at a lower level than the first robot.

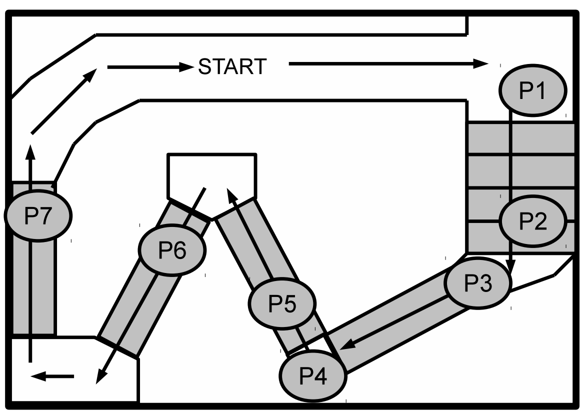
The operators of the robots collaborate to move the robots safely and smoothly especially in the case shown in Figure 11 (a). In this case, the operator of the first robot, OP_1, does not see the conditions beneath the robot. If the operator of the second robot, OP_2, loses sight of the first robot, this may cause the same failure as a single operation such as the robot falling from the landing. Cooperation and communications between the multi-robot operators such as “wait a minute.”, “hurry.” or “keep watching my robot.” are necessary to the operations. The communication between OP_1 and OP_2, and the sharing of images from the two cameras are useful in operating the robots.

Table 4 lists utterance in tandem operations. Figure 12 shows seven places where

Table 4: Communication between operators.

Category	Example of utterance	Location	Numbers
A	Hurry. Catch up with me. Come here.	P1,P3,P5,P6	4
B	Keep watching my robot. Wait a minut. Watch the right side of my robot.	P2, P4, P7	3

Adapted from Advanced Robotics, Vol.27, No.5, pp.387



Adapted from Advanced Robotics, Vol.27, No.5, pp.387

Figure 12: Communication places(P1-P7).

operators had conversations. They are categorized in two groups; contents in category A are robot operation, and ones in category B are related with camera works. The operators communicated at places: P1-P7. The places are showed in the map on the right side of Table 4. They are places where robot operations are difficult. OP_1 needed OP_2' s robot camera image in order to move robot safely and stably. The numbers of utterances on robot operation and camera works were about the same.

2.5.2 Results of experiments

Experiments with the following two themes in multi-robot operations were performed:

Table 5: Time at preliminary drills.

operator	time	std.
a	89	1.2
b	96	5.3
c	98	7.5
d	98	2.9
e	99	5.6
f	99	5.6
g	116	11
h	162	12.2

Adapted from Advanced Robotics, Vol.27, No.5, pp.389

Table 6: Simulation time of Pair Operations.

pair	Left is leader		Right is leader		No leader		diff.	
	time	std.	time	std.	time	std.	L.L-R.L	personal record
e + b	128	8.0	121	2.9			6.7	3.4
g + e	165	9.9	157	14.7			8.0	16.9
e + a	118	4.0	109	2.6			9.3	9.9
d + f	122	1.5	112	5.0	122	12	9.5	-1.6
h + c	169	7.5	159	34.0	263	145	10.0	64.9
g + b	132	5.3	114	3.6			18.3	20.3

Adapted from Advanced Robotics, Vol.27, No.5, pp.390

Communication between operators: The operators, OP_1 and OP_2, sit side-by-side and communicate normally with each other. Does their communication really improve the performance of robot operations?

Pairing of operators: It can be believed the scheduling of robot operators is important in situations that there are a few operators. The skills of the operators are different and stable operations are desired. Is there a method of pairing operators for good robot operations?

Eight subjects practiced in the field with a textured wall shown in Figure 10. The subjects are male students of 20s. Table 5 lists the operation times averaged of five drills, and they are arranged by time. Table 6 lists the operation times for pairs of subjects operating multi-robots in the field without all walls. The average operation time and standard deviation are listed for three cases: 1) the left operator leads the operation, 2) the right operator leads, 3) no one leads, namely there is no communication between them. They are arranged by the difference between 1) and 2).

The followings could be discerned from the tables:

1. The eight subjects can be categorized into two groups: a good operators group, from OP_a to OP_f, and a bad operators group, OP_g and OP_h. The performance was bad when a pair included OP_g or OP_h, even if the other member was a good operator.

2. Excluding pairs that included OP_g or OP_h as a member, consider pairs OP_e+OP_b, OP_e+OP_a, and OP_d+OP_f. Among these three pairs, OP_e+OP_b and OP_e+OP_a performed better when the right operator led the operations. The OP_d+OP_f pair shows similar individual performances for both cases which are loads. They show it is good that the operator whose time at preliminary drill is fast leads the team.

3. In the cases with no communication, the OP_h + OP_c pair showed poor performance, whereas the performance of the OP_d + OP_f pair, who had similar individual performances,remained the same. The big gap between the individual performances of OP_h and OP_c is one reason for the poor performance.

2.6 Summary

TEPCO's press announcement and the blog of an operator at FNDR presented us many tasks that are different from ones as rescue tasks. Two issues have been directed in the robot operations: 1) multi-robot operation has required at some tasks, and 2) workers with no experience operated the robots after drilling the robots at sites. A rescue robot operation-training platform was proposed. The proposed platform was based on USARSim that enables the operator’ s performance improve by doing drills, which ranged from mastering necessary robot operations to operations in destroyed environments.

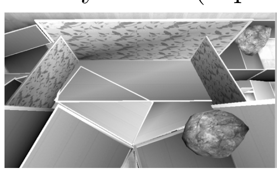
In this chapter, the following two themes were focused for multi-robots operations:

1. Communication between operators: Does the communication between operators really improve the performance of robot operations?

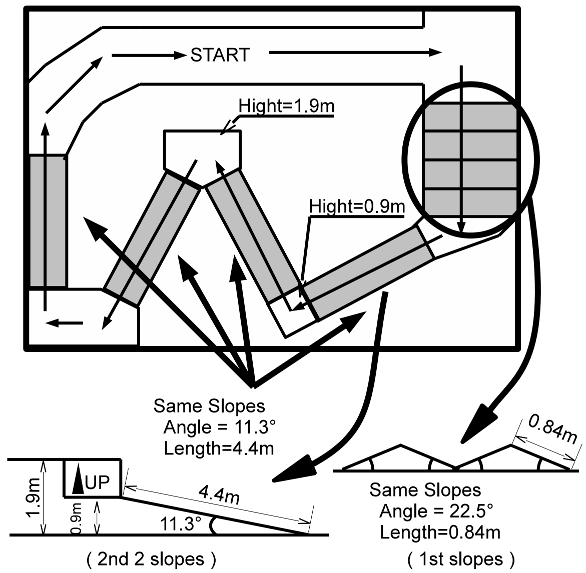
2. Pairing of operators: Is there a method of pairing operators for good robot operations?

Experiments showed that communication between operators is important in multiple robots operations especially at places that robots are hard to pass. Pairing members from good skill group is better than pairing from all, and performances of a better operator leads the pair are better than the performance that the other operator leads the pair. It can be believed that these may be helpful in real robot operation as well as the training platform is useful for rescue robot operations.

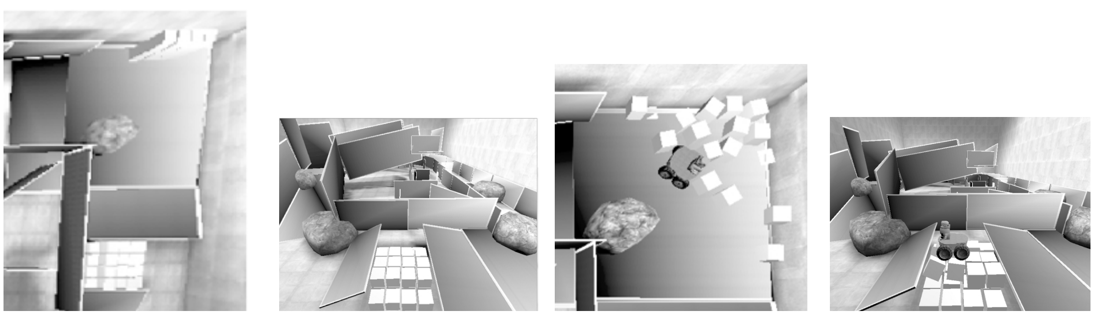
(a) bird-eye view (top view)



(b) corner in the center



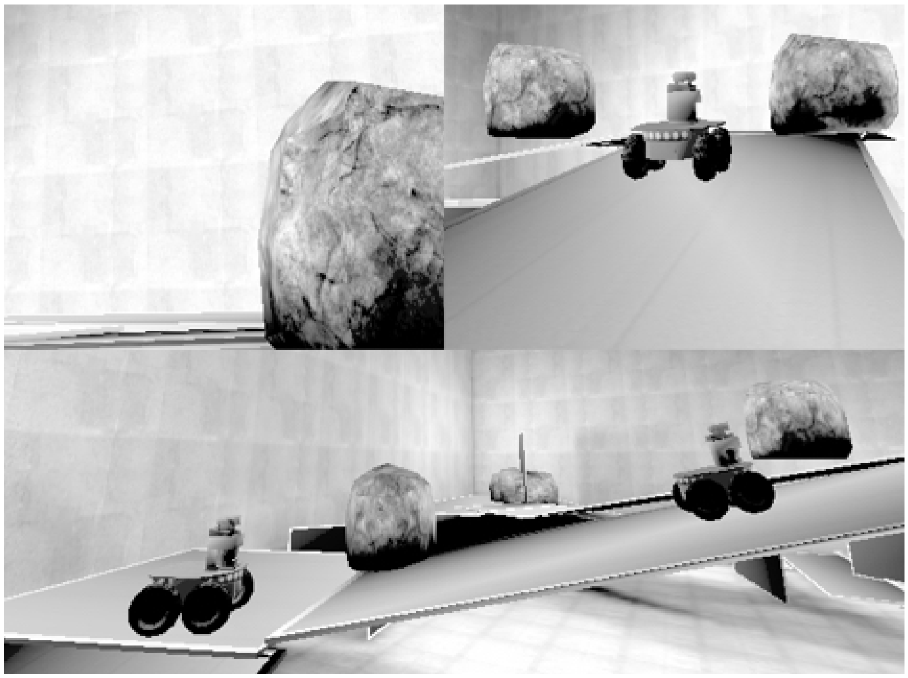
(c) layout of test field



(d) top right corner where noise occur when wall collapses and robots move the unstable floor instead of the 1st slopes.

Adapted from Advanced Robotics, Vol.27, No.5, pp.388

Figure 10: Training field setting



(a) The snapshots on the upper row are the camera images of the first (left) and the second (right) robot, respectively. The lower row shows the robots moving in tandem.

(b) The operator's table.

Adapted from Advanced Robotics, Vol.27, No.5, pp.388

Figure 11: Multi-robot operation at 2nd slopes: (a) robot movements in tandem at slopes, (b) snapshot of operations

Chapter 3 Evaluation field constructed for modeled uneven terrain for automatic map-generating methods of rescue robots

3.1 Overview of this chapter

Robots were used to explore the World Trade Center (WTC) site after the September 11 terrorist strike, and the interior of the Fukushima Daiichi Nuclear Plant (FDNP) that was destroyed by the March 11 tsunami. Over the next several decades, robot design should focus on the use of robots in unstable and dynamically changing environments such as those of the WTC and FDNP. An important mission for rescue robots is making maps that can easily be understood by humans from gathered information on the changed terrain and victim locations in a disaster area. This automatic map-generating function is a popular topic in the research on rescue robots. The performance of new and enhanced automatic map-generating functions must also be evaluated. In this chapter, a method for quantifying the evaluation fields constructed for modeled uneven terrain is presented and the effect of a robot's movements on the performance of simultaneous localization and mapping methods is showed.

3.2 Introduction of this chapter

A rescue robot was used for exploration work inside the building of the TEPCO Fukushima Daiichi Nuclear Power(FDNP) Station after it was damaged by the Great East Japan Earthquake of 2011.The FDNP disaster in 2011 and the 9/11 terrorist attack on the World Trade Center (WTC) in the United States in 2001 were disaster situations that exceeded the preventive measures taken in previous disasters.Although there was not enough time to prepare rescue robots for those disasters, they still demonstrated sufficient performances.Robots are expected to demonstrate their abilities at FDNP over the next few decades in the following work: obstacle removal, indoor and outdoor monitoring and mapping, equipment maintenance, hazardous material removal, the transportation of goods, the assembly and installation of piping, etc. [77].It is necessary to develop new mechanisms and algorithms for mid- to long-term decommissioning work [78].It is important to check a new robot' s functions in various situations.Furthermore, during robot operations, it is necessary to pay attention to the following points [73].

1. It is very difficult to operate a panel or robot while wearing thick gloves and to check a user interface screen through goggles.
2. Rescue robots should not act alone; it is better to work in pairs and team activities.
3. Robot maneuvering training enables agile robot operation.

Under harsh circumstances like the WTC and FDNP, it is necessary to train operators to operate robots based on the situation.In order to operate disaster countermeasure robots in the future, their work content and training environment need to be standardized [79] [80].

Adding a new sensor to the robot also requires a new user interface.For example, a laser range sensor (LRS) outputs a data series.The data are displayed on the panel to assist the robot' s operator.The data and images sent from sensors change drastically as the robot moves through an unstable floor.Standards for evaluating the entire system, including the LRS software, are also necessary so that it can be stably operated when subjected to a sudden inclination and shaking.

Until now, the performance evaluations of rescue robots were mainly done in the physical evaluation field.The development and improvement of rescue robots in the future will include software such as robot autonomous motion and map creation algorithms.Repeated experiments under the same conditions are required for algorithm verification.Furthermore, because rescue robot development is being performed on a worldwide scale, it is necessary to share the same evaluation criteria among researchers all over the world.There is a simulation evaluation platform that satisfies these requirements.

In this chapter, the authors propose an evaluation field model of rough terrain in the simulation environment to evaluate the operation and sensing ability of a rescue robot.In addition, the effectiveness of the experimental results of two simultaneous localization and mapping (SLAM) algorithms using the evaluation field is showed.Section 3.3 explains the research background and related research, and section 3.4 explains the grading method proposed by the authors.Section 3.5 presents the results of prototype experiments using the proposed method. Section 3.6 gives the conclusion and summarizes the direction of future research.

3.3 Research background and related research

To develop effective sensors and robots for rescue exploration activities at disaster sites, it is desirable to evaluate a robot' s performance in a disaster site environment.The performance measurement environment of a disaster response robot has been standardized by the National Institute of Standards and Technology (NIST) and American Society for Testing and Materials (ASTM) International [79].The evaluation method consists of items such as the mobility performance evaluation; Wi-Fi communication evaluation; operability evaluation; response performance as a system, which includes people such as pilots; and sensor evaluation.The mobility performance evaluation is based on a planar floor, a landform composed of inclined slopes inclined to the pitch axis or roll axis at a normalized angle, a terrain with 0.1 m steps along one side , and an inclined plane. It includes obstacles such as stairs and landings.In the sensor evaluation, for example, how well the image transmitted by the video is displayed is evaluated.

The LRS outputs a coordinate group (a cloud of point data: CPD) of the points hit by the laser emitted from the sensor.The CPD are used both for the robot's autonomous action plan and to assist the operator in robotic manipulation by properly displaying it.Albrecht et al. performed a simulation at the device level using the rescue robot field [81].As the development of the SLAM method progresses, the function continues to improve to allow the rescue robot to move autonomously and assist the operator in robotic maneuvering [66].Most SLAM methods can construct a map in the world coordinate system using the CPD from the LRS and present the present location and movement route of the robot.Rescue robots that do not have the ability to travel on floors with slopes or steps will have very low mobility performance assessments by NIST and ASTM.In a cooperative mission with multiple robots, it is expected that one map that integrates a wider area will be output. It is very difficult to integrate multiple maps constructed in the different coordinate systems for individual robots into a single unified map [67].

The RoboCup rescue project is held annually for the purpose of promoting research and development related to rescue robots [82].While participating in the RoboCup Rescue Real Robot League, Quince was used to conduct a search at the FDNP affected site, and its performance was greatly appreciated [83]Quince developers are reporting four items learned from the mission at FDNP.One of these is the influence of the unknown environment.

Disaster City in Texas, USA has several samples of actual collapsed buildings [19].These are effective for evaluating a robot' s mobility performance.NIST has proposed a large evaluation field that combines units with specific evaluation functions and a square floor shape with 1 m sides.The robot evaluation field of NIST was used by RoboCup's Rescue Real Robot League, and the two-dimensional map automatically generated by the robot was also evaluated.Fields composed of 1 m square units are easier to prepare and reproduce than real disaster environments.

The RoboCup rescue league includes a virtual robot league that uses a simulation environment called USARSim.Based on a game engine called Unreal Tournament, USARSim realizes a highly accurate and realistic rescue robot environment simulation that uses a three-dimensional virtual environment for rescue robots and emulates a Wi-Fi communication environment and sensors.The virtual environment includes several types of buildings, indoor and outdoor environments, cities, wide undulating terrain, and so on. Furthermore, several types of robots that are on the market can be used, including robots participating in the Rescue Real Robot League, along with several kinds of sensors such as LRS [84].

The merit of using the simulated evaluation field for a rescue robot is considered by comparing it with an actual evaluation field like the NIST evaluation field(Table 7). In an actual evaluation field, there are restrictions with respect to the evaluation item, including those related to the production cost and installation location.For example, a wall may be high enough for the LRS assessment, but have an insufficient height to reproduce the wireless environment.When you want to evaluate outdoor mobility, it is difficult to use an actual town. Even in Disaster City, it is difficult to change the arrangement of the roads, buildings, rubble, etc. according to the experimental conditions.On the other hand, a simulation is not suitable for the final evaluation with physical constraint conditions, which must be performed in the real world. However, it is suitable for algorithm evaluation and iterative experiments under specific conditions.Furthermore, even when constructing arbitrary disaster situations in a simulation, it can be realized in a shorter time and at a lower cost than in the actual evaluation field.These advantages show that simulation is an effective method to reduce the time and cost for a wide range of usage scenarios such as evaluation field production in the robot and sensor development stages, field creation for robot operator training, and evaluation field sharing.

Table 7: Comparison of rescue robot results in simulated and actual evaluation fields with regard to evaluation points and usability.

Types	Mapping performance		Mobility performance		Wi-Fi performance		Detecting task performance	
	Simu.	Real	Simu.	Real	Simu.	Real	Simu.	Real
flat single floor	○	○	△1	○	-	-	-	-
uneven floor	○	○	△1	△1	-	-	-	-
obstacles	○	○	△1	○	○	○	○	○
steps and slope	○	○	△1	○	○	○	-	-
walls	○	○	-	-	○	△2	-	-
multi floors	○	△1	△1	○	○	△2	-	-
outdoor	○	△1	△1	△2	○	○	-	-
victim detection	-	-	-	-	-	-	△1	△1
Ability to represent disaster situation	○	△2	○	△2	○	△2	○	△2
Repeatability of past evaluation condition	○	△2	○	△2	○	△2	○	△2
Sharing ability	○	△2	○	△2	○	△2	○	△2

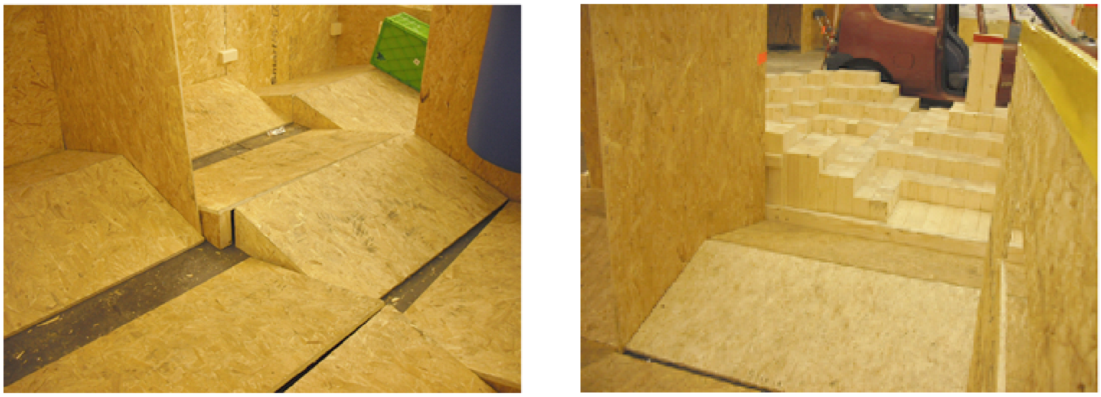
Simu. : Simulation
△1 : partly realized, but not enough.
△2 : requires a long time and/or high cost.

3.4 Evaluation field and field parameterization method

3.4.1 Influence of field flatness

Figure 13 shows part of the field used by the RoboCup 2013 Rescue Real Robot League.Figure 13 (a) shows a floor surface composed of slopes with normalized angles, Figure 13 (b) shows a floor surface composed of a random step field (RSF). The RSF is an evaluation unit of NIST, in which the floor consists of squares with 1 m sides and squares with 0.1 m edges, with heights differing in 0.1 m units, arranged as a two-dimensional array of 8 rows and 8 columns. These are used to reproduce an arbitrary rough terrain.Appropriate evaluations of a robot' s mobility performance are conducted using the constructed slopes, steps, and clearances, according to NIST's evaluation method [79].

Figure 14 (a) and (b) show the state of the sensor when the robot moves across flat and uneven terrains, respectively.Figure 14 (c) and (d) are the results of measuring a portion of the square room from the same position in the middle SLAM image of the robot in situations (a) and (b), respectively. SLAM is a method for comparing and combining the latest and past CPDs.When CPD are measured in a situation where the slope of the LRS changes as shown in (b), SLAM outputs the wrong result.Therefore, CPD correction is required.By correctly projecting the CPD to the floor surface to correct the slope of the LRS, the straight line was distorted inside the SLAM, as shown in (d).This occurred because the CPD are processed on the premise that the CPD of the used SLAM are radially arranged around the measurement coordinate origin of the LRS at equally spaced angles.In order to further correct this, it is necessary to re-sample the CPD so that the CPD are orthogonally projected onto the floor surface and then aligned at equal intervals.These problems will be improved in the future.The processing capability of the SLAM can be graded by gradually changing the amplitude and period of the uneven ground in (b).In the case of a robot moving on rough terrain, the movement of the robot affects the precision of the automatically created map, as well as the robot's maneuvering.



(a) floor with slope. (b) floor with random steps.

Figure 13: Fields of RoboCup 2013 Rescue Robot League with slopes and gaps.

3.4.2 Parameters of rough terrain

Rubble is the main component of the unstable terrain [85].The rubble consists of concrete from furniture and buildings, along with various other objects in the environment.The rubble has various sizes and shapes, with an even greater variety resulting from combining the different types of rubble.There is also a difference between the rubble in the FDNP building and the rubble in a collapsed sample of Disaster City.Therefore, first the state of the rubble was divided into two categories.The first category (category I) was rubble that was arranged in a relatively planar fashion like NIST's robot evaluation field.The second category (category II) was debris stacked at a height of several meters like the rubble found in a collapsed building of Disaster City.

In the proposed evaluation field, the surface of the rubble was modeled as follows using sinusoidal synthesis.

$$\begin{aligned} S(x,y) &= f(x) \times f(y) \\ f(x) &= A_x \sin(\omega_1 x + \theta_1) + a_x \sin(\omega_2 x + \theta_2) \\ &\quad \text{where } A_x >> a_x \ , \omega_1 << \omega_2 \ . \end{aligned}$$

Here, x and y are mutually orthogonal, biaxial variables parallel to the floor surface, and $S(x,y)$ represents the height of the rubble from the floor surface.The first term of function f creates a surface composed of rubble as a whole, and the second term expresses the unevenness of its surface.Specifically, the coefficient A expresses the undulation of the surface composed of all of the rubble stacked at a height of a few meters, the coefficient a expresses the size of the small- and medium-sized debris that exists on the surface composed of rubble.In addition, A, a, ω_1, and ω_2 a functions of x and y. θ_1 and θ_2 are offsets given to the sinusoidal function.$S(x, y)$ expresses the height of the two-dimensional rubble using the product of $f(x)$ and $f(y)$.

When $A_x = a_x = A_y = a_y = 0$, the surface constituting all of the rubble is a plane.In the category I evaluation field, A is 0 and a is a value other than 0.When the value of A is not 0, the evaluation field is category II.In category II, small rubble is found on the large debris, and there is accumulated rubble.

3.5 Evaluation experiment for SLAM method

3.5.1 Evaluation field for grading and robot used for experiment

In this experiment, category I and loose undulation category II evaluation fields were prepared.The evaluation fields were constructed using USARSim, which was also used for the robot in this experiment.The robot was a 4-wheel drive type robot (P3AT), which is the most frequently used type of robot for creating an autonomous map.P3AT was equipped with a sensor that emulated an LM 200, which is SICK's LRS.The LM 200 was fixed to the upper part of the P3AT' s main body, with the front side of the sensor facing forward without using the pan tilt head.Table 8 lists the dimensions of the virtual model of the crawler type robot Kenaf (old model of Quince), which has an extremely high mobility performance and the same size as P3AT, as a reference for another robot.The total length of P3AT listed in Table 8 is the total length excluding bumpers.There was a problem with the experiment when the bumpers were used, which will be described later. Therefore, the bumpers attached to the front and back of the vehicle were removed from the P3AT registered in USARSim.

The debris size is less effective as rubble for rubble that is too small for a robot, and all the wheels tend to float in the air up to rubble of the same size .Therefore, those conditions was eliminated and the rubble was made twice in the size of the

Table 8: Dimensions of P3AT and Kenaf.

Robot	Width(m)	Length(m)
P3AT	0.31	0.26 (Wheel Base)
Kenaf	0.51	0.60 (Vertical Crawler Arms)
		0.90 (Horizontal Crawler Arms)

robot to be able to be run around by the robot.

A triangular prism was used as a basic component to express rough terrain (Figure 15).For the triangular prism used, four parameters were given for the width (w), length (l), and height (h_1, h_2).By setting different heights at both ends of the triangular prism, an angle change occurred not only in the pitch axis but also in the roll axis of the robot riding over this triangular prism.Various types of rubble could be expressed by adjusting the parameters of the triangular prism.For example, when the width of the triangular prism was longer than its height, it could be used as a slope, and when the height of the triangular prism was longer than the width, it could be used as a step.By arranging various triangular prisms on the floor, it was possible to construct rough terrain like the evaluation field of NIST.

In the experiment conducted at this time, the main traveling direction of the robot was set perpendicular to the longitudinal direction of the triangular prism. Two types of rough terrain were prepared to compare the case where the pitch axis and roll axis of the robot also had an effect on getting over the debris.The former corresponds to category I, and the latter corresponds to category II.

In the category I evaluation field, $h_1 = h_2$, and 10 triangular prisms with the same height constituted the rubble.In order to perform grading, five evaluation fields with heights of $0.0, 0.04, 0.08, 0.12, and 0.16$ m were prepared.The maximum height of the triangular prism was determined from the total length of the P3AT, the slope length, and the hill climbing ability (Table 9). $Length_{P3AT}$ of Table 9 indicates the total length of P3AT, and $Length_{Ramp}$ is the length of the slope of the triangular prism.$\frac{Length_{P3AT}}{Length_{Ramp}}$ of Table 9 indicates that the slope length of the triangular prism is about twice the total length of P3AT. This is consistent with making the size of the rubble twice the size of the robot as an experimental condition. *Angle* in Table 9 indicates the angle between the slope of the triangular prism and the floor surface. When *Angle* exceeded 20° in a test run, the slip increased, and difficulty was found for carring out the experiment.Therefore, the slope angle was less than 20° . The height of the triangular prism was determined to make it easy to handle a uniform height change.The grade was based on Table 9 h.

Table 9: Heights of leveled ramps and P3AT dimensions for category I.

Grade	h(m)	Angle (degree)	$\frac{Length_{P3AT}}{Length_{Ramp}}$
1	0.00	0.00	0.520
2	0.04	4.58	0.518
3	0.08	9.10	0.513
4	0.12	13.5	0.506
5	0.16	17.8	0.495

In category II, 10 triangular prisms with different values for h_1 and h_2 were used for the rubble.Among these 10 triangular prisms, up to the 5th triangular prism, the height of the center of the triangular prism was gradually increased. From the 6th triangular prism to the 10th triangular prism, the triangular prisms gradually became lower.In category II, the top edge of the triangular prism was made to tilt. Parameter h_1 and h_2 were set so that the slopes of the upper edges of the triangular prisms were exchanged at every triangular prism (Table 10).

3.5.2 Map creation by SLAM

When operating a robot at a disaster site, the operator of the rescue robot refers to a map created by the SLAM in order to confirm the current position, movement trajectory, unsearched area, etc. of the robot.In this experiment, two kinds of SLAM algorithms were used: Gmapping SLAM and Hector SLAM [79].Gmapping SLAM also uses odometry information obtained from robot sensors as input.On the other

Table 10: Values of h_1 and h_2 for 10 prisms in category II.

Number of Prism	h_1(m)	h_2(m)
1	0.00	0.08
2	0.10	0.02
3	0.04	0.12
4	0.14	0.06
5	0.08	0.16
6	0.16	0.08
7	0.06	0.14
8	0.12	0.04
9	0.02	0.10
10	0.08	0.00

Table 11: Features of SLAM used in experiments.

SLAM	Merit	Demerit
Gmapping	Quick response	Needs odometry
Hector	Does not need odometry	Requires good range data or fail matching range data

hand, Hector SLAM does not require odometry information as a characteristic of its algorithm (Table 11).

Figure 16 was generated by Gmapping SLAM using (a) the whole view of the SLAM operation preliminary experiment field and (b) the CPD obtained by the LRS of the P3AT circulating within this field. It is a map.The outlines of rooms and obstacles are clear, making it a clear map.

Figure 17 shows a panoramic view of the proposed grading evaluation field and the running route of P3AT.The size of the evaluation field prepared in this experiment was 10 m × 10 m.P3AT traveled in the direction of the arrow shown in Figure 17 in all the experiments of category I and the experiment of the first line of category II, as listed in Table 10.The experiment shown on the second line of category II is a case where P3AT moved while leaning with the roll axis.Only the running route of Figure 17 was rotated counterclockwise by 90° .The floor of the evaluation field was covered with the aforementioned triangular prism.The width of the triangular prism w was 1 m and the length l was 10 m.

Table 12 [1] shows the SLAM results for each grade of Table 9 in category I, and the following conclusions can be drawn:

1. Hector SLAM has more error such as map distortion as the triangular prism becomes higher.
2. Since Gmapping SLAM uses odometry information, it is more stable than Hector SLAM even if the grade changes.
3. Hector SLAM also improves the error when correcting the robot attitude.

If CPD with corrected rotation around the roll, pitch, and yaw axes are not used, SLAM creates an incorrect map.

Correcting the distance data using the odometry sensor information corrects the distorted map.As listed in Table 12, Hector SLAM with the uncorrected distance data outputs normal maps for grades 1 and 2, corrected distance data are required for grades 3 and 4, and recognizable maps are not output for grade 5.The category II rough terrain is similar to a building' s indoor floor after a natural disaster, and as listed in Table 13, Hector SLAM did not output a normal map even if corrected distance data were given.

In the grading method using the evaluation field of the proposed simulation, both the performance evaluation of the SLAM method and performance evaluation of the robot as a whole, including the mobility performance and performances of the other mounted sensors, were shown to be effective.The discussions related to Table 12,

[1]The P3AT registered in USARSim had bumpers on the front and rear of the body.When triangle pole h was set to 0.5 m and the experiment was carried out, the tip of the bumper struck the slope of the next triangular prism when going down the slope, the front wheel could not ground, and it could not climb the slope.For this reason, in the experiment, the front and rear bumpers were deleted from the P3AT model.

Table 13, and the SLAM methods could also be applied to the robot performance evaluation as a whole.

3.6 Summary and future considerations

3.6.1 Summary

Methods for evaluating the mobility performance of a rescue robot have been proposed by NIST and ASTM.The performance evaluation of a rescue robot includes not only its mobility performance but also map creation, sensor, Wi-Fi communication, and autonomous algorithm performance evaluations.When evaluating the map creation performance, it is necessary to judge not only whether or not a readable map can be made, but also the extent of the map creation.In addition to the mobility performance evaluation, in order to evaluate the ability of the rescue robot, such as in mapping, the floor of a disaster site where rubble was scattered was modeled. In addition, an evaluation field for evaluating the performance of a rescue robot using simulation was proposed. In experiments involving mapping with SLAM, it was showed that the SLAM results for rough terrain were distorted compared to those for a flat floor, and it was difficult to read the results. This showed the effectiveness of the proposed evaluation field.

Rescue robots are expected to be usable in FDNP in various situations and for different purposes.For example, rescue robots are expected to improve the monitoring and mapping performance inside and outside of buildings, as well as work such as the assembly and arrangement of pipes. Rescue robots are designed for these purposes, and their performances are always evaluated at the end.A grading evaluation field for a rescue robot and its standardization are useful for rescue robot development.

3.6.2 Future considerations

As future research tasks for FDNP, it is necessary to incorporate the evaluation items listed in Table 14.These evaluation items show the situations evaluated by the RoboCup rescue actual machine league, the virtual robot league, and other rescue robot competitions.Table 15 lists the corresponding evaluation items from the viewpoints of map creation, mobility, Wi-Fi communication, and human detection.

1. Type 2 unprepared land is necessary to evaluate the performance of 3D or 6D SLAM and the robot mobility performance.Performance evaluation fields for 3D or 6D SLAM in rough terrain are not available.

2. Obstacles of Type 3 are necessary to evaluate the 3D or 6D SLAM performance, robot mobility performance, Wi-Fi communication performance against large obstacles, and obstacle detection performance.For example, the grading of the obstacle detection performance is useful for verifying the effectiveness of the travel course and the safety of the robot’ s behavior in the environment where the obstacle is present.

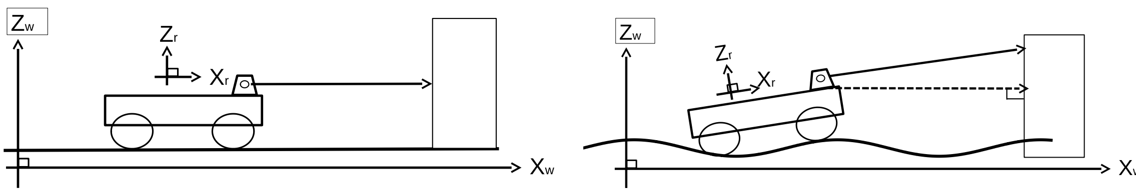
3. Types 4, 6, and 7 involve steps, tilts, multiple floors, and outdoor environments, which are necessary for evaluating the 3D or 6D SLAM performance, robot mobility performance, and Wi-Fi communication performance.

4. Type 5 walls are necessary for evaluating the 3D or 6D SLAM performance and Wi-Fi communication performance.

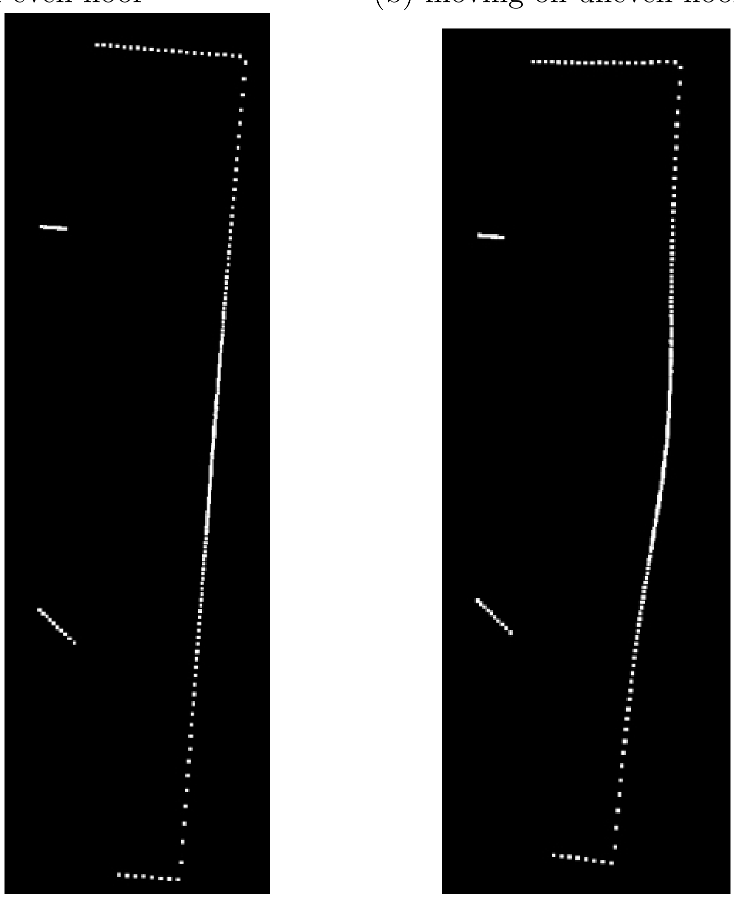
5. The required rescuers of type 8 are necessary for evaluating sensors and image processing algorithms.For example, it is increasingly important for rescue robots to search autonomously in hazardous areas where pollution by high-concentration radiation makes communication unstable, as well as in a Wi-Fi communication environment, and obtain integrated information. They are expected to be commercialized after their rapid development and performance evaluation.

In the RoboCup Rescue Real Robot League and Rescue Virtual Robot League, some of the evaluation items given for types 2 $\sim$ 8 are adopted to determine the score of the game.In the score calculation of the game, the human judge comprehensively judges the precision of the automatically created map and its readability by human beings. The grading method proposed in this chapter could be used to determine objective scores for the map creation algorithms installed in each robot.

The evaluation field proposed in this chapter is expected to be as useful as a new sensor, algorithm, operator, or method in evaluating the performance of the rescue strategy.The performance evaluation field of the robot needs to be standardized to supply common evaluation criteria to researchers, developers, and the users of rescue robots.



(a) moving on even floor (b) moving on uneven floor



(c) data from robot (a) (d) data from robot (b)

Figure 14: SLAM images based on laser range sensors mounted on robots moving on even and uneven floors.

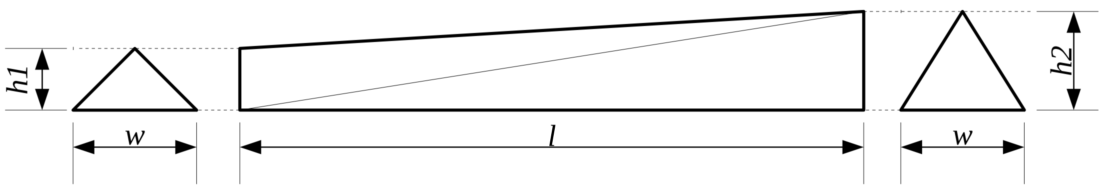
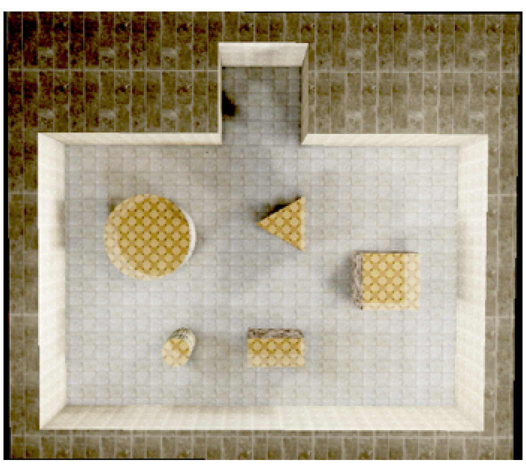
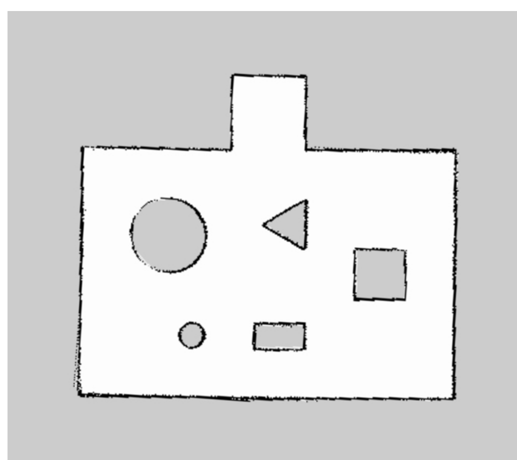


Figure 15: Model of debris making floor uneven.



(a) Top view of simple room with obstacles



(b) Simple room and obstacles map by Hector SLAM

Figure 16: Sample of SLAM image.

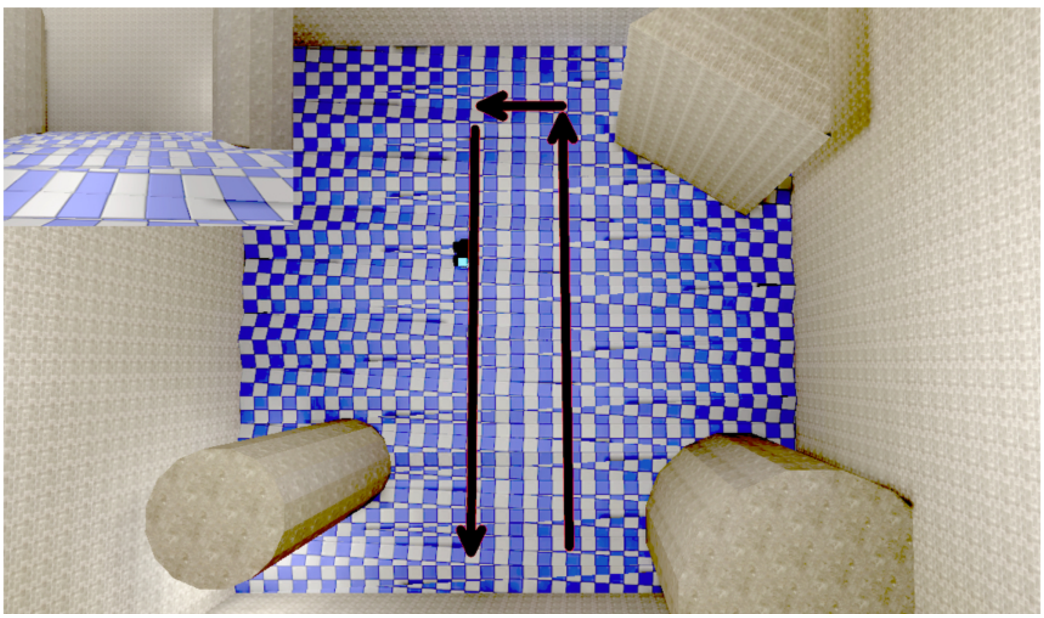


Figure 17: Route taken by robot.

Table 12: SLAM results of Gmapping SLAM and Hector SLAM with variety of obstacles for category I.

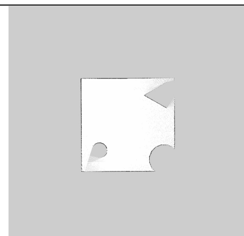
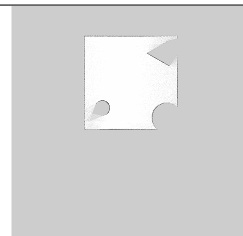
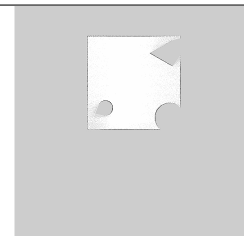
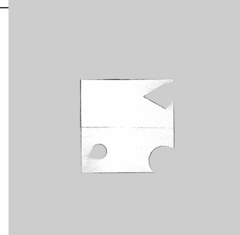
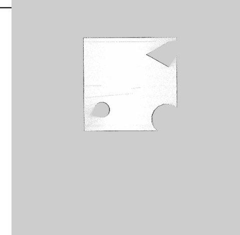
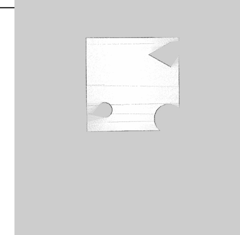
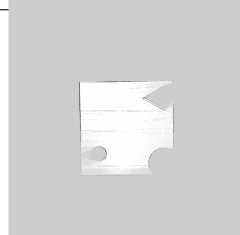
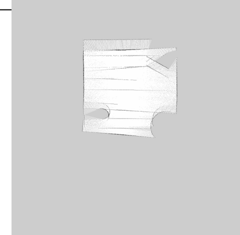
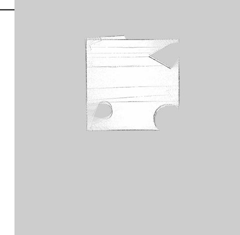
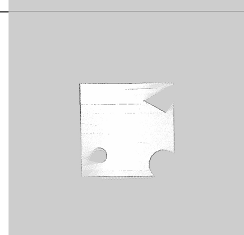
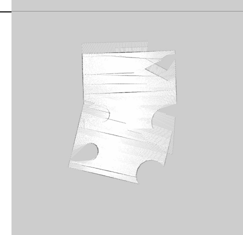
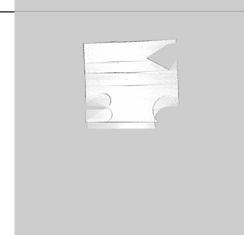
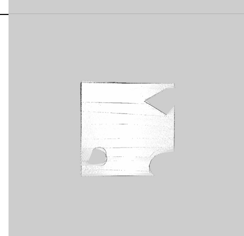
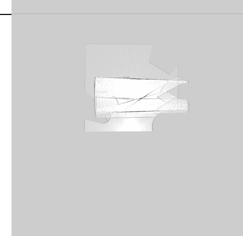
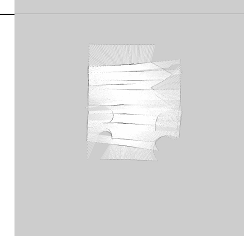
Category	Condition	SLAM Result		
		Gmapping SLAM with non-fixed range data	Hector SLAM with non-fixed range data	Hector SLAM with fixed range data
Category I	Grade 1			
	Grade 2			
	Grade 3			
	Grade 4			
	Grade 5			

Table 13: SLAM results of Gmapping SLAM and Hector SLAM with variety of obstacles for category II.

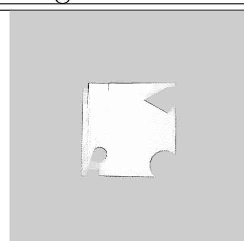
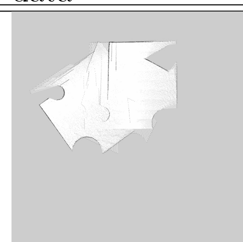
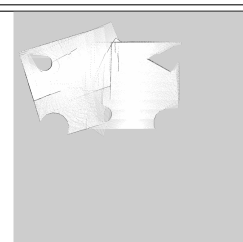
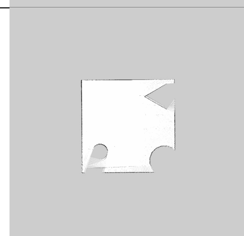
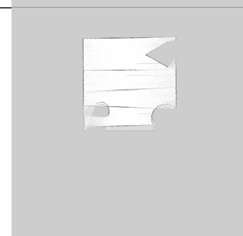
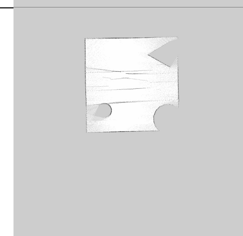
Category	Condition	SLAM Result		
		Gmapping SLAM with non-fixed range data	Hector SLAM with non-fixed range data	Hector SLAM with fixed range data
Category II	Robot moved UP and DOWN			
	Robot moved LEFT and RIGHT			

Table 14: Comparison of test points between RoboCup Virtual Robot League and NIST test field.

Number	Types	RoboCup Virtual Robot League	RoboCup Real Robot League (NIST test field)
1	flat floor	○	○
2	uneven floor	△	○
3	obstacles	△	○
4	steps and slope	△	○
5	walls	△	△
6	multi floors	△	△
7	outdoor	△	△
8	victim detection	△	△

△ : partly realized, but not enough.

Table 15: Reasons for development of each type of test field in Table 14.

Number	Types	Mapping performance	Mobility performance	Wi-Fi performance	Detecting Task performance
2	uneven floor	○	○	-	-
3	obstacles	○	○	○	○
4	steps and slope	○	○	○	-
5	walls	○	-	○	-
6	multi floors	○	○	○	-
7	outdoor	○	○	○	-
8	victim detection	-	-	-	○

Chapter 4 Databased fluctuating Wi-Fi Signal Simulation Environment for Evaluating the Control of Robots

4.1 Overview of this chapter

Robots were used at the site of the World Trade Center disaster, and they are being used to explore the interior of the Fukushima Daiichi Nuclear Plant(FDNP). Robots will be used at the FDNP for the next few decades, until the nuclear reactor is finally decommissioned. Wired communications systems have been used to teleoperate robots in hazardous areas where humans cannot work. In this chapter, the fluctuation of Wi-Fi power strength in a real environment is showed and it's presented that the fluctuations utilization is one of the key points to be considered while developing rescue robots for disaster-prone areas. And simulation environment that simulates the fluctuation of the Wi-Fi power strength with a database and evaluates the performance of the robot with unstable Wi-Fi connectivity are proposed.

4.2 Introduction of this chapter

Ever since the Great East Japan Earthquake of 2011, robots have been used to explore the interior of the Fukushima Daiichi Nuclear Plant (FDNP) and they will be used to perform a variety of tasks over the next several decades, until the nuclear facilities are finally decommissioned [77]. These tasks include clearing debris, monitoring the interiors and exteriors of buildings, setting up instruments, shielding and decontaminating, transporting materials, and constructing pipes and equipment. The robots will also be required to perform day-to-day activities; for example, monitoring the tanks used to store water that has been contaminated by radioactive materials [86] [87].

It is assumed that the robots will be operated remotely to prevent accidents. With a wired connection, the trailing cable limits the range and movement of the robot. On the other hand, buildings, walls, furniture, or other objects act as obstacles to the propagation of a Wi-Fi signal. A hybrid system using both wired and wireless connections is a possible solution to these issues, and this approach was used to explore the buildings in the FDNP [88]. A Packbot pair was configured with one Packbot connected by a cable and acting as a wireless access point, while the second Packbot was operated wirelessly. To perform these operations, testing their behaviors that satisfy their mission in the FDNP is necessary [78].

In this chapter, a simulation environment that can reproduce realistic unstable Wi-Fi connectivity behavior is proposed, for evaluating such response robots working in hazardous areas, by using the databased radio-wave power strengths measured at actual locations. This environment can also be used to conduct rehearsals for using the response robots in the areas with unstable Wi-Fi connectivity and where humans cannot enter and work.

Section 4.3 describes the environment where a response robot is used. Section 4.4 presents a fluctuation model and describes the proposed method for reproducing the fluctuations in the Wi-Fi signal and estimating the Wi-Fi connectivity in a given area. Section 4.5 describes two results of the proposed simulation; one is for the fluctuating Wi-Fi radio-wave strength similar to that in a normal environment and the other is for a similar situation in a disaster area. Section 4.6 discusses future areas for robot testing and concludes this chapter.

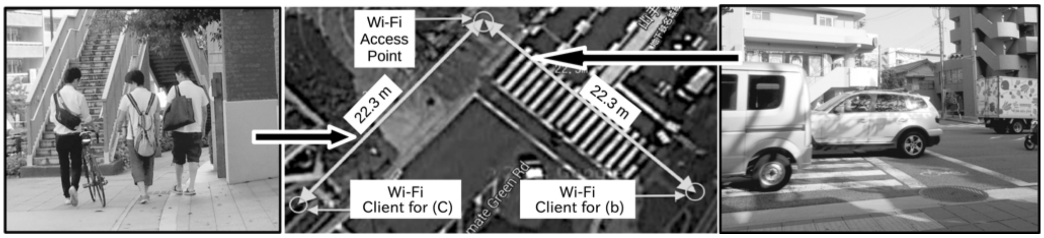
4.3 Background and related works

Disaster situations require investigatory tasks to be undertaken by teleoperated robots rather than by human operators. When sensors and robots are newly developed for investigating buildings in disaster zones, testing the sensors and robots can help in verifying and improving their performance. Simulations have been used to shorten the development time and to check the functions of the sensors. Competitions, such as RoboCup Rescue, provide platforms on which the response robots and algorithms can be tested in the simulated environments of disaster zones where they are intended to operate [46] [89] [38].

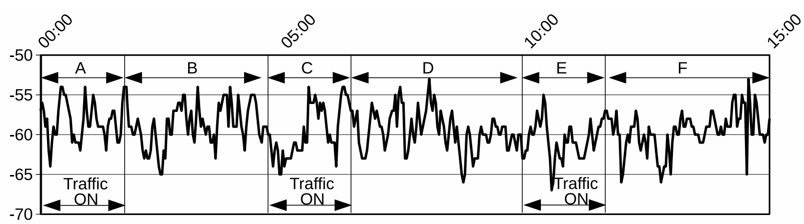
Response robots are operated both indoors and outdoors in a disaster area and some robots are assumed to be teleoperated by Wi-Fi. Stable Wi-Fi connectivity is desired, however, as the strength of radio wave signals varies indoors and outdoors and fluctuates especially in the presence of large objects such as water tanks [86] [87]. In the worst case, the robots that move outside the range of Wi-Fi signals cannot be controlled and may actually be lost. The following are required to test rescue robots: mobility at uneven areas, manipulating objects, sensing circumstances, and communication under unstable wireless conditions.

Calculating the signal strength requires the values of all reflected signal strengths that pass through that location and the influence of the fluctuation at a given location [90]. The calculation involves lapses in connectivity caused by unexpected objects in the path of the signal in disaster areas. This makes it difficult to calculate the reflection because whether an object, such as a wall, reflects the radio waves or not depends on the material constituting that object, which is not always known. Some methods, such as the ray-tracing method, provide an easier means for estimating the Wi-Fi connectivity status; however, they do not provide the fluctuation in the strength of radio waves.

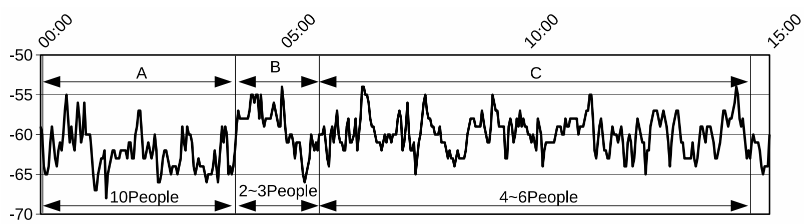
A lightweight calculation method for simulating the actual Wi-Fi problem with the fluctuation of the radio-wave power strength is proposed [91]. The proposed method reproduces the fluctuations in the strength of the radio wave by using a radio-wave power-strength database containing measurements taken at actual locations. Given the increased amount of available computational power, simulations provide a more effective means for evaluating the mobility of response robots.



(a) Measurement situation of Figure 18 (b) and (c).



(b) Strength of fluctuation caused by traffic at a crossing.



(c) Strength of fluctuation caused by people at a walking bridge.

Figure 18: Wi-Fi signal strength fluctuations measured outdoors depending on situations. The x-axis of graphs represents time in min:sec, and the y-axis represents the received radio-wave power in dB respectively.

4.4 Method for reproducing fluctuations in radio-wave signal strengths

4.4.1 Radio-wave signal strength fluctuations

Measured fluctuations in strength of Wi-Fi signal received outdoors

Figure 18 (a) shows the measurement situation of (b) and (c). Figure 18 (b) indicates the Wi-Fi signal strength at a crossing for approximately 15 minutes. The signal is interrupted by vehicle movement. Every five minutes, a traffic signal stops vehicles for two minutes. Table 16 shows the means and deviations of Wi-Fi signal strength for spans when traffic signals are on and off. Table 16 indicates that the number of vehicles does not cause the Wi-Fi signal strength to fluctuate.

Table 16: Means and deviations of outdoor Wi-Fi signal strength fluctuations caused by traffic.

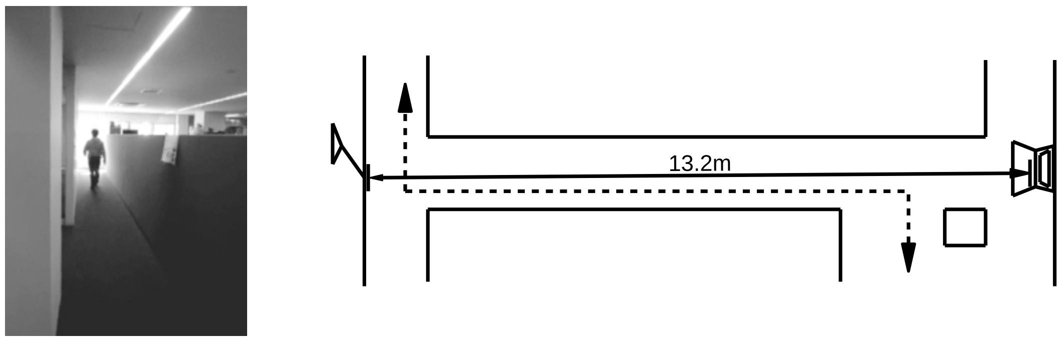
Time span	Mean(dB)	Deviation	Traffic
A	-57.9	2.4	ON
B	-58.4	2.6	OFF
C	-58.4	3.0	ON
D	-59.4	2.5	OFF
E	-57.4	2.5	ON
F	-58.7	2.4	OFF

Figure 18 (c) shows the strength of Wi-Fi signals at a walking bridge. During the first four minutes, more than 10 people were moving around between the Wi-Fi access point and the Wi-Fi client. From the fourth minute to the sixth minute, very few people were moving around. Lastly, from the sixth minute to the fifteenth minute, several people were present. The three spans are represented as A, B, and C, respectively in Table 17.

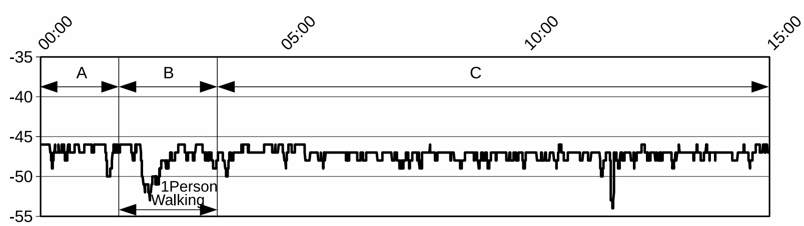
Table 17: Means and deviations of outdoor Wi-Fi signal strength fluctuations caused by people.

Time span	Mean(dB)	Deviation	Number of people
A	-62.2	2.5	10
B	-59.1	2.9	$2 \sim 3$
C	-60.0	2.2	$4 \sim 6$

Table 17 shows the means and deviations of signal strength at different periods. The Wi-Fi signal strength outdoor varies according to the number of people and fluctuations are caused.



(a) This figure shows a plan view of the Wi-Fi power-measurement space of Figure 19 (b).



(b) Strength of fluctuation caused by people at a corridor.

Figure 19: Wi-Fi signal strength fluctuations measured indoors. The x-axis of graphs represents the time in min:sec and the y-axis represents the received radio-wave power in dB respectively.

Measured fluctuations in the strength of Wi-Fi signal measured indoors

Figure 19 (a) shows a small indoor corridor. A Wi-Fi transmitter is located at the left end, and a notebook PC acting as a Wi-Fi receiver is located at the right end. The dotted line indicates the route followed by the people. Figure 19 (b) presents the measured fluctuations in the strength of the Wi-Fi signal when it is interrupted by people moving around indoors. The x-axis of this graph corresponds to a duration of approximately 15 minutes.

Table 18 lists the means and deviations of the signal strength and shows that the fluctuation caused by people indoor is smaller than the fluctuation in the Wi-Fi signal

Table 18: Means and deviations of indoor Wi-Fi signal strength fluctuations caused by people.

Time span	Mean(dB)	Deviation	Number of people
A	-46.7	0.96	0
B	-47.9	1.7	1
C	-47.3	0.82	0

strength outdoor.

Discussion on fluctuating Wi-Fi signal strengths outdoors and indoors

From Table 16, 17 and 18, the following is inferred:

1. The constant fluctuation at a given location depends on the surrounding environment, such as outdoor/indoor, and the number of people around.

2. The constant fluctuation is not influenced by movement of people or vehicles.

Thus, the width of the constant fluctuation in the signal strength depends on the surrounding environment.

4.4.2 A databased simulation environment for fluctuations in the signal strength

The fluctuations in the signals depend on the situations. Many methods have been proposed to calculate the strength of radio-wave signals [90]. The following databased Wi-Fi signal simulation environment is proposed.

Algorithm 1 is a flow to calculate fluctuation of the Wi-Fi power strength between Wi-Fi access points and robots. This method of calculating the fluctuations simulates the fluctuations in the power of the radio waves and determines whether the wireless communication status is "connected" or "disconnected," even in cases involving combinations of open spaces, buildings, and narrow corridors within buildings, as in

for $A_i \leftarrow$ Access points **do**
  for $R_j \leftarrow$ Robots **do**
1. Calculate path P_{ij} from A_i to R_j.
2. Calculate Wi-Fi strength S_{ij} along P_{ij}.
3. Determine environment parameters from database.
4. Calculate fluctuation in signals F_{ij} using the environment parameters.
5. Calculate Wi-Fi strength with fluctuation : $FS_{ij} \leftarrow S_{ij} + F_{ij}$.
6. Determine Wi-Fi connectivity status C_{ij} by thresholding FS_{ij}.

Algorithm 1: Algorithm for calculating fluctuating Wi-Fi power strength.

the FDNP [92]. In homes, offices, factories, schools, or disaster areas, there are many locations where fluctuations can occur, both indoors and outdoors.

4.4.3 Modeling the fluctuations in signal strength

Equation (1) is proposed to simulate the fluctuation of the radio-wave power in step 4 of Algorithm 1.

$$\begin{aligned} f_{fluctuation}(t) = a_1 \sin(\frac{2\pi}{t_1}t) \\ +a_2 \sin(\frac{2\pi}{t_2}t) \\ -a_3 Rand\left|\left(\sin(\frac{2\pi}{t_3}t)\right)^p\right| \\ -a_4\alpha \end{aligned} \tag{1}$$

Equation (1) describes three waves.

a_1 is the width of the radio-wave fluctuation power spectrum, and t_1 is the length of the cycle of the radio-wave fluctuation power.

a_2 is the width of the radio-wave noise power spectrum, and t_2 is the length of the cycle of the radio-wave noise power.

a_3 is the width of the strength of the radio-wave peak noise power, *Rand* is a random number between 0 to 1 in the normal distribution, t_3 is the length of the cycle of the radio-wave peak noise power, and p is a multiplier used for producing a peak.

a_4 represents the decreasing radio-wave power caused by people walking. α is 1 when people are around the path and 0 otherwise.

Table 19: Databased parameters for various places and scenarios.

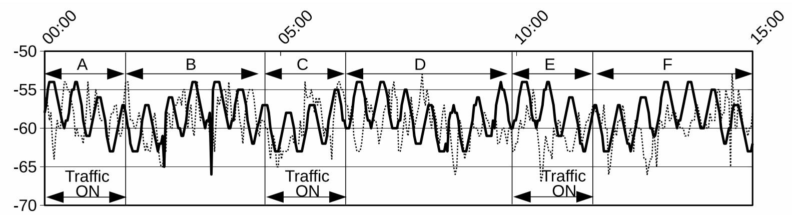
Parameters	Outdoor		Indoor
	With Vehicles	With Walking people	With Walking people
a_1(dB)	2	2	1
t_1(Sec)	180	200	1200
a_2(dB)	3	2	0.5
t_2(Sec)	30	30	30
a_3(dB)	20	20	6
t_3(Sec)	120	120	180
p	10000	10000	10000
a_4(dB)	0	5	3

4.5 Simulation results

4.5.1 Simulation results of fluctuating Wi-Fi radio waves

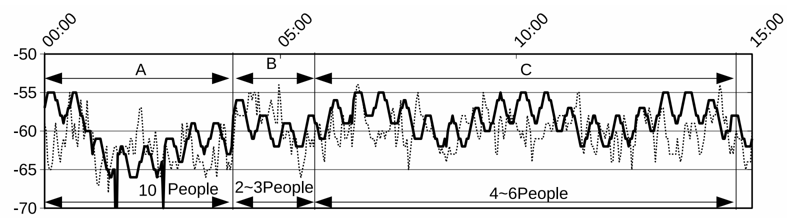
An experiment is conduced to demonstrate the capability of the proposed method for reproducing fluctuation phenomena by using databased fluctuation parameters. To calculate S_{ij}, the Friis free-space path loss equation was used [93]. To calculate diffraction, a knife-edge diffraction model was used [90] [91]. The method can calculate the strength with diffraction effect and -92 dB is used to threshold FS_{ij}.

Table 19 presents the database of fluctuation parameters. The second, third, and fourth columns of the table correspond to Figure 18 (b), (c), and Figure 19 respectively. The three situations correspond to the environments : outdoor with vehicles, outdoor with people and indoor with people. Table 19 is a start-up database.



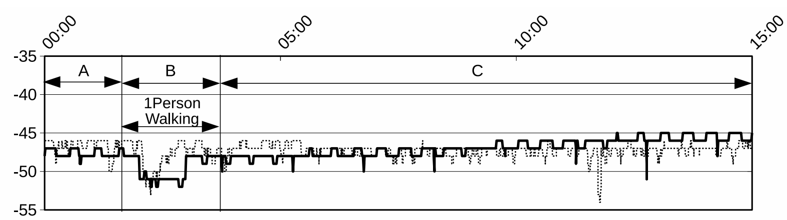
Time span		Mean(dB)	Deviation
A	Simulated	-58.5	2.6
	Measured	-57.9	2.4
B	Simulated	-58.4	2.6
	Measured	-58.4	2.6
C	Simulated	-58.4	2.6
	Measured	-58.4	3.0
D	Simulated	-59.3	2.5
	Measured	-59.3	2.5
E	Simulated	-57.4	2.3
	Measured	-57.4	2.5
F	Simulated	-58.7	2.6
	Measured	-58.7	2.4

(a) Outdoors with vehicles moving between the Wi-Fi access point and the Wi-Fi client.



Time span		Mean(dB)	Deviation
A	Simulated	-61.3	3.4
	Measured	-62.2	2.5
B	Simulated	-59.4	1.9
	Measured	-59.1	2.9
C	Simulated	-58.4	2.0
	Measured	-60.0	2.2

(b) Outdoors with people moving between the Wi-Fi access point and the Wi-Fi client.



Time span		Mean(dB)	Deviation
A	Simulated	-46.5	0.50
	Measured	-46.7	0.96
B	Simulated	-47.9	1.6
	Measured	-47.9	1.7
C	Simulated	-45.0	0.68
	Measured	-47.3	0.82

(c) Indoors with people moving between the Wi-Fi access point and the Wi-Fi client.

Figure 20: Simulated fluctuations in Wi-Fi signal strength for comparison of situations with means and deviations. Continuous lines correspond to simulated values; dotted lines indicate actual measured Wi-Fi signal strengths. The x-axis represents time in min:sec, and the y-axis represents the received radio-wave power in dB.

To calculate F_{ij} in an environment, one can select a similar situation from the database and use the parameters related to the situation.

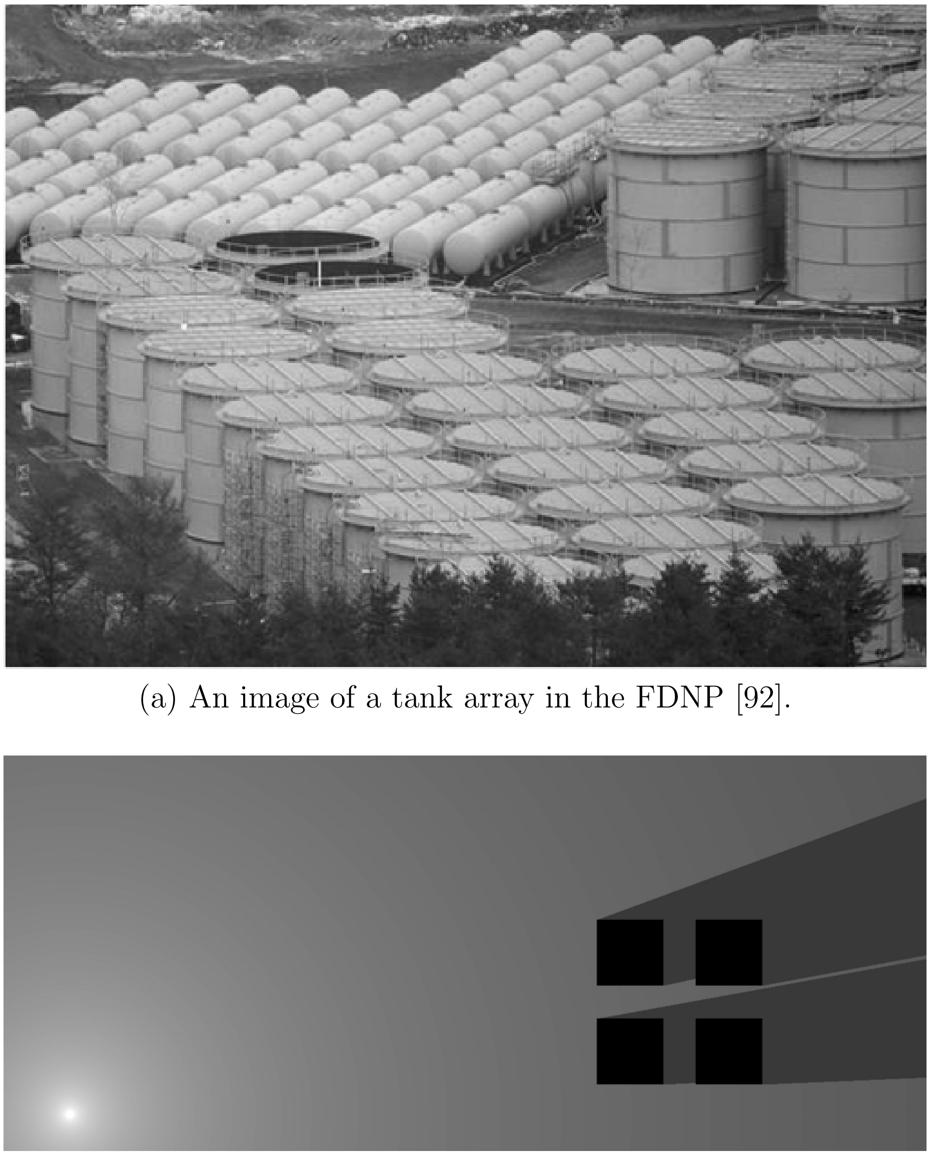
The parameters in the database are used to calculate the Wi-Fi radio-wave signal strength. Figure 20 shows the results of a simulation of the fluctuations for 15 minutes that occur indoors and outdoors. The continuous line in each graph indicates the simulated values of the fluctuations in the signal strength. The dotted line shows the measured signal strength. The continuous line is similar to the dotted line. As the tables in the right column of Figure 20 (a), (b), and (c) show, the means and deviations of the three curves are also similar to the measured values.

4.5.2 Simulation experiments in a similar real situation

Table 20: Three cases of Wi-Fi radio-wave situations.

Situation	Fluctuation	Diffraction
Case 1	OFF	OFF
Case 2	OFF	ON
Case 3	ON	ON

A simulation field that is similar to an array of tanks in the FDNP was made [92]. Figure 21 (a) is an image of a real tank array at the FDNP. There are some shadow areas of Wi-Fi radio waves in the tank array. Figure 21 (b) shows a top view of the environment of this experiment that simplifies the tanks in the FDNP. Four black boxes indicate a tank array, and the small white point on the left is the Wi-Fi access point. The size of each box tank is 10 m by 10 m. The tanks are separated by 5 m width corridors. The distance between the Wi-Fi access point and the left bottom tank is 90 m. The brightness of the pixels corresponds to the strength of the received signal at a given point. The area is a mesh with a resolution of 0.1 m by 0.1 m and Wi-Fi radio-wave strength is calculated for each mesh. Black pixels correspond to a received signal strength of less than -92 dB, in which case the Wi-Fi signal will be disconnected.



(a) An image of a tank array in the FDNP [92].

(b) Simulated Wi-Fi results with only attenuation.

Figure 21: Simulated Wi-Fi signal strength image maps similar to a real situation.

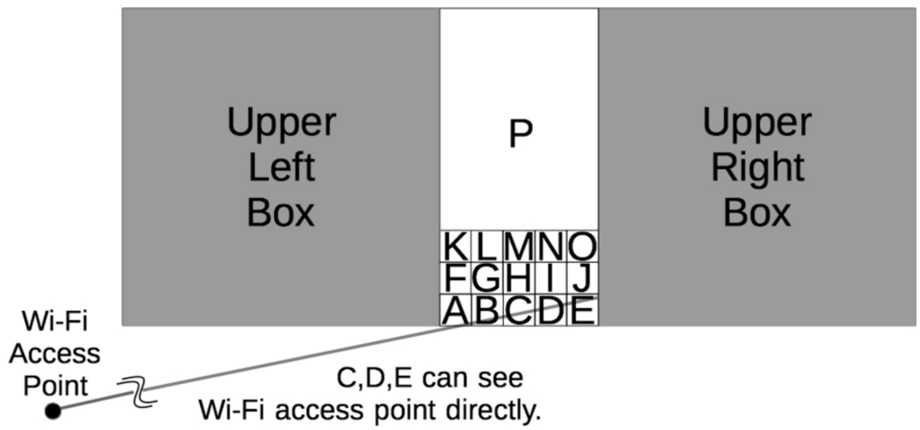


Figure 22: Simulated Wi-Fi signal-strength image maps in three situations.

An experiment is conduced in three situations for radio-wave power strength (Table 20).

Case 1: The simulated Wi-Fi radio-wave power strength was calculated with only attenuation.

Case 2: The simulated Wi-Fi radio-wave power strength was calculated with diffraction.

Case 3: The simulated Wi-Fi radio-wave power strength was calculated with fluctuation in a situation of weak radio-wave power strength.

Figure 21 (b) is the result of Case 1. Response robots should be tested in such unstable Wi-Fi radio-wave strength environments as Case 3, but not Case 1.

Discussion of fluctuations in the strength of radio-wave power

Table 21: Statistics of simulated Wi-Fi radio-power strength in segment A ∼ P with case 1, 2, and 3.

Segment	Statistics of Wi-Fi power strength in case 1, 2 and 3								
	Case 1			Case 2			Case 3		
	Mean[dB]	Deviation	Wi-Fi connection	Mean[dB]	Deviation	Wi-Fi connection	Mean[dB]	Deviation	Wi-Fi connection
A	NRW	-	None	-100	0.0	None	-101	2.6	None
B	NRW	-	None	-87.5	0.0	Always	-88.1	2.6	Sometimes
C	-79.8	0.0	Always	-79.8	0.0	Always	-80.3	2.6	Always
D	-79.8	0.0	Always	-79.8	0.0	Always	-80.4	2.6	Always
E	-79.9	0.0	Always	-79.9	0.0	Always	-80.4	2.6	Always
F	NRW	-	None	-109	0.0	None	-110	2.6	None
G	NRW	-	None	-106	0.0	None	-107	2.6	None
H	NRW	-	None	-102	0.0	None	-103	2.6	None
I	NRW	-	None	-98.1	0.0	None	-98.7	2.6	None
J	NRW	-	None	-93.2	0.0	None	-93.7	2.6	Sometimes
K	NRW	-	None	-112	0.0	None	-113	2.6	None
L	NRW	-	None	-111	0.0	None	-111	2.6	None
M	NRW	-	None	-108	0.0	None	-109	2.6	None
N	NRW	-	None	-106	0.0	None	-107	2.6	None
O	NRW	-	None	-104	0.0	None	-105	2.6	None
P	NRW	-	None	-116	0.0	None	-116	2.6	None

NRW : No radio wave (the radio-wave receiver cannot see the Wi-Fi access point directly)

In Figure 21 (b), a shadow area of radio wave was divided into sixteen segments. In Figure 22, the sixteen segments are named A to P between two boxes. The dimension of each segment from A to O is 1 m by 1 m, and that of segment P is 5 m by 7 m, respectively. The gray line in Figure 22 is a boundary of whether a point can see Wi-Fi access point directly or not.

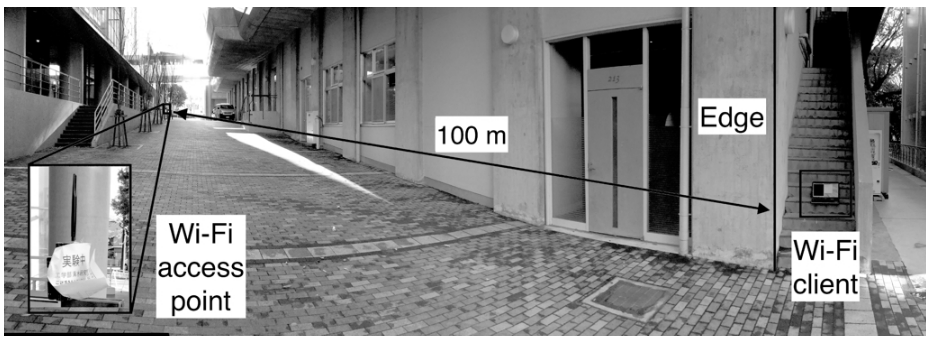
Table 21 shows the means and deviations of the Wi-Fi radio-power strength at the center of each segment from A to P. The mean and deviation of Wi-Fi power strength are calculated from 10 minutes simulated Wi-Fi radio-wave strength at the place. For case 1 of Table 21, at only segment C, D, and E, the Wi-Fi access point could be seen directly, and the Wi-Fi radio wave was received. Case 2: Segment B received a connectable Wi-Fi radio-wave strength by diffraction. Case 3: Segments B and J received a sometimes connectable Wi-Fi radio-wave strength by fluctuation. At segment B, the minimum Wi-Fi radio-wave strength was -93 dB. At segment J, the maximum Wi-Fi radio-wave strength was -89 dB.

Measurements in real world

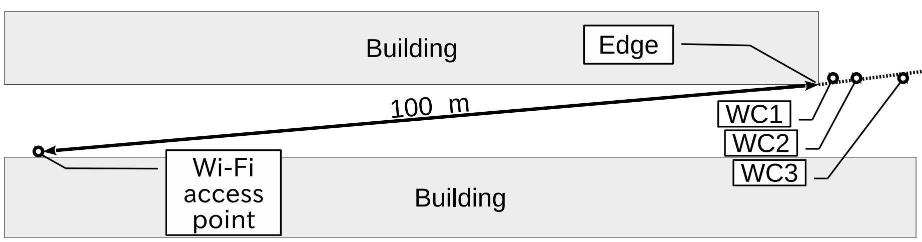
Table 22: Means and deviations of the measured three real places for validation.

Place	Mean(dB)	Deviation	Wi-Fi Connectivity
WC1	-101	5.2	None
WC2	-97.2	6.0	Sometimes
WC3	-64.7	3.8	Always

The proposed method can provide a robot simulation platform with unstable Wi-Fi connection. For validating the simulated fluctuation of signal power strengths, some real Wi-Fi radio-wave power strength was measured at a place similar to that in Figure 22 . Figure 23 (a) shows the place used for measurement. Figure 23 (b) shows the positions of a Wi-Fi access point, and three measured points - WC1, WC2, WC3 - that correspond to A, B, C respectively in Figure 22. There is a building instead of the left box in Figure 22 that made a shadow place of Wi-Fi radio-wave. A Wi-Fi access point was located at 100 m on the left of the building edge. WC1



(a) Panoramic view of the measurement place.



(b) Layout of the Wi-Fi access point and Wi-Fi client places.

Figure 23: An image of the validation place and layout of a Wi-Fi access point and Wi-Fi client places.

, WC2 and WC3 were located at a distance of 1 m , 2 m , 4 m on the right of the building edge respectively.

The Wi-Fi radio-wave signal strength of the three points was measured during an hour simultaneously. The Wi-Fi radio-wave signal strengths were measured per second and the means and deviations of the measurement results are shown in Table 22. At WC1, the signal strength of the Wi-Fi radio-wave was not connectable level. The mean value at WC2 was not connectable level, however the deviation was so large that it was connected at sometime and the other time, it was not connected. At WC3, it was connected all times. Measurements in real environment show that the three types of connections - no connection, sometimes connection and always connected - occurred in the real situations.

4.6 Discussion and Summary

The performance for the response robot should be tested before response robots can be used at the spot. Targets include training the operators, enhancing robot mobility, and undertaking tasks after disasters indoors and outdoors [94] [80]. A realistic wireless communication simulator considering the effects of fluctuations and diffraction in Wi-Fi signals will be essential for simulating the environments in which robots operate. The investigation of the tanks in the FDNP is an example.

In this chapter, a simulation method was proposed for reproducing the fluctuations in radio waves, and using the radio-wave power strength from a database of the measured actual radio-wave power strengths was proposed too. Two experiments were performed to demonstrate the effectiveness of the proposed method. The first experiment revealed that the proposed radio-wave fluctuation simulation closely matched the actual fluctuation behavior. The second experiment showed that the proposed simulation of the simultaneous fluctuation and diffraction of the Wi-Fi signal behavior resembled the actual signal behavior.

The proposed evaluation method for addressing actual Wi-Fi problems is expected to be useful for evaluating the performance of existing and new response robots, robot behavior algorithms, operators, and rescue strategies. The experiments show that the proposed Wi-Fi test field considering the fluctuations of Wi-Fi signals can evaluate the response robots intended for use in disaster zones before they are actually deployed. By increasing the number of measurements of Wi-Fi situations and corresponding environments, our method will provide a simulation environment for testing robot operations. It can be believed that proposed method will be able to check robot operations in disastrous environments.

Chapter 5 Proposal of simulation platform for robot operations with sound

5.1 Overview of this chapter

In recent natural disasters, robots have played an important role in search and rescue operations in places that are not easily accessible to humans. The key functions of robots in search and rescue operations are mobility in rough terrain, monitoring of surroundings when searching for victims, and creating disaster maps. A robot test field should provide reaction loops between operators, robots, and the environment, with natural information for human robot operators. Simulations should therefore provide more realistic information, more naturally. A simulation platform with realistic sound reactions from robot operations and noise from the environment is proposed. This chapter proposes and discusses the need for simulating inspection tasks to include sound information, and presents new tasks using sound. A prototype shows that the use of sound makes robot simulation applications more robust.

5.2 Introduction of this chapter

The RoboCup Rescue League aims to mitigate the losses caused by disasters and emergencies, by supporting the development of robots. On September 11, 2001, many robotics researchers brought their robots to search the wreckage of the World Trade Center [95]. The robots surveyed and reported the status of the areas in which unforgiving environments prevented the activities of rescue workers. A decade later, a robot that participated in the RoboCup was used to investigate the insides of the Fukushima Daiichi Nuclear Power (FDNP) buildings. Robots were also used in difficult conditions during the initial stages of the FDNP accident [83] [73]. After the initial stages, the FDNP decommissioning plan was announced, and new robots were designed and developed for use with this plan over the next several decades [96].

Aging infrastructure, such as bridges and tunnels, exerts severe pressure on human society. After several decades in service, the robustness of infrastructure decreases. Maintenance and replacement are the common measures taken to enhance the stability of such infrastructure, and robot technology is believed to be effective for both inspection and maintenance, as well as rescue operations [97]. Setting standard tasks and contesting robot performance accelerates research and development of robots in their fields of application.

In the RoboCup Rescue Virtual Robot League (RVRL), rescue tasks have been modeled to verify the algorithms and operations of rescue robots [84]. For example, map generation and victim searches have been set as typical tasks. In reality, these tasks are performed in challenging environments; for example, the floors are filled with debris, it is dark, and the air is contaminated with dust [74]. Simulation platforms that represent robot activities in such environments provide realistic test areas to meet not only the needs of the rescue operation, but also those of inspection tasks at plants, bridges, tunnels, and other locations [96].

In this chapter tasks where sound plays an information role and propose a simulation platform that incorporates the sound field are discussed. Robot competitions and their simulation platforms are surveyed in Section 5.3. In Section 5.4, robots' activities with sound information are discussed . Some sample tasks are demonstrated in Section 5.5. In Section 5.7, a discussion and summary of this chapter are presented.

5.3 Simulation platform in robot competitions

During disasters, human rescuers use their sight, hearing, smell, and touch to explore the area, search for victims, and to assure their own safety. Regarding infrastructure maintenance, nondestructive testing (NDT) plays a key role in validating tunnel structures, bridge components, and pipe connections in plants. Some NDT inspection tasks have been completed by workers with suitable devices, such as a hammer. Figure 24 shows visual inspection being carried out, and a hammering test.

Table 23: History of rescue robot competition and test field(Reprint of Table 2).

Year	Title of competition	Target		Field	Background case
		Operation	Robot		
1997	Disaster City	rescue training	land/air	Standardized Real Test Field	Oklahoma City Bombing (1995)
1998	RoboSub	rescue	sea		
2000	RoboCup Rescue (Real Robot)	rescue	land/air	Real Field	Hanshin-Awaji Earthquake(1995)
2005	Robotics Test	facility	field/facility	Real Field	Real Disasters
2006	RoboCup Rescue (Virtual Robot)	rescue	field/facility /land/air	Simulation	Real Disasters
2006	ELROB		land/air		
2008	Roboboat		sea		
2011	Guardian Centers	rescue training	land/sea/air	Real Field	
2012	ICARUS	rescue	land/sea/air		Earthquakes in l'Aquila, Haiti
2013	DARPA	rescue	land	Real /Simulation	Fukushima nuclear disaster
2013	euRathlon	rescue	land/sea/air		Fukushima nuclear disaster
2014	ARGOS challenge	survey	land	Real Field	
2015	JVRC	maintenance /rescue	land	Simulation	Sasago Tunnel Ceiling Accident
2018	WRS	maintenance /rescue	land/air	Simulation	Tunnel Accident , Plant maintenance and response

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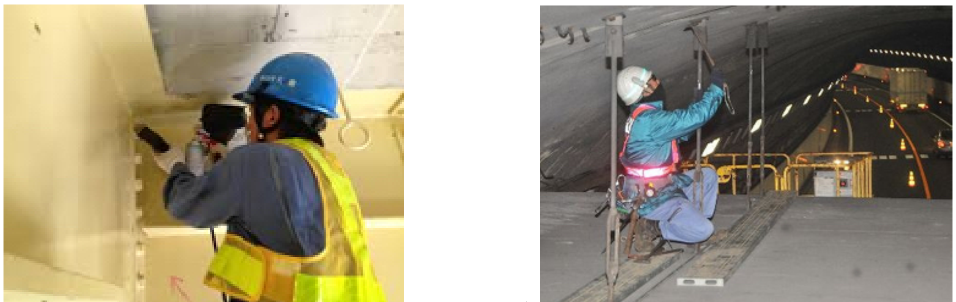

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Figure 24: Inspection task examples: Visual inspection and hammering test.

Robots are designed to perform tasks in specific applications, with the necessary sensors mounted onto the robot. Robotics competitions promote many projects relating to robots and rescue tasks, and their purposes range from search-and-rescue operations at disaster sites, to inspections of social infrastructure and oil platforms. In some competitions, simulation platforms are provided to develop and assess the robots in concert with the tasks in real competitions (Table 23). The RoboCup RVRL (the Gazebo used in the DARPA Robotics Challenge (DRC) [3, 11]), and the Japan Virtual Robotics Challenge(JVRC) [15] are such examples.

Almost all simulated fields for evaluating rescue robot performance are set to reproduce real-life situations, and are composed of many elements. These include complex terrain, rubble, moving objects, diffracting light, environmental sounds, temperature, humidity, CO_2, wind, gas, and unstable wireless conditions [98] (Table 24). The situation fields are currently simple and include, for example, flat floors, uniform lighting, and no sound. Table. 25 lists typical scenarios that appear in harsh environments; this table indicates that sound is one of the key factors in identifying the environment around a robot.

Table 24: Elements in robot evaluation field(Reprint of Table 3).

Elements	Robot	Field	Situation
Rough terrain	ground	land	rescue / home
Brightness in environment	ground / aerial / under water	every where	rescue / home / autonomous vehicle
Town or City size field	autonomous vehicle	land	rescue / autonomous vehicle
Dynamic changeable environment	ground / aerial / under water	every where	rescue / home
Wi-Fi	ground /aerial	land / midair	rescue / home / maintenance
Sound	ground / aerial / under water	every where	rescue / home / maintenance
Vibration	ground / aerial / under water	every where	rescue / home / maintenance
Touch feeling on a surface	ground	land	rescue / home / maintenance
Air flow	aerial	land / midair	rescue / maintenance
Water flow	rescue	land	rescue
Water pool	under water	sea / lake / pond	rescue / maintenance
Gas	ground/aerial	land / midair	rescue / home / maintenance
Heat	ground / aerial /under water	every where	rescue / home / maintenance

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Table 25: Scenarios, sounds and robot actions.

Scenario (In/Outdoor)	Robot	Sound	Action by hearing sound
Strong Wind (Outdoor)	Aerial Vehicle	Wind whistle	Avoid to be driven away
Old Bridge (Outdoor)	Ground Vehicle	Creaking sound	Go back
Fragile Old Floor (Indoor)	Ground Vehicle	Creaking sound	Select other ways
Sandy Soil (Both)	Ground Vehicle	Grinding sound	Slowdown to avoid slipping
Muddy Puddle (Outdoor)	Ground Vehicle	Water sound	Evacuate from pond
Rescue (Both)	Every Robot	Victim voice	Go for the voice

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5.4 robot activity scenarios for simulation with sound

5.4.1 Scenarios with sound information

Robots are used in various scenarios during emergencies, and Figure 25 shows one such scenario. The robot enters the disaster site, and the primary task is to map the inside of the site. While performing the mission however, the robot finds an injured person who requires help, and the robot operator corresponds with the person through the robot. On moving deeper inside the site, the robot operators may notice sounds relating to water and gas leaks, or unstable walls and stairs.

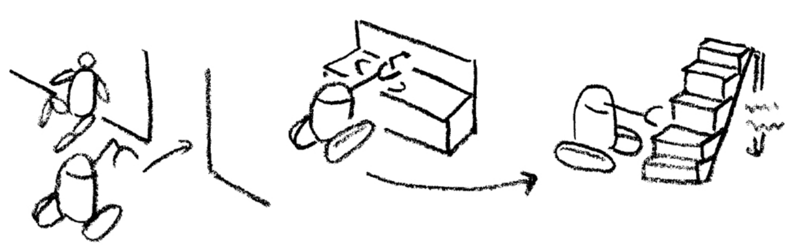

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Figure 25: Associated tasks with map generation: Helping injured people, checking leaks, and monitoring interiors.

The proposal is that the simulation platform should represent such tasks, and the illustrated scenario is composed of the following three tasks.

T1 - Search for the injured and monitor

A robot operator notices an injured person through cameras or microphones, approaches the person using the robot, and asks whether they are all right through the speakers installed on the robot. When they respond, the operator changes the robot’ s mission. The points to note are as follows:

- The injured person and operator communicate with each other about the state of the person and the surrounding environment, using the robot’ s speaker and microphones.
- When the person provides new information on the task—for example, that there are more people in the next room, or that a nearby area is completely corrupted—the information improves the rescue performance.

T2 - Gas and water leakage inspection

Laboratory buildings and factories are generally equipped with gas and water pipelines, and falling furniture can damage these pipelines. Checking for gas leaks prevents potential accidents. Sounds of leaking gas and water are important to an operator attempting to identify leaks.

T3 - Checking inside area

Damaged floors, doors, and stairs of buildings will prevent robots from moving deeper inside, and a collapse may damage the robots. The sounds generated by the robot’ s movements and NDT, are a key indicator of the possibility of collapse.

5.4.2 Sound caused interactions with environment

Sound is generated while performing the aforementioned tasks, and this information plays an important role in executing the tasks. The following are ways in which sound is generated during those tasks.

Sound 1: Communication between the robot operator and the injured person is facilitated by making the injured person (object) reply orally while the robot (operator) speaks to the object through speakers.

Sound 2: The leakage of water or gas constantly generates sound. When the operators notice the sound through microphones, they direct the robot hand to shut the valves. The operations are confirmed by the changes in sound.

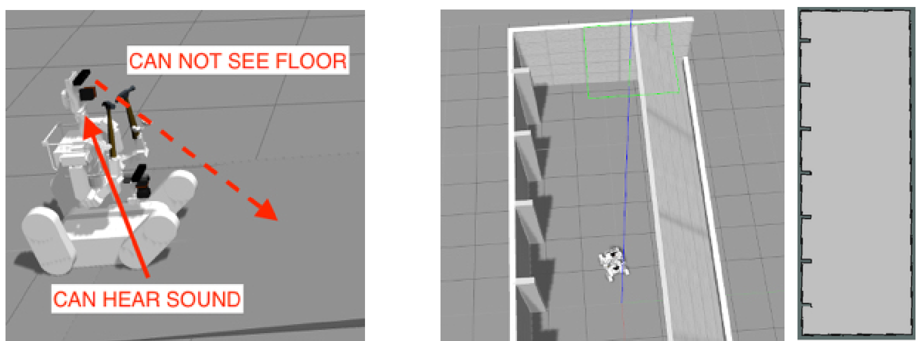
Sound 3: Sound is generated by the interaction between objects. Palpation, percussion and auscultation tests, using devices that are used to diagnose the status of targets and the sounds created by movement on unstable floors, are used to determine whether to proceed further. These sounds are created by collision between objects of robots and environments.

In some scenarios the collision between objects in a task environment generates sounds. Moreover, the manner in which a collision occurs affects the quality of the sounds [99].

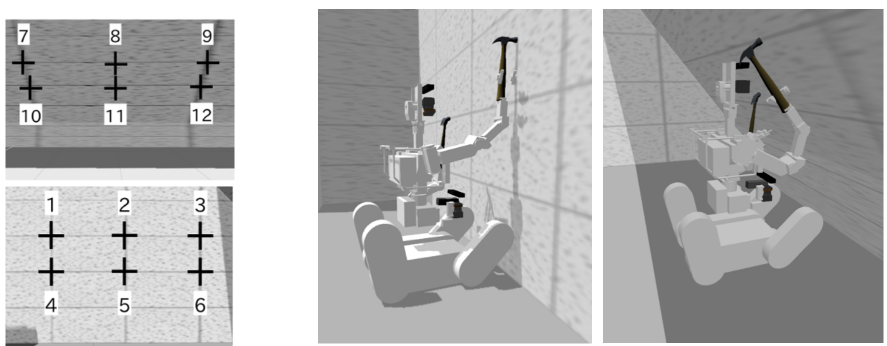
5.5 Proposed simulation environment for robot operation tasks with sound

Figure26 shows a task that using sound for an investigation robot is proposed. The mission of the robot is to map the inside of a room and inspect one wall by the hammering test. Figure26 (a) shows a centaur type robot that was used in the demonstration [100]. This type of robot won the first prize at JVRC that was held at 2015 and the hammering test was set as one of tasks. The robot has one microphone and one camera with which the operator can see ahead, but not the robot's footsteps simultaneously.

Figure26 (b) shows the overhead view of the room that the robot explores, and the map generated by the SLAM algorithm. The right wall is to be inspected by the hammering test; the lower half of the wall is vertical and the upper half is inclined at 45°. Test points on the wall are assigned for inspection , with the + signs in Figure26 (c) indicating the points to be tested. The signs numbered 1 to 6 are the points on the vertical wall, while points 7 to 12 are those on the slanted wall. The points are not actually marked on the wall during the execution of the task.



(a) Centaur robot. (b) Top view of target area and its generated map.



(c) Hammering test points. (d) Hammering on vertical and slant walls.

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Figure 26: T3 task: map generation and wall inspection (vertical and slant parts).

The operator is asked to inspect the wall by testing 12 equally spaced points. The screenshots in Figure26 (d) show how the operator controls the robot to hammer the wall, and Algorithm 2 shows the flow of robot operations.

The function `ROBOT-HAND OPERATION` is repeated during the inspection task, and a function of generating hammering sound [99] is called at every human operation; this means that the operator can determine the effectiveness of the hammering operations by listening to the generated sound. Table.26 shows the results of the hammering

```
procedure ROBOT-HAND OPERATION
    Approach assigned point
    Manipulate hand to hammer the point
    Check the hammer sound
    if The sound is abnormal then
        Repeat hammering test
end procedure
```

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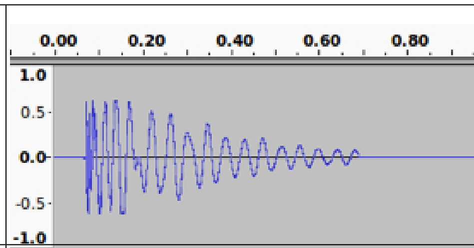
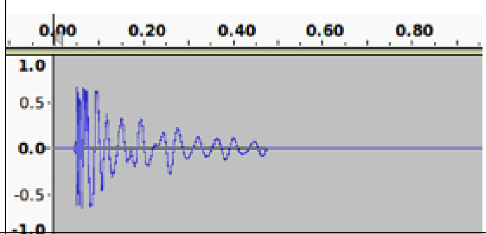
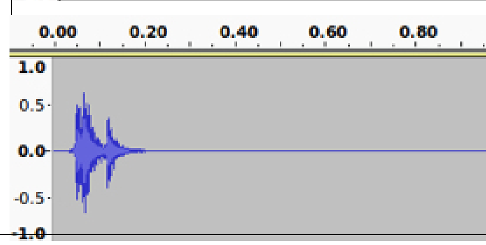
Algorithm 2: robot operations in a hammering test.

tests at points 1, 2 and 5. The second column shows the collision vectors of the hammer in system world coordinates (Σ_W). The sound waves are replayed based on algebraic quantities; the vector and speed of collisions in Σ_W that the operator who see them in the robot coordinate (Σ_R) cannot get.

The operators hear the sound of the hammer through the microphone, and are expected to judge whether the hammer strikes the wall correctly. The operations are valued using the consistency between the conditions used to generate sound, and the results of the operator decisions. For example, the operator is expected to repeat the hammering test at point 5 if the quality of the sound is incorrect. At points 1 and 2, where the hammering sounds are generated correctly, the monitored sounds are sent to the operator and are used for diagnosis of the wall integrity [101]. It is expected that the robot task would then move on to test other points. The operation action sequences are scored, and the points added to the total evaluation points awarded for task execution.

Figure27 shows the proposed simulation platform with noise from the environment. Table.27 shows sound waves with or without the sound of noise. Figure27 (a) shows a hammering test with tunnel fan noise; this situation originated from a JVRC O2 task. Figure27 (b) shows a victim search task, with the sound of road noise; this situation originated from a JVRC R12 task. The first and third rows of Table.27 show sound waves with sounds of noise from the environment. Noise increases the level of difficulty faced by the robot operator when deciding upon the next robot operation.

Table 26: Examples of sound waves monitored during the simulations.

point	collision vector in Σ_W	generated sound wave collision status	judgements of status	
			hammering	wall
1	$\begin{pmatrix} 0.11 \\ 0.96 \\ -0.26 \end{pmatrix}$		proper	good
2	$\begin{pmatrix} 0.03 \\ 0.94 \\ 0.34 \end{pmatrix}$		proper	need to be analyzed
5	$\begin{pmatrix} 0.04 \\ 0.76 \\ 0.65 \end{pmatrix}$		improper	-

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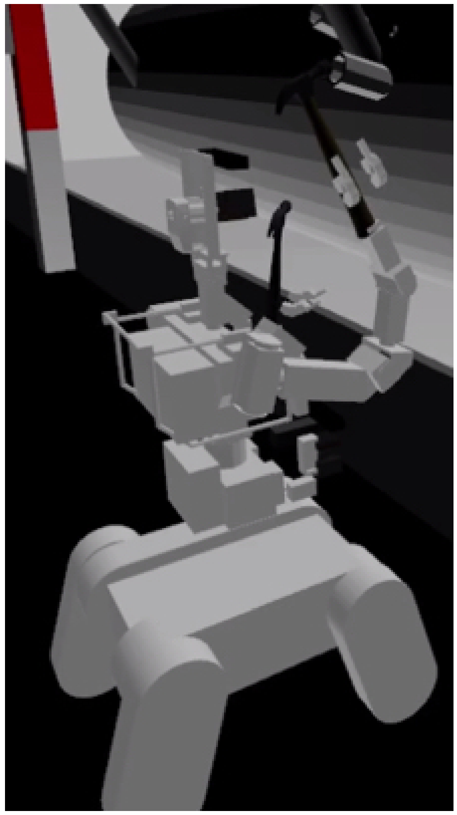
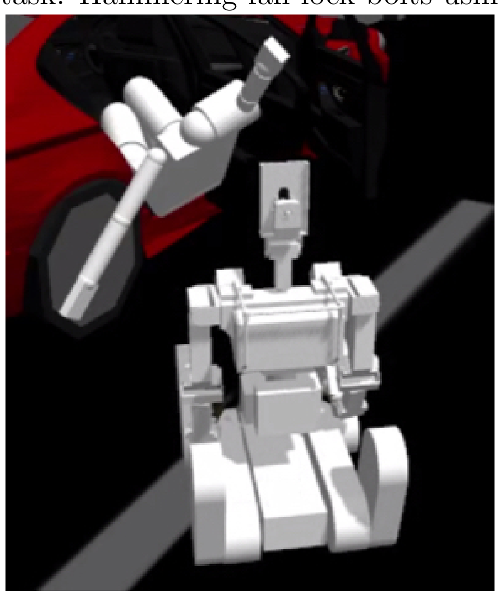


(a) O2 task: Hammering fan lock bolts using noise.



(b) R12 task: Searching for a victim using road noise.

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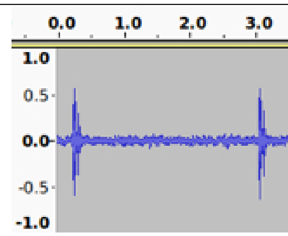
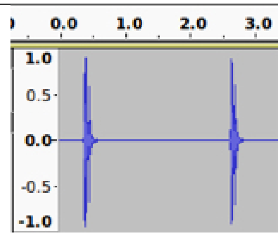
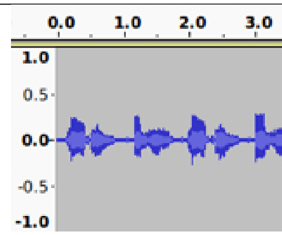
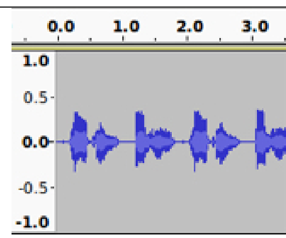
Figure 27: O2 and R12 tasks: Situations with and without noise.

Table 27: Examples of sound waves monitored during the simulations with or without noise.

JVRC task No.	noise	generated sound wave in the task	situation	source of noise	increasing difficulty with noise
O2	ON		hearing hammering sound with noise	Fan Noise	noise makes hammering retry decision difficult
O2	OFF		hearing only hammering sound	-	-
R12	ON		hearing victim help voice in noise by robot itself	Moving Robot Crawler Noise and Road Noise	The robot operator can notice the victim voice at more near point from victim than a noise less environment
R12	OFF		hearing only victim help voice	-	-

Adapted from IEEE International Symposium on Safety Security and Rescue Robotics(SSRR) 2017 ShanghaiTech University, pp.80

5.6 Summary and Discussion

5.6.1 Summary

In this chapter, a realistic simulation platform using sound was proposed, and discussed the importance of the sound information when performing operations and daily infrastructure maintenance tasks. The prototype uses a hammering test from JVRC as an example of a set of tasks. In a task, the robot operator decides upon the next course of action based on sound information. Other prototype tasks with noise from the environment incorporate an increasingly difficulty. The prototype demonstrates that the use of sound makes robot simulation applications more realistic and robust.

5.6.2 Additional discussion

Tasks in previous robot competitions were designed from the perspective of view that rescue robots are expected to operate as first responders in the event of a disaster. It has been recognized that the functionality required in rescue robots is similar in many respects to that required in service robots employed in daily infrastructure maintenance tasks. Developing robot systems that include human interaction is thought to be useful in simulating the robot movement and the interaction with human operators, simultaneously. A rescue robot controlled by an operator causes some changes in the disaster environment, and those environment changes affect the robot actions and the operator' s decisions as to the next operations of the robot. There is a reaction loop between the robot, the operator, and the environment, using natural information such as sound.

As the service robot task images in Figure 25 show, some basic functions are common in other field simulations; these include robots used in a home or industrial setting. The proposed simulation platform is not limited to rescue and maintenance tasks, but can also be applied to other fields.

Chapter 6 Conclusion

6.1 Summery of this study

This study presented proposals of new simulation method of robot evaluation environmental elements with some examples of simulation platforms, including real environmental factors that had never been used in any simulated robot evaluation platform. The effectiveness of using real environmental factors in simulated robot evaluations is revealed.

Chapter 1 described the concept of this study, the importance of a simulated robot evaluation and the relationship between robot evaluation and real environment factors through actual examples from some major robot competitions.

Chapter 2 presented a sample exercise simulation field for robot operators. A robot operator team could have team exercise time in the simulation platform. Communication between operators is important in multiple-robot operations, especially in places where it is difficult for robots to pass. It is preferable to pair members of a well-skilled group, and the performance of a pair led by a well-trained operator is better.

Chapter 3 showed that generated obstacles of differential difficulty can be generated, and a better map can be generated by SLAM, depending on the terrain, without corrected range information. An evaluation field for evaluating the performance of rescue robots using simulations was proposed. From the experiments involving mapping with SLAM, the results of the SLAM performed on rough terrain are distorted and difficult to read, compared to the results on flat floor. This revealed the effectiveness of the proposed evaluation field.

Chapter 4 described a simulated fluctuating Wi-Fi radio behavior and a sample simulation platform with Wi-Fi environment. It is possible to make fluctuating Wi-Fi zones to evaluate the autonomous ability. Two experiments demonstrated the effectiveness of the proposed method. The first experiment revealed that the proposed radio-wave fluctuation simulation closely matched the actual fluctuation behavior. The second experiment showed that the proposed Wi-Fi simulation of the simultaneous fluctuation and diffraction of the Wi-Fi signal behavior resembled the actual signal behavior. The experiments showed that the proposed Wi-Fi test field, considering the fluctuations of Wi-Fi signals, could evaluate the response robots intended for use in disaster zones before they are actually deployed.

Chapter 5 presented a realistic simulation platform using sound, and discuss the importance of the sound information when performing operations and daily infrastructure maintenance tasks. The prototype platform for reproduction of sound showed a sample representation of hammering test tasks. In the represented hammering task, the robot operator decides upon the next course of action based on sound information as same as in the real hammering task. And other prototype tasks were showed sound representations with noise from the environment incorporate an increasingly difficulty. Those sound prototype platforms demonstrate that the use of sound makes robot simulation applications more realistic and robust.

6.2 Discussion

Owing to the growth of the robot market, shortening of the development cycle and performance evaluation items are required not only for response robot development but also for general-purpose robot development. The robot simulation platforms are effective for qualitative performance evaluation such as robotic algorithms and robot behaviors. If the performance evaluation of the robot in the simulation is feasible, there are many items that can automatically evaluate the performance that the robot should satisfy, which can shorten the development period of the robot and reduce the development cost. The dynamic environmental change method proposed in Chapter 2 in the operator training environment is effective not only for operator training, but also for evaluating autonomous safe behavior of the robot. The method of reproducing the shape change of the terrain proposed in Chapter 3 is effective not only for the evaluation of sensing performance like SLAM but also for the mobility evaluation of robots. It is also effective for evaluating autonomous robots and multicopters with a wide range of movement, by using Wi-Fi wireless fluctuation reproduction method proposed in Chapter 4 to construct a changing Wi-Fi connection behavior. By using the sound environment reproduction method proposed in Chapter 5, it is possible to construct an evaluation environment in which the difficulty level of sound information changes due to noise even in simulation, and it is possible to evaluate the response of robot and operator against to the environmental information by sound.

6.3 Future works

Figure 28 shows that rescue robot evaluation items can also be applied to home robots and service robots. Adjusting evaluation items due to some differences caused by evaluation environment of new category robots will lead developments of new evaluation items for rescue robots. In the future, the simulated reproduction of heat, gas, and vibration propagation is becoming increasingly important. And the number of kinds of evaluation in simulation platform will be increased not only for mobility but also for automatic generating mapping, multi-robot collaboration, robot-human interface, stability of robot behavior in losing Wi-Fi connection, sustainability of standalone mission and so on. I believe that this study can contribute to the development of research on robot evaluation in the future.

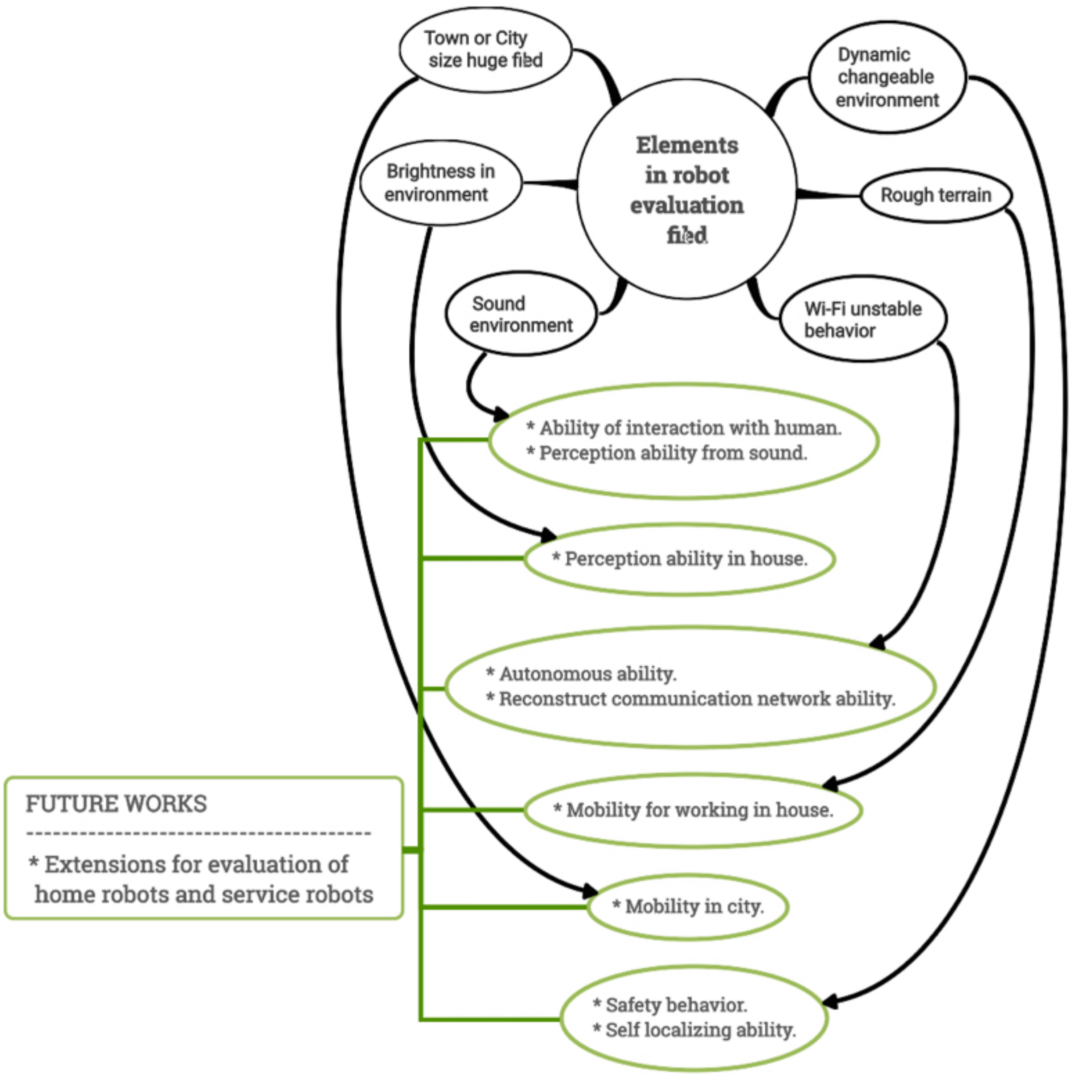


Figure 28: The remained elements of robot evaluation from this study.

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