Improvements to the Rescue Robot Quince Toward Future Indoor Surveillance Missions in the Fukushima Daiichi Nuclear Power Plant

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Abstract On March 11 2011, a huge earthquake and tsunami hit eastern Japan, and four reactors in the Fukushima Daiichi Nuclear Power Plant were seriously damaged. Because of high radiation levels around the damaged reactor buildings, robotic surveillance were demanded to respond to the accident. On June 20, we delivered our rescue robot named Quince which is a tracked vehicle with four sub-tracks, to Tokyo Electric Power Company (TEPCO) for damage inspection missions in the reactor buildings. Quince needed some enhancements such as a dosimeter, additional cameras, and a cable communication system for these missions. Furthermore, stair climbing ability and user interface was implemented for easy operation for novice operators. Quince have conducted six missions in the damaged reactor building. In the sixth mission on October 20, it reached to the topmost floor of the reactor building of unit 2. However, the communication cable was damaged on the way back, and Quince was left on the third floor of the reactor building. Therefore, an alternative Quince is requested recently. In this paper, we report the situation of the missions for Quince, and introduce enhancements of the next Quince for future missions.

1 Introduction

On March 11, 2011, a huge earthquake and tsunami hit eastern Japan, and four reactors in the Fukushima Daiichi Nuclear Power Plant were seriously damaged. There were explosions in three reactor buildings, and a large quantity of radioactive materials was released. The operator of the power plant, Tokyo Electric Power Company (TEPCO), was unable to manage the situation because of the high radiation levels

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measured around the perimeter of the reactor buildings, which prevented people from safely entering the affected areas. They ware unable to plan the best approach for handling the crisis because the situation inside the building was unknown. Therefore, robotic surveillance was required.

The first robot that entered the reactor building was Packbot [1], which was developed by iRobot. On April 17, Packbot opened an airlock gate, which was composed of dual doors, and investigated the situation on the first floor of the reactor buildings [2, 3]. The result of the mission confirmed fears that the radiation dosage in the building was very high humans would have been able remain there for only a short time. Packbot was controlled via a radio communication system, and the radio waves could reach only some parts of the first floor. Furthermore, Packbot could not climb up or down the stairs. Therefore, even after the Packbot mission, TEPCO still needed a robotic surveillance system that could cover extensive areas in the building.

At that time, our joint research group, supported by the New Energy and Industrial Technology Development Organization (NEDO), had been researching and developing tracked robots to assist rescue crews in search and rescue missions in dangerous environments. Quince, the robot developed by us, has high mobility on rough terrains. However, it could not have been mobilized to the reactor building at the time of the crisis because it needed to be reconfigured for the target environment. Therefore, we began to redesign the Quince to resolve the following concerns, which enabled it to be used for surveillance in the reactor building [4].

Communication system At the beginning of the project, we did not know whether the wireless communication system would have been able to control the robot in the reactor building from the outside. We conducted communication tests in the reactor building of the Hamaoka Nuclear Power Plant, which was of the same model as the reactor in the Fukushima Daiichi Power Plant. The test result suggested that a wireless communication link was possible in only a very limited area, so we decided to develop a cable communication system.

Radiation tolerance Our robot was composed of conventional electric devices, and we had very little information about how well it would survive when exposed to gamma rays. Therefore, we conducted experiments to ascertain the radiation tolerance of the components of Quince [5]. The results showed that the essential components of Quince can survive up to 160 Gy of radiation dose.

Reliability We would not have been able to maintain Quince directly after its delivery to the site. Therefore, we focused on improving the reliability of its mechanisms, components, and software by performing numerous tests in a test field.

Operability A good user interface for remote operation was required for Quince to be used by the operators from TEPCO, who had not undergone prior training in its use. This was also significantly improved by performing tests.

Additional sensors In this mission, dosimeter readings were very important. Small dosimeters were supplied by TEPCO and were mounted on Quince. The dosimeters used were the same device used by humans and clipped onto the chest pocket in nuclear power plants. The measured value is displayed on the embedded display of the device, but the device has is unable to communicate with external devices. Therefore, we attached a small camera close to the display for transmitting display images to the operator.

Moreover, at the beginning of May 2011, TEPCO requested two more functions to be added to Quince. At that time, water had been continuously injected into the primary pressure vessels to cool down the fuel core, and the contaminated water had spilled onto the basement floor. It was not possible to measure the depth of water in the basement floor. Thus, functions to install a water level gauge and to sample the contaminated water needed to be added to Quince. Therefore, the following enhancements were added.

Additional functions A simple manipulation mechanism was mounted on Quince. The mechanism included a crane and a winch to install a water level gauge, and a simple mechanism for handling a water-sampling cup.

Mobility improvement For the revised target, the stairs leading down to the basement floor were steeper and narrower than those leading to higher floors. Because of such difficult to maneuver terrain, the robot was required to have a more enhanced stair-climbing ability. Therefore, we optimized its track mechanisms.

On June 20, 2011, the redesigned Quince (Quince 1) was deployed to the Fukushima Daiichi Power Plant. After that, Quince 1 conducted six missions in the damaged reactor buildings. The results of the missions contributed significantly to efforts to restore the plant to a degree of normalcy. However, in the process of doing this, some unforeseen technical issues developed.

The first important issue concerned its communication cable. On October 20, 2011, Quince 1 was left inside the reactor building after its sixth mission because the communication cable failed. The cable rewinding device on Quince 1 was not designed to rewind very long cables. During the mission, Quince 1 had navigated a very long course, and while attempting to rewind the cable, the rewinding device failed and damaged the cable. This limitation and failed operation contributed greatly to the loss of communication.

The second important issue concerned the requirement of additional functions. TEPCO requested a new mission to sample air dust after the first mission by Quince 1 ended. They attached timer-triggered air pumps on Quince 1 to conduct the mission. In this case, the operator was required to direct Quince 1 to the target location within a specific time period, and this was very stressful for the operator. The ability to remotely trigger the air pump would have simplified this process.

Through the six missions, we also identified many others issues that needed improvement, and TEPCO requested an alternative Quince model. Therefore, we developed a revised model of Quince that dealt with the above issues. In addition, to address the communication cable problem, we defined a communication recovery scenario by providing another robot that acts as a communication repeater to re-establish a data link to Quince via a wireless link between the robots.

In this paper, we report the missions performed by Quince 1 in a real disaster site and discuss issues that arose during the missions. Furthermore, we introduce a revised model of Quince that is able to resolve earlier issues and perform a communication recovery scenario.

Table 1 A brief timeline of missions for Quince 1

Date	Event
June 20, 2011	Quince1 was delivered to the site
June 24, 2011	The first mission at unit 2 was conducted. Quince was not able to install a water level gauge
July 8, 2011	The second mission at unit 2 was conducted. Quince was reached the third floor of the building and two sets of air dust samples were successfully captured
July 26, 2011	The third mission at unit 3 was conducted. Target facilities were successfully observed
September 22, 2011	The forth mission at unit 2 was conducted. Target facilities were successfully observed
September 24, 2011	The fifth mission at unit 3 was conducted. Target facilities were successfully observed
October 20, 2011	The sixth mission at unit 2 was conducted. Quince was successfully reached the fifth floor. However it lost a data link at the third floor on its way back

2 Missions of Quince 1

In the damaged reactor buildings in the Fukushima Daiichi Power Plant, a total of six missions were conducted with Quince 1 (Table 1). Furthermore, many practice tests were performed in the reactor building of unit 5, which was not seriously damaged. In this section, we report the missions conducted in the damaged reactor buildings.

2.1 The First Mission on June 24, 2011

The first mission of Quince 1 was conducted on June 24, 2011, at the reactor building of unit 2. The objective of the mission was to install a water level gauge into the contaminated water pool on the basement floor. At that time, water had been continuously injected into the primary pressure vessels to cool down the fuel core, and the injected water had accumulated in the basement floor. An urgent mission was required to survey the status of the contaminated water pool because there was a possibility that the contaminated water could overflow and spill into the sea. To conduct this mission, Quince 1 was fully equipped with a crane, a winch, and a water level gauge.

Quince 1 attempted to descend the staircase and reached the first stair landing. However, the size of the landing was much narrower than what had been communicated to us in advance by TEPCO. In the building, there were multiple staircases to the basement floor, and Quince 1 attempted to descend two of them. However, it was impossible to navigate the landings of the first set of stairs. Ultimately, Quince 1 was unable to accomplish the objective of the first mission.

2.2 The Second Mission on July 8, 2011

The second mission was conducted on July 8, 2011, at the reactor building of unit 2 [3, 6]. The objectives of this mission were to measure the radiation levels of the upper floors and to sample air dust in the building. Quince 1 was equipped with two timer-triggered air pumps for this task. The crane and the winch were removed because they were not required for this mission.

Quince 1 climbed up the staircase and reached the third floor. During this motion, the air dust samplers were activated at the second and third floors. However, on the way back to the entry point, the motor driver boards mounted on Quince 1 encountered problems because the air temperature inside the building was extremely high. The problems were successfully resolved by sending low level commands to the motor driver boards instructing them to reboot. Finally, the robot returned to the entry point, and the second mission, which included the air sampling and dose measurement tasks, was completed. However, it had not been far from being a failure.

2.3 The Third Mission on July 26, 2011

The third mission was conducted on July 26, 2011 [3], at the reactor building of unit 3, which was heavily damaged by an explosion. The objectives of this mission were to investigate the damaged piping of the core spray system and to measure the dose levels around the facility. In the event that the damage was minimal, it may have been possible to re-activate the spray system to cool down the reactor core directly, instead of using the reactor feed water system.

Quince 1 climbed up the staircase and reached the second floor. Then it approached the target piping and captured high-resolution photographs of the target facilities. After that, Quince 1 tried to climb up the staircase to the third floor, but found that the staircase was damaged and blocked with rubble.

Figure 1 shows the high-resolution photographs captured by the wide-angle camera on Quince 1. The left photograph shows the piping of the core spray system, which was located next to the primary containment vessel. The right photograph is of the staircase to the third floor, showing the rubble blocking the staircase.

Based on the exploration results, the restoration process was planned and the core spray system was re-activated on September 1, 2011 [3, 7].

2.4 The Fourth and Fifth Missions on September 22 and 24, 2011

The fourth and fifth missions were conducted on September 22 and 24, 2011, respectively. The objectives of these missions were to inspect the first floor of the reactor buildings of units 2 and 3. The missions were a part of the preparation for the project to investigate inside the primary containment vessel using a borescope. Quince 1 explored the target area, obtained many photographs, and measured the dose rate.

Fig. 1 High-resolution photos captured in the reactor building of unit 3. The *left* shows the piping of the core spray system and the *right* shows the rubble blocking the staircase to the third floor

2.5 The Sixth Mission on October 20, 2011

The sixth mission was conducted on October 20, 2011, at the reactor building of unit 2. The objectives of the mission were to investigate the damage to the the facility on the third floor and to inspect the spent fuel pool on the fifth floor. Air temperature measurements were also a part of tasks performed during this mission, and a conventional thermometer was placed on Quince 1 within the range of vision of a spare camera on Quince 1. The camera image was displayed on the operator console.

Quince 1 climbed up the staircase and reached the third floor. Then, it approached the target facility and captured some photographs. After that, it explored the third floor to measure the radiation level, and climbed up the staircase to the fifth floor. On the fifth floor, it opened a metal accordion curtain with its sub tracks and approached the lid of the primary containment vessel. It measured the radiation level and temperature in the immediate vicinity and took photographs. The dosimeter display showed very high radiation levels (over 200 mSv/h) around the lid.

After inspection of the fifth floor, Quince 1 returned to the entry point. However, the communication cable was caught on piping on the third floor. At the same time, the cable had become jammed in the cable reel because the cable had been continuously rewound from the fifth floor. As a result, the communication cable could not be rewound or be released. Eventually, communication cable was lost and Quince 1 remains there up to the present.

3 Lessons Learned from the Missions of Quince 1

As shown in Sect. 2, the missions completed by Quince 1 contributed significantly to recovery work at the plant. Especially, its mobility and clear camera images were highly evaluated. Quince was the only robot which can climb up the staircases and explore the upper floors. Furthermore, its mobility on rough terrain was very important because there were number of obstacles such as steps, dikes, cables and debris. Still images captured by Quince are very clear and high-resolution (2048 × 1536 pixels). Therefore, Quince was chosen out of other robots for the missions on September 2011, even the targets were on the first floors of the buildings.

Aside from these advantages, the following problems were encountered.

Communication cable The most significant problem was with the communication cable. The cable rewinding device did not function properly toward the end of the sixth mission., and eventually failed causing us to abandon Quince 1 on the site. In our initial implementation of Quince, the ability to make preemptive moves was the first priority. Furthermore, we supposed that the communication cable would have been replaced after each mission, so no rewinding function was installed in the early stages of the project to redesign Quince. However, to enable the switch-back motion of the robot in narrow environments, we added an ad hoc rewinding function, which did not have the ability to wind the cable evenly. Therefore, we specified that it should not be used to rewind cables longer than 20 m. In practice, the device worked much better than we had expected, and at times rewound over 200 m of cable in trial runs. Therefore, during the real missions, longer cable exceeding 20 m was rewound.

Unknown environment In the information received from TEPCO, the the staircase landing down to the basement was reported to 91 cm wide. We built a mock environment in our laboratory using these dimensions, and tested Quince 1 in the mock environment. However, the actual width was 71 cm, and this prevented us from realizing the objectives of the first mission. The data received from TEPCO was based on the construction drawings of the building, but repeated modification to the structure of the building reduced the width of the staircase landing. However, all information pertaining to the re-construction had been washed away by the tsunami.

Carrying method Quince 1 was carried on a stretcher or by manually holding each of the sub tracks. A stretcher could not always be used because of the narrow corners en route to the entry point. After the mission in the reactor building, contaminated dust was stuck on the tracks of Quince 1. When the operators held the sub tracks to transport Quince 1, they became exposed to the radiation source from a very close range.

Additional components The request to sample air particles in the reactor building was requested after Quince 1 had been delivered to the site. The mission was conducted with two timer-driven pumps attached on Quince 1. The timer had to allow a delay time to ensure the robot's arrival at the requested position. This increased the duration of the mission. Furthermore, air temperature measurements were requested for the sixth mission. To do this, a conventional thermometer was attached to Quince 1 within the range of vision of a spare camera. The temperature value was recorded by capturing the screen of the operator console.

These additional functions were not requested until after Quince 1 had been redesigned in our laboratory.

Environment conditions not covered by prior tests Two extreme conditions that were not covered in our laboratory tests were encountered in the missions: strong illumination and high temperature.

The radiation level was displayed on a small screen on the dosimeter, and a small camera captured the screen image and transmitted it to the operator. The screen was a raster scan device. In the reactor building, the only external light was that on Quince 1, and the dosimeter's screen was captured by the camera without any problems. However, in locations that received direct sunlight, e.g., the carry-in-entrance and a location near the blow out panel, the shutter speed of the camera became very fast, and the camera was unable to capture a full frame of the screen on the dosimeter.

In the second mission in the reactor building of unit 2, the air temperature around Quince 1 was very high. The main motor driver overheated and the temperature exceeded its safety limit (50 °C). As a result, the main motor driver was shutdown temporarily. The driver was recovered by remotely sending reset commands, and eventually, Quince 1 returned to the entry point. After the mission, the threshold temperature for shutting down the driver was changed to 80 °C. However, it was difficult to foresee this situation.

4 Enhancements for the New Versions of Quince

The sixth mission was the final mission for Quince 1, as it was left on the third floor of the reactor building unit 2. TEPCO still required a robotic surveillance system that covers extensive areas (particularly upper floors) in the building. Therefore, we prepared two new versions of Quince robots: Quince 2 and Quince 3 (Fig. 2). We redesigned the robot to resolve critical issues encountered in the missions of Quince 1. The enhancements over Quince 1 are as follows:

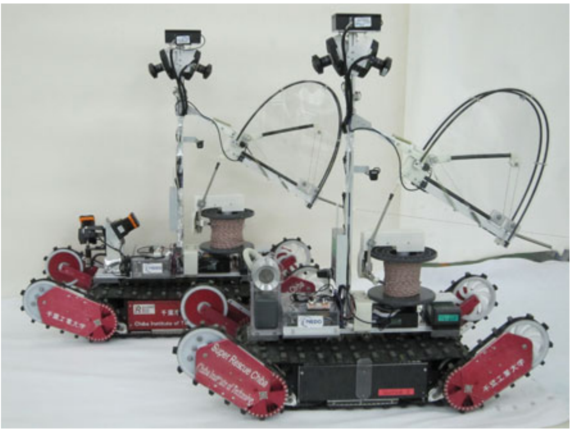

Fig. 2 New versions of Quince. The image on the *right* is Quince 2, which is equipped with an air dust sampler and the image on the *left* is Quince 3, which is equipped with laser scanners

- Detachable carrying handles
  After surveillance missions, the robot may be contaminated by radioactive materials. To carry the robot with minimum radiation exposure to workers, we installed detachable carrying handles to the robot body.
- USB thermometer and hydrogen meter
  To digitally record air temperature and hydrogen concentration values, we mounted a USB thermometer and a hydrogen meter on both of the robots.
- Enclosed dosimeter
  To prevent difficulties in recording reading from dosimeter, we put the dosimeter and a small camera into an opaque box for protection from direct sunlight.
- Remote-controlled air pump
  We mounted a remote-controlled air pump for the air dust sampling mission on Quince 2. This was considered as standard equipment.
- Laser range scanner
  To obtain details of the target environment, we mounted laser range scanners on Quince 3. More information about the scanner is included in previously published papers [4, 8].
- Cable rewinding device
- Backup robot system
- Improvement of the operator console.

The last three enhancements mentioned above are described in detail in the following subsections.

4.1 Cable Rewinding Device

The simple cable rewinding device present on Quince 1 encounters difficulties while rewinding long cables. This is because it does not have the capability to wind the cable evenly. Figure 3 shows the simple rewinding device on Quince 1. The cable is pulled and reeled out passively as Quince 1 moves, and it is rewound by rotating the cable guide by the motor. If the unreeled cable is too long, the rewound cable accumulates on the upper part of the reel. This is because the end of the cable guide arm is aligned at the top of the reel. The robot motion may shake the reel, causing the rewound cable to fall and become jammed. In this case, the reel would no longer be able to release the cable.

The revised Quince models are equipped with a new cable handling device redesigned to avoid the above problem. Features of the device are as follows:

- The cable is rewound evenly on the reel,
- It can handle about 500 m of cable continuously,
- An operator wearing thick gloves can easily change the cable reel,
- The ability to automatically release and rewind is included, and
- It has the mechanical compliance to respond to a sudden change of cable tension.

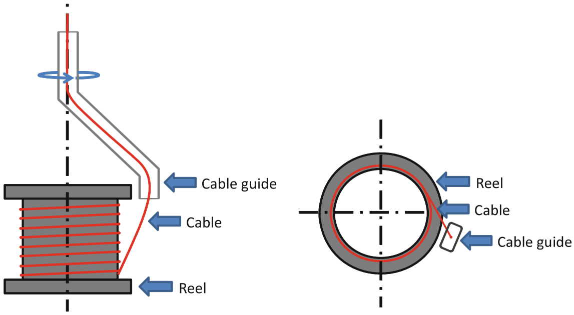

Fig. 3 A cable rewinding device on Quince 1. When the cable is pulled as Quince 1 moves, the cable guide rotates passively and releases the cable. When the operator instructs the device to rewind the cable, the guide is driven by the motor to rotate in the reverse direction, and the cable is rewound

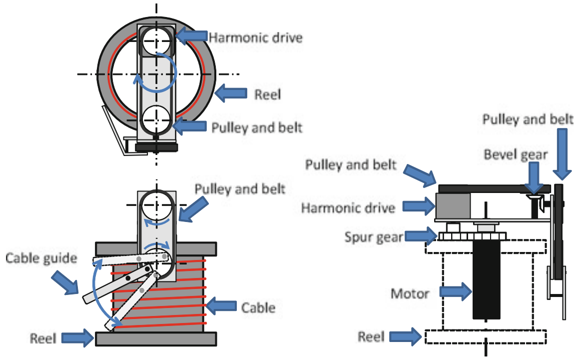

Fig. 4 Cable rewinding module on the reel. The module is driven by a motor located inside the reel. As it rotates around the reel, the cable guide swings up and down to evenly wind the cable

Figure 4 shows the new cable rewinding device. A motor rotates the cable rewinding module, which is shown in the upper part of the right figure, around the reel to wind the cable. While the module rotates around the reel, the cable guide arm is swung up and down to evenly wind the cable around the reel. One of the advantages of the system is that the module can be easily detached, so an operator wearing thick gloves can effortlessly change the cable reel.

To incorporate the automatic release and rewind functions, we implemented a tension control mechanism. Figure 5 shows the mechanism. The tension in the cable pulls down the upper arm that is supported by a spring located at the root. Thus, we can measure the cable tension by measuring the angle θ. By controlling the cable rewinding motor to keep the angle θ constant, the cable will be released or rewound as the robot moves.

To evaluate the new device, we conducted some tests in our mock field, and we identified two problems with the constant-tension control of the cable.

One problem was the difficulty with cable release in case of obstacles. When the cable was obstructed by obstacles, it was difficult for it to be released, because a constant-tension control of the cable was specified. To solve this problem, we installed a “no rewinding mode.” In this mode, the tension control mechanism is disabled and the tension in the cable is lowered. This increases the possibility that the cable will be released from the obstacle. In this mode, when the cable is pulled, it releases the cable to prevent damaging it.

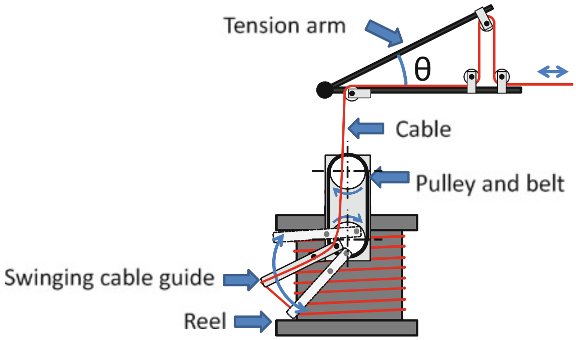

Fig. 5 Redesigned cable handling device. Tension in the cable can be measured by measuring the angle θ, and, by controlling the angle constant, the cable will be either released or rewound

The other problem was due to loosening of the cable after it is caught by obstacles and then released quickly. In such cases, excessive amount of the cable was loosened and lay on the ground for a while. The loosened cable may be run over by the robot while moving backwards. To avoid this situation, the robot should wait until the proper cable tension has been recovered. Therefore, we implemented an alert icon system and tension meter display on the console, which gives a warning to the operator about any abnormal status of the cable.

4.2 Backup Robot System

With Quince 1, there was no communication redundancy, and only one cable failure resulted in loss of the robot. Therefore, to handle such situations involving cable failure, we implemented a backup communication function on a secondary robot to restore the data link of the primary robot using a wireless communication link between the primary and secondary robots.

Figure 6 shows the structure of the backup robot system. Both robots possess a VDSL cable communication system and a 802.11 g wireless LAN system. The primary robot conducts the mission using the cable communication system. If the cable fails, the backup robot is directed to the location, and it approaches the primary robot until a wireless connection is established between the two robots. Then, the data link to the primary robot is restored via the cable communication system of the second robot and the wireless connection between the robots.

For this system, the requirement is simply to mount a wireless transceiver device on both robots. While this was easily implemented, it significantly improved our ability to help stuck robots. Additionally, Quince 2 can function as both a primary and a backup robot, depending to the mission.

The Quince robot has four small cameras and two wide-angle view IP cameras. Images from these cameras are encoded in the MJPEG format and transmitted to the operator console. The VDSL modem on Quince (ABiLINX 1511) has a bandwidth of around 25 Mbps with a 500 m long thin cable. Since multiple video streams are

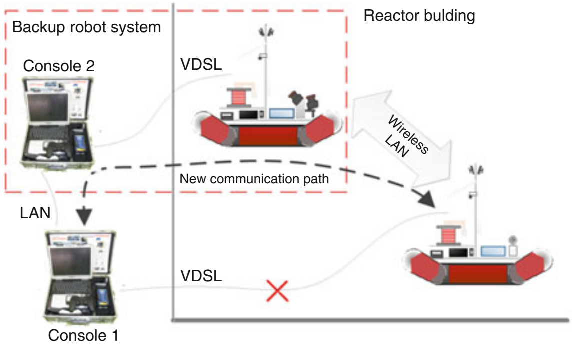

Fig. 6 Use of a secondary robot to restore the data link to the primary robot. The data link would be restored using the cable communication system of the backup robot and a wireless link between the two robots

transmitted over the data link with limited bandwidth, we allocated an optimal bandwidth for each video stream depending on its contents. However, when the cable of the primary robot dies and the backup robot restores the data link, the required bandwidth of the data stream doubles. and the actual data flow may exceed the bandwidth capability. Therefore, we setup two communication modes: the primary mission mode, in which each robot can use a bandwidth of up to 20 Mbps, and the emergency communication mode, in which each robot can use a bandwidth of up to 8 Mbps.

Switching between these communication modes is done by just a few clicks. Therefore, switching from the primary mission mode to the emergency communication mode can be done easily in a real mission.

4.3 Improvement of the Operator Console

The operator console screen of Quince 1 displayed camera images, the robot's posture, battery voltage, and motor driver temperatures. The operators used a gamepad to assign the speeds for the motors of the main and sub tracks. Furthermore, there were two buttons on the console screen that could be used to instruct the sub tracks to take a predefined postures.

The new operator console was improved to consider the feedback given by the operators of the missions conducted by Quince 1. Figure 7 shows the new console screen. The major improvements in response to the feedback were as follows:

The amount of cable remaining should be displayed.

A reel counter is implemented and the value is displayed on the screen.

Abnormal conditions should be signaled.

In the case where abnormal conditions are detected, flashing alert icons will be displayed over the camera image. The conditions include low battery, short

Fig. 7 Improved operator console screen for Quince 2. Status indicators for information such as the amount of cable remaining, temperature, and wireless signal strength, and some alert signals were added

length of cable remaining, low cable tension, and abnormal inclination of the robot.

Commanding sub tracks to take predefined posture should easily be activated

This function was assigned to the gamepad buttons for quick activation.

In addition to the above improvements, we added indicators displaying readings from the newly added components such as sensors for temperature, humidity, wireless signal strength, and cable tension.

5 Summary

Quince 1 was a rescue robot developed to perform surveillance missions in the damaged reactor buildings in the Fukushima Daiichi Reactor Power Plant, and it conducted six missions. The results of the missions significantly contributed to the restoration of the site. However, several issues were identified during the missions. These included the reliability of the communication cable handling device, the method for transporting the contaminated robot, and other problems encountered in the extreme environmental conditions that were not covered by tests in our laboratory environments. In the sixth mission, the communication cable failed and Quince 1 was left on the third floor of the reactor building of unit 2.

TEPCO has requested modified Quince robots, so we upgraded the robots to resolve the critical issues. The upgraded robots were recently completed and delivered to TEPCO in February 2012. We hope that these robots will contribute to the project aimed at recovering from the Fukushima Daiichi Nuclear Power Plant disaster.

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