Redesign of rescue mobile robot Quince
–Toward emergency response to the nuclear accident at Fukushima Daiichi Nuclear Power Station on March 2011–

Keiji Nagatani, Seiga Kiribayashi, Yoshito Okada, Satoshi Tadokoro

Tohoku University
6-6-01, Aramaki-Aoba, Aoba-ku,
Sendai, Miyagi 980-8579, Japan
keiji@astro.mech.tohoku.ac.jp

Takeshi Nishimura, Tomoaki Yoshida, Eiji Koyanagi

Chiba Institute of Technology
2-17-1, Tsudanuma, Narashino,
Chiba, Japan
koyanagi@furo.org

Yasushi Hada

Kogakuin University,
1-24-2, Nishi-shinjuku,
Shinjuku-ku, Tokyo, Japan
had@cc.kogakuin.ac.jp

Abstract — On March 11, 2011, a massive earthquake and tsunami hit eastern Japan, particularly affecting the Tohoku area. Since then, the Fukushima Daiichi Nuclear Power Station has been facing a crisis. To respond to this crisis, we considered using our rescue robots for surveillance missions. Before delivering a robot to TEPCO (Tokyo Electric Power Company), we needed to solve some technical issues and add some functions to respond to this crisis. Therefore, we began a redesign project to equip the robot for disaster response missions. TEPCO gave us two specific missions. One was to explore the inside and outside of the reactor buildings to perform dose measurements. The other one was to sample contaminated water and install a water gauge in the basement of the reactor buildings. To succeed in the above two missions, we redesigned our mobile robot, Quince, and performed repeated operational test to improve it. Finally, one of the robots was delivered to the Fukushima Daiichi Nuclear Power Station on June 20, 2011. In this paper, we will introduce the requirements for the above two missions and report how we fulfilled them.

Keywords: *Rescue robot, Disaster response*

I. Introduction

On March 11, 2011, a massive earthquake and tsunami hit eastern Japan, particularly affecting the Tohoku area, and claimed many lives. Furthermore, the Fukushima Daiichi Nuclear Power Station was also damaged, and resulting in meltdown accidents and the release of radioactive material. This emergency is still continuing (June 2011).

In this emergency, the first disaster response mission was to check on the damage to the target environment, including dose measurements at the disaster site. However, the site, including the outside and inside of the nuclear reactor buildings, is very dangerous for humans because of the potential for high radiation exposure. Therefore, there is a great need to use mobile robotic technology for such exploration missions, instead of humans.

Our joint research group with support from NEDO (New Energy and Industrial Technology Development Organization) has been researching and developing tracked robots to assist rescue crews in search and rescue missions in dangerous environments [1]. Some of the robots that we have developed, called Quince, are designed for practical use in search and rescue missions. The Quince was waterproof and highly mobile over rough terrain. However, its hardware reliability, communication, and basic sensors were not sufficient to employ it as part of the disaster response in Fukushima. Therefore, we began a project to redesign the Quince robot.

The first disaster response task given to us by TEPCO (Tokyo Electric Power Company) was an exploration and dose measurement mission inside and outside the reactor buildings that were seriously damaged. In this mission, we needed to consider the following issues:

1) **Hardware reliability**
   It was impossible for us to control the robot ourselves. Instead, operators from TEPCO needed to tele-operate it. This meant that the robot would be controlled by a novice operator, who might damage it. Furthermore, once the robot was given to TEPCO, it was impossible for us to maintain the robot. This was because the robot was going to be exposed to radiation, making it unacceptable for us to maintain the robot after delivery to TEPCO. Considering the above situation, we needed to ensure that the hardware used for our robot was very reliable.
2) **Communication reliability**
   In NEDO's project, we developed a hybrid mesh network that included a wired mesh network and wireless mesh network for multi-robots tele-operation over a wide area [2]. In this mission, the target area was not very large. However, the reactor buildings contain very thick concrete walls that block gamma rays, making it highly probable that they would block radio communication. Therefore, non-wireless communication was required to maintain the reliability in this mission.
3) **Checking radiation hardness**
   In comparison with other disaster situations, a feature of this mission was high radiation exposure. Our robot was composed of conventional electric devices, and we had

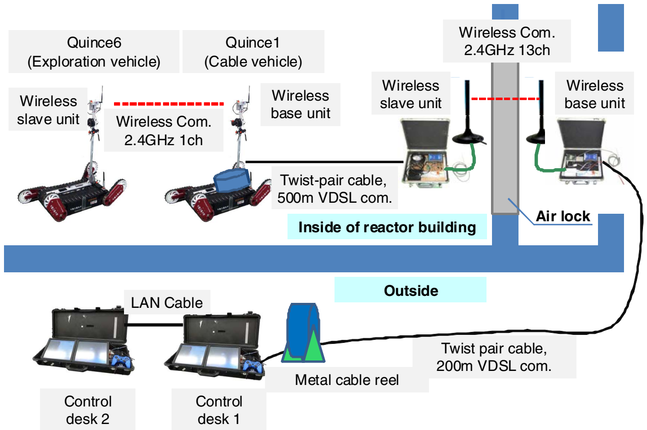

Fig. 1. Overview of configuration proposal for dual-robot system.

very little information about how well it would survive exposure to gamma rays. We will report the results of a gamma-ray irradiation test of the electric components that we performed in another study.

4) **Additional sensors**
One of the important requirements in this mission was to equip Quince with a dose measurement function, which the original robot lacked. Furthermore, 3D mapping was a very good tool for understanding the disaster environment. Therefore, some modifications of the sensors were required.

5) **Easy tele-operation for first responders**
In this mission, it would be impossible for skilled operators from our research group to operate the robot directly, as described above. Therefore, a good user interface for tele-operation was required for first responders.

During our redesign of the robot (called the Fukushima-version Quince, in this paper), TEPCO gave us an additional specific urgent mission. It included (1) a contaminated water-sampling task and (2) a water-gauge installation task in the basement of the reactor buildings. In this extra mission, we needed to consider the following issues:

6) **Manipulation function**
The task required an object handling such as a scooping motion for water and installing a water gauge. Therefore, an additional manipulator needed to be mounted on the robot.

7) **Countermeasures against overweight**
It was necessary to mount additional equipment on the robot, including the manipulator. Thus, we needed to consider an overweight problem, because we did not assume the presence of such heavy functions/sensors on the robot in its original design.

Finally, we redesigned the robot and after training TEPCO's operators, it was delivered to the Fukushima Daiichi Nuclear Power Station on June 20, 2011.

In this paper, we will introduce the requirements of the two missions and report how we fulfilled them.

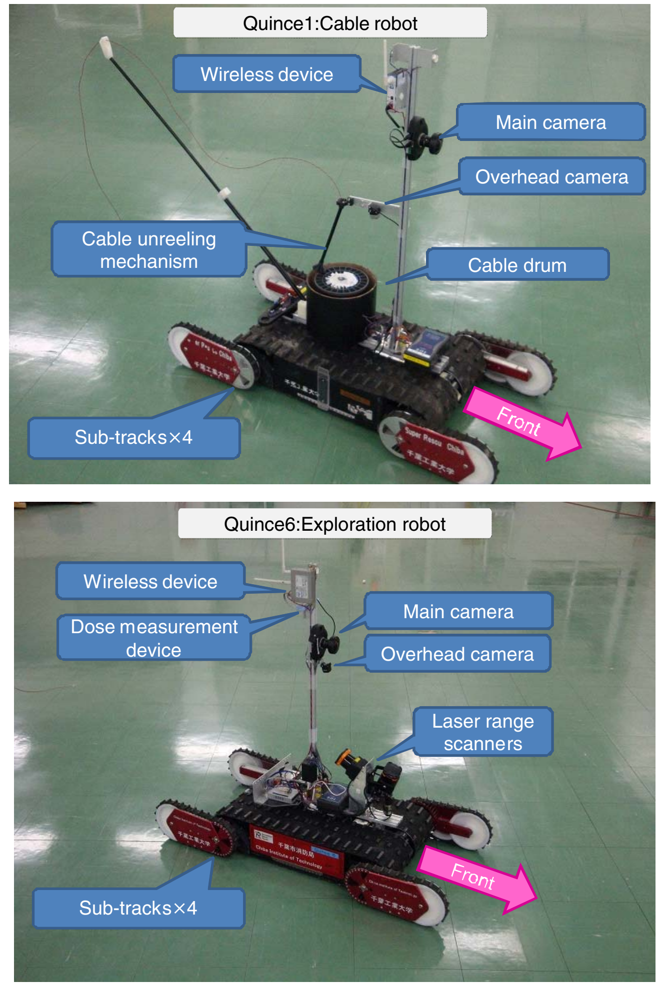

Fig. 2. Overview of cable robot (upper) and exploration robot (lower).

II. Approach for First Mission

As shown in the introduction, the first mission was to perform exploration and dose measurement inside and outside of the damaged reactor buildings. For the operator's safety, an operation box for the operator controlling the robot needed to be located as far from the target area as possible. However, the target environment included thick concrete walls, a reactor vessel, and higher elevations. In such an unfriendly environment for transmitting and receiving radio waves, we judged that conventional wireless communication was unsuitable for this mission.

To secure a reliable communication, we configured a communication system using a wired/wireless combination network, which was a simple version of the hybrid mesh network that we developed in NEDO's project. Figure 1 shows an overview of our proposal at the beginning of May 2011. (Note that our configuration proposal had been extensively revised because the situation had changed in Fukushima.) Two developed robots, a cable laying robot and exploration robot, are shown in Fig.2. The details for the items used in the redesign are shown in the next section.

III. Redesign items for mission

The changes from the original Quince are itemized in the following:

A) Additional hardware and sensors
B) Improvement in reliability of the power supply system
C) Wired/wireless combination network
D) Simplification of operating procedure
E) Improvement of the tele-operation system.

We will report on the above topics in detail, in the following.

A. Additional hardware and sensors

1) **Dosimeter**
   Dose measurement was one of the basic tasks in this mission. However, obviously, the original Quince did not have a dose measurement function. Therefore, we mounted a conventional digital dosimeter (CPXANRFA-30, Fuji Electric Co., Ltd.) at a height of 1.2m, which was almost the same height as internal organs of a human. To read the value displayed on this sensor, we used a CCD camera located very close to the dosimeter.
2) **Main camera**
   In an original Quince, we typically mounted an optional pan-tilt-zoom camera, Axis 213 PTZ. However, this camera has movable parts that may be broken easily. Furthermore, it is not waterproof, and it would be difficult to make it waterproof because of the movable parts. Therefore, we replaced it with an AXIS212 PTZ camera. This uses a wide-angle lens combined with a three mega pixel sensor and realizes instant pan/tilt/zoom by clipping an image from the high-resolution image without any mechanical motion.
3) **LED light**
   To obtain useful images when using the cameras in a dark environment, lighting was very important. At the beginning of our implementation, we just attached a light source that was purchased in a climbing gear shop. However, it was not sufficient. Therefore, we mounted two LED lights (7 W each) in front and back, along with extra IDX battery (IDX Endura 7, 14.8 V, 4.8 Ah).

B. Improvement in reliability of power supply system

In the power supply system of the original Quince, there were safety measures to protect from overcurrent. When an operator commanded the robot to perform an unreasonable motion, the power supply system was stopped to protect the DC-DC converters and avoid motor malfunctions. The IDX battery (IDX PowerCube 14.8V 5.7Ah) that the Quince used also had a circuit breaker function that used a poli-switch. Unfortunately, it could not return to normal operation until the main switch was turned off and then back on. This was a very serious problem because the robot might stop and wait for the operator's off-and-on action in the reactor building.

To solve this problem, we added a small electric circuit that watched the battery voltage. When the voltage dropped below a threshold, the circuit performs an off/on action for the main power switch every 2 s.

Fig. 3. Cable reel-out mechanism.

Furthermore, in rare cases, the PC was not booted, even if the power supply system worked correctly. If this occurred during the above off/on action, the robot never worked. To avoid this risk, we added another function to the small circuit. In a case where the startup beep sound was not detected within 10 s, it performed the off/on action for the main power switch.

We installed the above small circuit in the Fukushima-version Quince and confirmed the rebooting function caused by a shutdown of the batteries.

C. Wired/wireless combination network

In this project, we decided to basically use a wired network for the tele-operation of the robot. However, in the target environment, there are double-entry doors, called an air lock, to prevent internal air from flowing outside. When considering this mission, the air lock should not be left open. Therefore, the communication needed to be established through the air lock without a cable. Furthermore, the exploration robot needed to be capable of gathering information without a cable.

Based on the above, we proposed and configured a wired/wireless combination network, as shown in Fig.1. The control boxes of the robots were supposed to be located outside the building, and a 200 m twisted-pair metal cable and VDSL (Very high-bit-rate Digital Subscriber Line) devices (NVF-200LS and NVF-200R: NetSys) were used to establish communication between the control boxes and the device that was located in front of the air lock (outside). To communicate through the air lock, we used 2.4GHz wireless communication devices (FXDS540STDMS, Contec Co., Ltd.). Between the cable robot and the device located in front of the air lock (inside), we also used a 500 m twisted-pair metal cable with the VDSL devices. The cable on the robot was reeled out when the robot moved forward, passively. Between the cable robot and exploration robot, we used 2.4 GHz wireless communication. The radio field strength of the communication was beyond the limitation set by Japanese law (10 mW/MHz), by permission of the Japanese government. This enabled about 2 km tele-operation of the robot from an unobstructed view outside. Figure 3 shows the cable reel-out mechanism mounted on the cable robot.

D. Tele-operation

The operation box for the original Quince is composed of two 15 inch touch-panel LCDs (liquid crystal displays), a game pad, and one PC (Aspire Revo: Acer, Atom, ION), packed in a pelican case (1700). The reference rotational velocities of the mounted motors would be specified by the game pad and sent to the robot. The battery voltage, internal temperatures of the robot, and images obtained by four cameras were sent to the operation box and displayed on the LCDs.

In this project, however, we could not use the above hardware, because the box was too large to use in the target field. Furthermore, one of our members would not be the operator. Thus, the operating procedures for the robot needed to be simplified. Therefore, we developed a new operation box for the two robots' tele-operation, which was composed of two PCs (Toughbook CF-30 mk1, Panasonic) and two game pads packed in a pelican case (1700). Then, we installed additional functions in our operation software, as follows:

1) An automatic recovery function in the case of instantaneous interruptions,
2) A motion function to return the sub-tracks to a prescribed pose,
3) An extra button to acquire all of the sensor data at once,
4) A screen capture function for the whole mission,
5) A function to display the poses of the robot and sub-tracks,
6) A real-time display of the scanned 3D range data.

When we installed the above functions, display-layout became one of the most important issues. For example, an additional function might cause a large change in the layout of the display. Therefore, we installed an adaptable layout-setting function in the operation software. Figure 4 shows a display layout for the exploration robot, which mounted a 3D laser range scanner [3].

E. Operation test

After the redesign of our mobile robots, we performed initial tests and repeated operational tests, and used feedback in our system-design to improve our robot system.

At the end of April 2011, the redesign project was almost completed. For example, two non-skilled operators from our group succeeded in carrying out a stable exploration task using the dual-robot system shown in the previous section. The target environment was the depot on the 1st floor of building 11 in Shibazono campus, Chiba Institute of Technology. The environment was about 100 m long and was dark at night. It included many racks, which formed a kind of maze, along with some obstacles to be surmounted and steep stairs.

Furthermore, in May 2011, TEPCO's staff joined in the tests to train for its operation. They also provided feedback to improve the system.

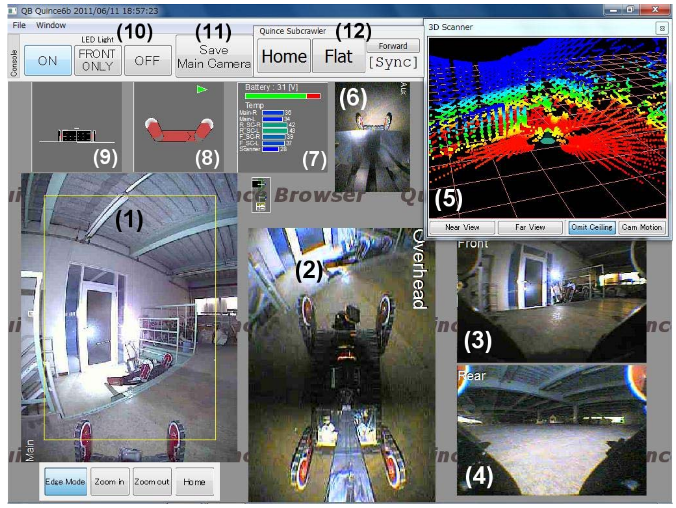

Fig. 4. Display layout of the operation software for exploration robot: (1) main camera view, (2) overhead camera view, (3) front camera view, (4) rear camera view, (5) 3D laser range scanner view, (6) dosimeter view (not installed yet), (7) battery indicator and temperature display, (8) pose of robot (pitch) and sub-tracks, (9) pose of robot (roll), (10) LED light switch, (11) total data acquisition button, (12) button for returning sub-tracks to prescribed-pose.

IV. Extra mission statement

By the end of the redesign project for the mission from TEPCO, the demand in the field had changed slightly, and an extra mission was proposed by TEPCO that was urgent. This involved sampling contaminated water and installing a water gauge in the basement of the reactor buildings. The mission was supposed to be performed by a single robot.

To complete this extra mission, we needed to consider an additional manipulation function. Therefore, we mounted a simple 2 DOF (degrees of freedom) manipulator on one of the Fukushima-version Quinces. Additionally, we equipped the robot with a water-gauge/sampling-bottle handling function.

Furthermore, the target stairs to the basement of the reactor buildings posed a greater challenge. They were too narrow to use passive cable-reel-out function with tangle-free motion. Therefore, we added an active cable rewind function.

During the above development, we needed to consider countermeasures against overweight. As shown in the introduction, we did not consider the use of such heavy functions/sensors on the robot in its original design. Finally, the Fukushima-version Quince with a manipulator reached a total weight of about 50 kg.

V. Redesign issues for the extra-mission

A. 2 DOF manipulator

In this project, we needed to develop a robot system rapidly to respond to the given mission as soon as possible. Therefore, we decided to develop a very simple 2 DOF manipulator just for this mission. Figure 5 shows an illustration of the mission scene, and Fig.6 shows a photograph of the developed manipulator. It had two actuators for pitch angle and yaw angle. The top limb of the manipulator was supported by a parallel linkage, and the tip of the manipulator was always

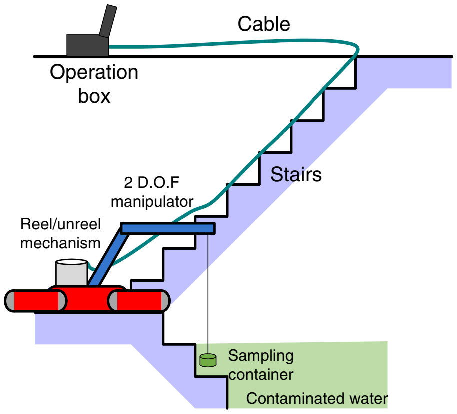

Fig. 5. Illustration of mission scene using 2 DOF manipulator.

Fig. 6. Photograph of developed 2 DOF manipulator with water gauge.

positioned perpendicular to the bottom plane of the robot. A CCD camera and a LED light (1 W) were mounted at the tip, and a sampling container (or a water gauge) was reeled out.

B. Handling function for water gauge/sampling bottle

To install a water gauge in the contaminated water in the basement of the reactor building, we needed to have a reel-out mechanism for the cable of the gauge. Furthermore, a sampling bottle to be moved up and down to sample the water. Therefore, we installed a crane mechanism at the tip of the manipulator to realize both of these functions.

C. Active cable-rewind-function

To enable tangle-free motion of the communication cable for the cable robot on the narrow stairs, we needed to add a cable rewind function to go back up the stairs. It was possible

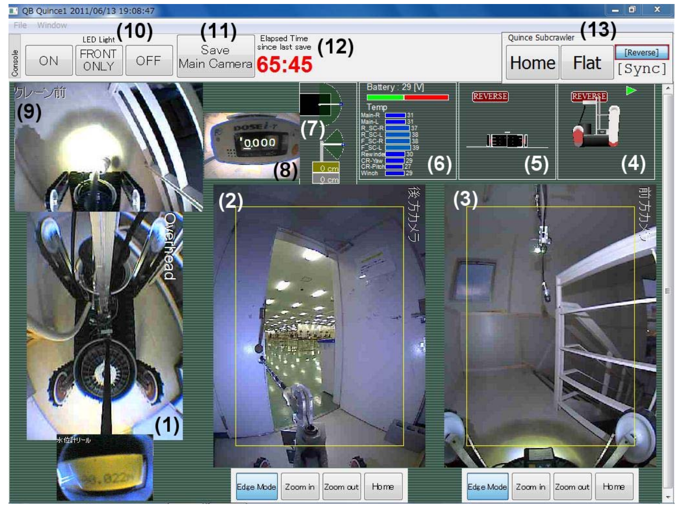

Fig. 7. Display layout of operation software for cable robot with 2 DOF manipulator: (1) overhead camera view, (2) rear camera view, (3) front camera view, (4) pose of robot (pitch) and sub-tracks, (5) pose of robot (roll), (6) battery indicator and temperature display, (7) pose of 2 DOF manipulator, (8) dosimeter view, (9) crane camera view, (10) LED light switch, (11) total data acquisition button, (12) mission timer, (13) button to return sub-tracks to prescribed pose.

for us to realize a tension based automatic reel control for the cable. However, we installed a teleoperated cable rewind function because rapid development was required at this time. When an operator sent a rewind command to the robot, the rewind function began. The torque of the rewind mechanism had a limitation, so that there was no risk of a tensile cut of the cable.

D. Improvement in tele-operation software

Accompanying the additional mechanisms of the robot, the tele-operation software was also changed. Figure 7 shows a display layout for the cable robot that mounted the 2 DOF manipulator.

Furthermore, to return up the stairs, we installed a reverse mode that enabled the switching of the front and rear cameras, flipping the pose-display of the robot between left and right, and sending inverted commands to the robot. Thus, the operator could control the robot as if the rear of the robot was its front.

E. Countermeasures against overweight

After development the above mechanisms, including the 2 DOF manipulator, the weight of the robot became about 50 kg. It was obviously overweight because the original Quince was 27 kg. To respond to the problems caused by this extra weight, we performed the following operations.

1) Load mitigation and heat check of motors
   In the extra-mission, the robot was typically on the stairs, and its weight was increased. Therefore, we increased the reduction ratios of the locomotion motors to mitigate its load. Furthermore, we put heat sensors on the motors to check their temperatures and increase their reliability.

Fig. 8. Impact absorption mechanism. The left side of the photograph shows the original one, which is broken. The absorption material is offset to the corners, and a phase shifting occurs (about 45 degree). The right side of the photograph shows the improved version.

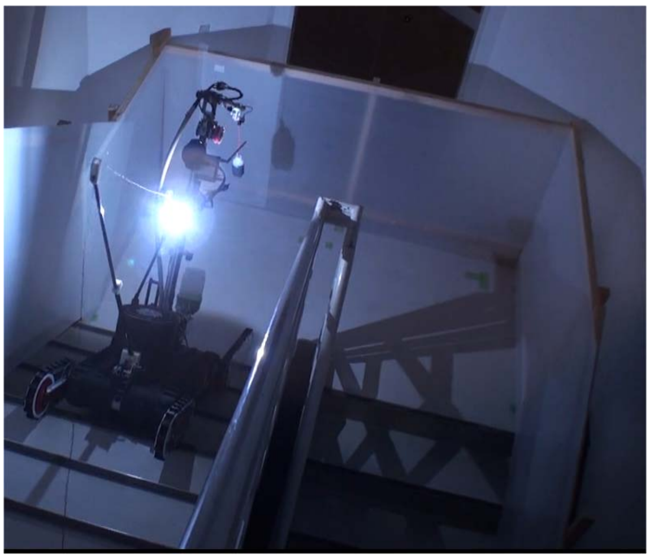

Fig. 9. Operational test scene of Fukushima-version Quince on stairs.

2) Improvement of impact absorption mechanisms for sub-tracks
In an original Quince, the impact absorption mechanisms were located at the joints of the sub-tracks to prevent motor malfunctions. However, during the initial tests of the Fukushima-version Quince, one of the mechanisms was dead, as shown in the left side of Fig.8. To avoid this situation, we replaced the nylon used as the impact absorption material with rigid urethane foam. However, in the case of the destruction of the impact absorption material, the joint might still malfunction. That is because the center component would rotate freely after the destruction of the material. Therefore, we made the center component slightly larger, as shown in the left side of Fig.8.
3) Substitution of long sub-tracks
When we performed steep stair-climbing tests using the Quince with the 2 DOF manipulator, it slipped many times. Therefore, we developed and installed long sub-tracks on the robot for pressure dispersion.

With the help of the TEPCO, we performed many tests. Their feedback was also included into the system.

F. *Operation test*

After May 26, 2011, we began operational tests for the extra mission. It was much more difficult than the first mission, because it included many tasks. An operational test scene on stairs is shown in Fig.9. One of the most difficult parts was turning at the narrow staircase landings without hitting the manipulator. The cable rewind mechanism worked effectively to assist the operator. Although it was originally designed just for stair climbing, it also worked fine during standard explorations.

VI. Summary

In this paper, we described two missions given to us by TEPCO as apart of the disaster response in the Fukushima Daiichi Nuclear Power Station and reported on the redesign of our rescue robot to enable it to perform these missions.

The modifications included the following:

A) Additional hardware and sensors,
B) Improvement in the reliability of the power supply system,
C) A wired/wireless combination network,
D) Simplification of operating procedures,
E) Improvement of the tele-operation system,
F) Construction of a 2 DOF manipulator,
G) An additional crane function for a water gauge/sampling bottle,
H) An active cable rewind function,
I) Improvement of the tele-operation software,
J) Countermeasures against overweight.

After their redesign for these exploration missions, on June 20, 2011, one of the Quinces was offered to the Tokyo Electric Power Co., for use in the actual disaster field. We hope that it will contribute to breaking away from this emergency.

Acknowledgement

We would like to thank NEDO and the Chiba Institute of Technology for the financial support needed to proceed with this research.

References

[1] Eric Rohmer, Tomoaki Yoshida, Kazunori 0hno, Keiji Nagatani, Satoshi Tadokoro, and Eiji Konayagi. Quince: A collaborative mobile robotic platform for rescue robots research and development. In *Proceedings of the 5th International Conference on the Advanced Mechatronics (ICAM2010)*, pages 225–230, 2010.

[2] Keiji Nagatani et. al. Development of a networked robotic system for disaster mitigation -system description of multi-robot system and report of performance tests-. In *Proc. of the 6th Int'l Conf. on Field and Service Robotics*, pages 333–342, 2007.

[3] Tomoaki Yoshida, Kiyoshi Irie, Eiji Koyanagi, and Tomono Masahiro. 3d laser scanner with gazing ability. In *IEEE International Conference on Robotics and Automation, WeA204.4*, 2011.