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Report of JSME Research Committee on the Great East Japan Earthquake Disaster

Chapter 5

Application of Robot Technologies to the Disaster Sites

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Abstract

During the Great East Japan Earthquake disaster, Japanese rescue robots were used for actual disaster sites for the first time. Many robot technologies were used and tested mainly along the Sanriku coast and at the Fukushima Daiichi nuclear power plant (NPP). They were used along the Sanriku coast to inspect critical infrastructures, to search for missing persons driven underwater by the tsunami, to remove debris in the disaster sites, and to inspect buildings that were in danger of collapsing. At the Fukushima Daiichi NPP, unmanned construction technology was used to remove outdoor debris, and several military robots and rescue robots were modified for radiation monitoring, damage investigation, and removal of radioactive debris, and were used in the exterior and interior areas of the reactor buildings. In the evacuation centers, the therapeutic robots named "Paro" were introduced to more than 70 centers to provide psychological support to sufferers. The robots and robot technologies applied to the disaster achieved certain results. The results and trials of the practical applications, however, reveal new issues regarding the management of these robot technologies. In particular, at the Fukushima Daiichi NPP, there were no robots applicable to the disaster site immediately after the accident due to the unexpected severity of the accident. The site was contaminated with radiation and significant amounts of debris. In such a situation, both the tele-operation function and the ability to move on debris are required for robots. Professional operators and robust robots are also needed. However, such robots and operators do not exist in Japan. Thus, the government is strongly encouraged to technically and economically support anti-disaster robotics technologies.

Keywords : Rescue robot, Underwater vehicle, Tele-operation, Unmanned construction, Remotely operated vehicle, Military robot, Robot for nuclear power plant

1. Introduction

During the Great East Japan Earthquake disaster, Japanese rescue robots were used and tested. Along the Sanriku coast, several remotely operated vehicles (ROVs) were used to search for victims driven underwater by the tsunami, to inspect critical infrastructures, and to examine the bottom surface under the sea. A newly developed robotic construction machine and a rescue robot were used to remove debris at the disaster sites and to inspect a gymnastic hall that was in danger of collapsing in Hachinohe, respectively. They are now being used at the Fukushima Daiichi nuclear power plant (NPP) to remove debris in the interior and exterior areas of the nuclear reactor buildings, to monitor irradiation levels, and to inspect buildings. In the evacuation centers, the therapeutic robots named "Paro" were introduced to more than 70 centers to provide psychological support to sufferers. In the following sections, the details of the robots that were used and their results are reported with respect to the locations and purposes of use. Then, the problems extracted from the reports will be summarized from operational and technical aspects.

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2. Robot technologies employed at the tsunami disaster sites

2.1 Robot activities along the Sanriku coast

The area devastated by the tsunami disaster was extensive and the amount of damage was unknown to the people in the other regions of Japan. The first robot activity that was employed at a tsunami disaster site began at a gymnasium that was in danger of collapsing seven days after the earthquake in Hachinohe. Prof. Matsuno from Kyoto University and his colleagues entered the disaster site from the northern part of the Sanriku coast on 18 March 2011 and tele-operated their developed mobile rescue robot “Kohga 3” to inspect the damage of the gymnasium, as shown in Fig.1. However, it was revealed that their robot was not able to locate survivors (Fig.2). On the other hand, it was revealed by their interview that the local governments along the Sanriku coast wanted an underwater investigation, since most of the victims died due to drowning. The local governments also wanted to conduct an underwater inspection of the damaged infrastructures and to investigate the amount of debris on the bottom surface of the harbors in order to ensure a prompt reconstruction of the damaged fishing harbors (Fig.3). Following a report by Prof. Matsuno on the robot activities and the investigation of the damage along the Sanriku coast, the Center for Robot-Assisted Search and Rescue (CRASAR) and International Rescue System Institute (IRS) collaborated and established a team to organize the operations for an underwater inspection. The operations began 18 April 2011 along the Sanriku coast. Prof. Hirose from the Tokyo Institute of Technology also began an underwater search for victims in the southern part of the Tohoku area on 19 April 2011. At the beginning of May 2011, the University of Tokyo Ocean Alliance and Mitsui Engineering & Shipbuilding Co., Ltd., surveilled the bottom surface of Otsuchi bay and found two victims. In the towns devastated by a tsunami, the new construction machine “ASTACO NEO”, with twin hydraulic arms, developed by Hitachi Construction Machinery Co., Ltd., were employed to remove debris.

(a) Kohga 3 in the gymnasium

(b) Operator controlling Kohga 3

Fig.1 Kohga 3 inspecting the gymnasium

(a) Shipbuilding yard in Kuji-shi

(b) Noda-mura

Fig.2 Damages in the northen areas of the Sanriku coast

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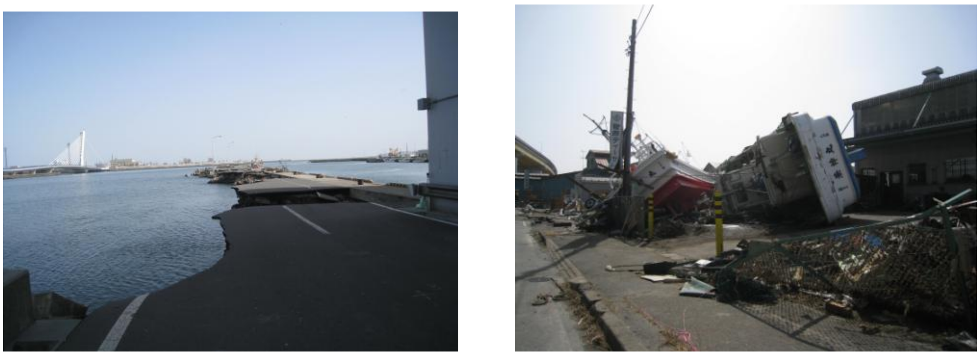

Fig.3 Damages to Hachinohe port

2.2 Underwater investigation

One month after the earthquake occurred, underwater robots were employed to carry out an underwater investigation so that the lives of divers would not be jeopardized. AC-ROB, SARbot, and Seamor ROV were used to search for victims and to inspect the underwater portions of piers and bridges to assess the damage at Minamisanrikucho and Rikuzentakada from 19–20 and 21–23 April 2011, respectively. Anchor Diver 3 was used at Waraticho from 19–20 April 2011. These missions were conducted in collaboration with the IRS and CRASAR. The University of Tokyo Ocean Alliance and Mitsui Engineering & Shipbuilding Co., Ltd., investigated the amount of debris on the bottom of the sea around Otsuchicho from 28 April to 2 May 2011 and around Minamisanrikucho from 14 to 19 May 2011 by using the remotely operated underwater vehicle “RTV-100”. Several other surveillances of the sea-bottom surface were conducted following their investigation.

2.2.1 Minamisanrikucho and Rikuzentakata (Matsuno et al., 2012) (Murphy et al., 2012)

The ROVs that were used and their specifications are shown in Fig.4 and Table 1, respectively. SARbot is a commercial underwater vehicle developed by SeaBotix Inc. and was mainly used due to its portability and rapid setup/deployment. It is equipped with an enhanced color video camera, the Tritech Gemini 720i multibeam imaging sonar, an accurate GPS system, and a limb grasping mechanism. Seamor ROV was developed by Seamor Marine Ltd., and is equipped with high-resolution sonar and a grasper. AC-ROB is a small robot driven by a battery and captures video. It is similar to a thruster with a video camera and was mainly used to investigate tight places, such as under floating houses. In Minamisanrikucho, SARbot and Seamor were used to check if obstacles were present within 5 m of the water surface in the newly constructed area of the Minamisanrikucho fishing port. Since the clearness of the water was very poor (30–50 cm), a sonar sensor was used to locate large obstacles. As a result, there were no obstacles in the area that was checked. The amount of time that SARbot was in the water was 17 min on 19 April 2011 and 268 min on 20 April 2011, and that of Seamor was 178 min on 20 April 2011. In Rikuzentakata, SARbot, Seamor ROV and AC-ROB were used to search for victims. Since victims were assumed to be trapped by floating debris, as shown in Fig.5, the investigation was conducted under the floating debris or around the heaps of debris where divers had not yet searched. Such locations were very dangerous for divers due to the presence of hazardous materials in the debris, which also made the use of robots essential for the searches. No victims were discovered during these activities. The amount of time that SARbot was in the water was 193 min on 21 April 2011, 97 min on 22 April 2011, and 44 min on 23 April 2011, that of Seamor was 42 min on 22 April 2011, and that of AC-ROB was 35 min on 21 April 2011 and 20 min on 22 April 2011.

From 23 to 26 October 2011, the same team investigated debris that was large in size on the bottom of the sea, such as cars with gasoline, which is harmful for fishing. Two robots, SARbot and RTV-100, were used. As a first step, abstract data pertaining to the shape of the sea bottom for a wide area were collected by side-scan sonar attached to a survey boat. Then, the details of any suspicious object that was obtained by the abstract data were verified by using an ROV. ISR and CRASAR conducted the investigations and the data obtained by both were integrated into the same geometrical map, which was very convenient for staff of the local government and fishermen. More than 100 obstacles were found during the investigations.

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Fig.4 Remotely operated vehicles (ROVs) that were used for the activities

Table 1 Specifications of the remotely operated vehicles (ROVs)

ROV	size (mm)	weight (kg)	tether length (m)	sensors	gripper	velocity (m/s)
SARbot	549×250×268	17.4	150	camera, sonar, GPS	○	3
Seamor	355×472×335	20	150	camera, sonar	○	3
AC-ROV	204×151×146	3	50	camera	×	1

(a) Floating debris driven by tsunami

(b) Image captured by the ROV under floating debris

Fig.5 Situation of floating debris

2.2.2 Wataricho (Huang et al., 2011)

Anchor Diver III, which is shown in Fig.6(a), was developed for the rescue activities of the Tokyo Fire Department by Prof. Hirose from the Tokyo Institute of Technology. It is equipped with a high-resolution video camera and 2D sonar, and driven by two thrusters. Anchor Diver III is connected to the operation site by a cable and can maintain its own position in tidal streams via the cable tension and thruster control, as shown in

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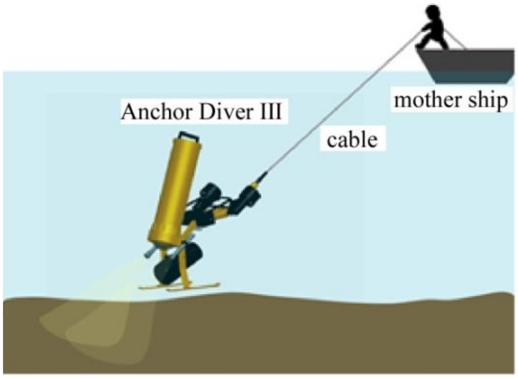
Fig.6(b). Since the direction of the thruster can be changed in the horizontal and vertical directions, the robot can move forward, upward, downward, and to the right and left, but the cable has to be rewound by the operator when the robot moves backwards. The shape of its main body is a cylinder, which is heavy at one end and light at the other. Therefore, the body always has a vertical orientation when in water. A sonar sensor and a camera are equipped on the heavy end of the body (the bottom end) and can continuously measure the bottom surface of the sea. Anchor diver III investigated an area of about 100 m^2 during a two day period. No victims were found during the investigation, but the conditions of the bottom surfaces of the ports were made clear.

(a) Photograph of Anchor Diver III



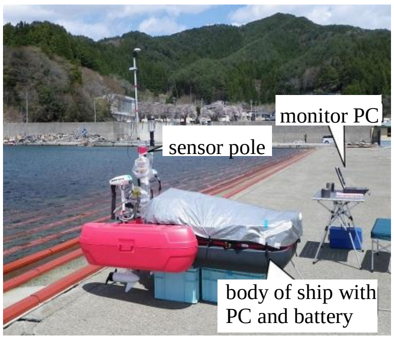
(b) Operation of Anchor Diver III

Fig.6 Anchor Diver III

2.2.3 Otsuchicho and Minamisanrikucho

The University of Tokyo Ocean Alliance investigated the bottom surface of Otsuchi bay and Shizukawa bay in collaboration with Mitsui Engineering & Shipbuilding Co., Ltd., from 28 April to 2 May and 14–19 May 2011, and found two victims. In Otsuchi bay, two remotely operated underwater vehicles (RTV-100 and RTV-100Mk2) and one autonomous surface vehicle (ASV), shown in Fig.7, were used. The length of the ASV was 2.1 m. The ASV can create maps of the sea bottom by using a GPS and its multibeam sonar. It can be autonomously controlled along a predetermined target path via its embedded computer. However, the ASV was not autonomously but remotely operated via a wireless LAN due to troubles with a controller. The map that was obtained is shown in Fig.8. An investigation by two ROVs was also conducted from a fish boat and it was found that a majority of the bottom surface was flat and that there was little debris. Two victims were also found. In Minamisanrikucho, only an RTV was used. The length of surveillance was about 12 hours and 14 locations were investigated.

(a) Remotely operated vehicles RTV-100 and RTV-100Mk2



(b) ASV

Fig.7 RTV-100, RTV-100Mk2, and ASV

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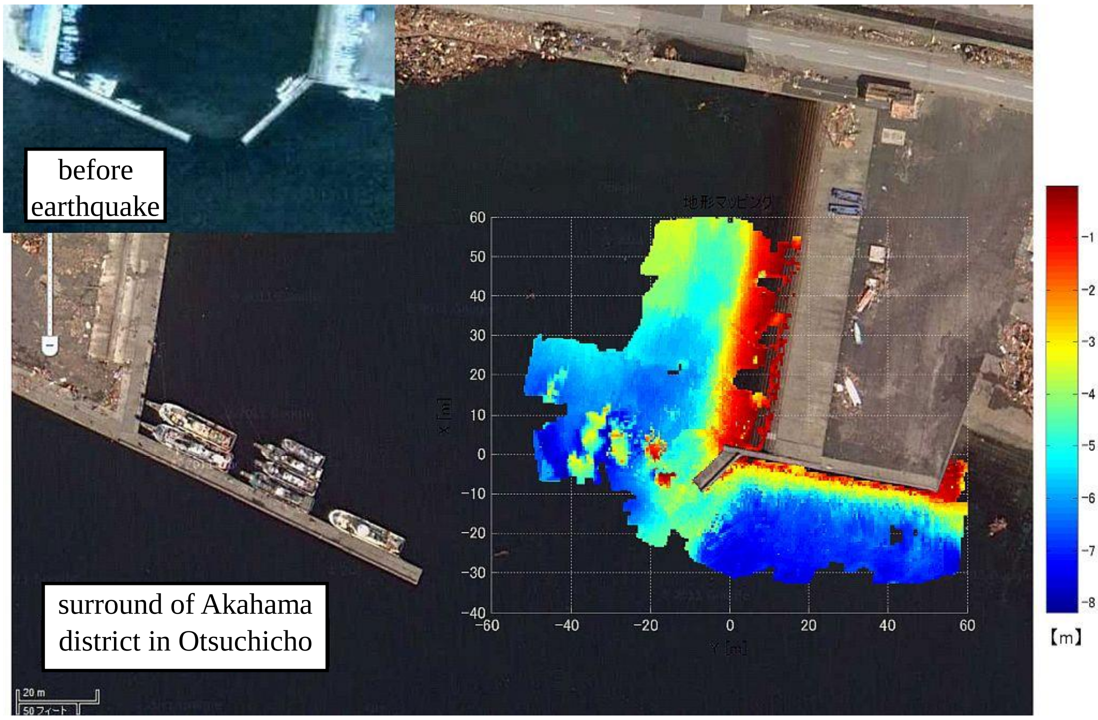

Fig.8 Bathymetry data obtained by the ASV. A photo of the area prior to the tsunami is shown in the top-left. Photos are from Google Earth (http://www.google.co.jp/intl/ja/earth/index.html).

During July 2011, the University of Tokyo Ocean Alliance conducted five visual surveys in collaboration with the Nippon Foundation and JF Zengyoren by using RTV-100 and the underwater vehicle “LEO”, which was developed by Tokyokyuei Corp. (Fig.9(a)). During the first four surveys, the boat shown in Fig.9(b) was anchored at a predetermined location and the sea bottom around this location was surveyed by the ROV. The depth was 40–70 m. During the fifth survey, the investigation was conducted using side-scan sonar equipped on a different boat and 60 anchoring points were determined in accordance with the measured data. Then, the surrounding area of the points was surveyed by the ROV the next day. This proved to be a very efficient method and most of the debris in an area of 3,300,000 m^2 was identified in just 4 days.

(a) Underwater vehicle LEO (b) Fishing boat used for the investigation

Fig.9 ROV and the boat that were used in July 2011

2.3 Removal of debris

A new construction machine, ASTACO NEO, with twin hydraulic arms, as shown in Fig.10(a), was employed to remove debris and dismantle a portion of a damaged warehouse in Ishinomaki at the southern end

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of the Sanriku coast during May and June 2011. ASTACO NEO was developed during a project that was sponsored by the New Energy and Industrial Technology Development Organization (NEDO) (Yanagihara et al., 2009). One arm operates as the main arm that can be attached with commercial tools, such as 11-ton hydraulic shovels, and the other is a sub arm that can be attached with the newly developed versatile hand shown in Fig.10(b), which can grasp small objects at its finger tips and cut reinforcing steel at the base of its fingers. The degrees-of-freedom of the main arm is 5 and that of the sub arm is 9, both of which include their attachments. The main arm is controlled by the joystick on the right side and the sub arm is controlled by the joystick on the left side. The operations applied to the machine were completed smoothly and the robot was verified to have high efficiency. As another robotic technology, Smart Suit Light, which is a passive powered suit developed by Prof. Tanaka of Hokkaido University, was used to reduce the loads of the workers when removing debris (Imamura et al., 2011).

(a) Removing the doors of a damaged warehouse

(b) Newly developed multifunctional hand

Fig.10 ASTACO NEO was used to remove the doors of a damaged warehouse

3. Robot technologies employed at the Fukushima Daiichi NNP

3.1 Robot activities employed at reactor No. 1 during the nuclear power plant accident

The hydrogen explosions of nuclear power units 1–4 affected a very wide area. Light debris was scattered along the road surrounding the power plant far from the buildings. Pieces of radioactive debris varying in size were also piled on top of cars and trailers around the reactor and turbine buildings, which disturbed the access of fire-extinguishing vehicles or concrete pumping tracks to the reactor buildings (Fig.11). Moreover, since it was strictly prohibited for workers to enter the buildings due to the high radioactivity, the amount of damage within the buildings was unknown. To recover from such an accident, it is essential to access the buildings and investigate the amount and type of damage; therefore, the development of many types of tele-operated robotic systems was urgently needed. However, there was no such robot in Japan applicable to the Fukushima Daiichi NPP immediately after the accident due to the unexpected severity of the accident. From the beginning of April 2011, unmanned construction technologies that were developed in Japan were used for the removal of radioactive debris outside of the buildings, which resulted in not only a clear accessible path to the buildings, but also a decrease in the level of airborne radiation. In April 2011, some U.S. military robots were modified for the Fukushima Daiichi NPP accident and were used to monitor the airborne radiation and to investigate the severity of damage. In June 2011, a Japanese rescue robot was utilized to investigate the interior of the reactor buildings. Currently, many robots have been developed in Japan and being used to remove debris, to monitor radioactivity or other physical parameters, and to inspect the damage to the nuclear reactors and buildings. Many more robot technologies related to the construction machines or rescue systems will be developed and used for the required tasks to decommission nuclear power units 1–4.

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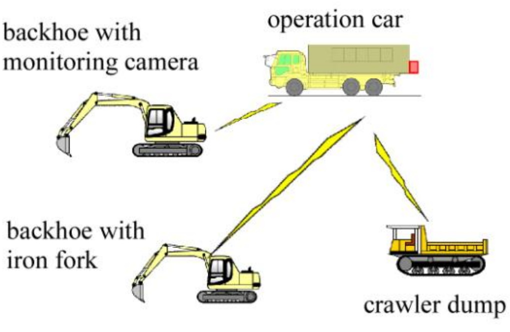
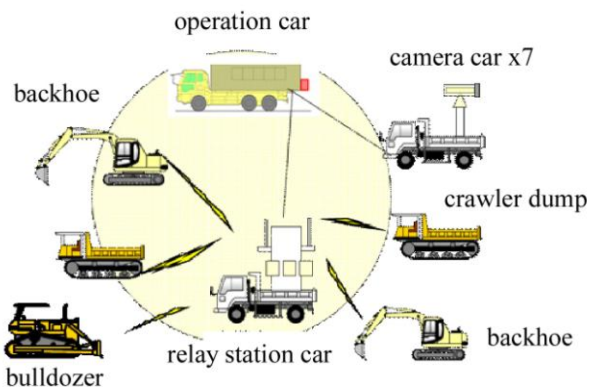
Fig.11 Debris that was scattered due to the hydrogen explosions

3.2 Removal of debris

Tele-operated construction machines modified for the disaster site were used to remove debris around the nuclear reactor buildings. At first, a backhoe with an iron fork attached to its tip, a crawler dump truck, a monitoring car with a camera, and an operation car were introduced as shown in Fig.12(a). The backhoe, dump truck, and monitoring car were tele-operated by operators in an operation car. Since the wireless communication range of this system limited the working distance to 150 m, it was impossible to use the system in high dose areas; thus, system 2 was introduced as shown in Fig.12(b). System 2 consisted of one operation car, one relay station car, seven camera cars, two backhoes, two dump trucks, and one bulldozer. The technologies installed in the tele-operation system were originally developed as unmanned construction technologies almost 20 years ago for the recovery activities of the evacuation of Mt. Unzen Fugendake and they have been continuously improved as construction robot technologies up until now (Yamamoto, 2007). At the time, there were about 20 skilled operators for unmanned construction machines in Japan, but it was impossible to place all the operators at the Fukushima Daiichi NPP, and the lack of operators was one of the most significant problems during the accident. It was also unclear whether the unmanned system would work well in high-radiation areas. If a machine became inoperable on an access road to the reactor buildings, the machine itself would have become a large obstacle that would seriously disrupt the recovery tasks. Despite these concerns it was determined to introduce the unmanned system into the disaster site.



(a) System 1



(b) System 2

Fig.12 Configurations of the unmanned systems used to remove debris

To collect the radioactive debris via the unmanned system, containers that were used in other nuclear power plants were modified for the grippers of the tele-operated backhoes so that they were able to open and

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close their flaps and used, but their radiation shielding ability was not high because they were designed for low level radioactive waste. All the debris was put into containers indiscriminatingly, as shown in Fig.13(a), and after being transported to the storage area, the containers were sorted according to the intensity of their radioactivity and stored as shown in Fig.13(b).

After introducing the unmanned system to remove debris, the level of the airborne radiation decreased. As the task became gradually easier, as shown in Fig.13(c), the applicable area became wider and almost 20,000 m^3 of debris was consequently removed from an area of 56,000 m^2. The system worked very well and the outdoor debris was almost completely removed by the middle of November 2011.

3.3 Pouring water into the pool of spent nuclear fuel

Just as the accident occurred, a periodic inspection was being conducted at reactor building 4, which had been eventually shut down. The pool of spent nuclear fuel on the top floor of the building was filled with the spent and unspent fuel removed from the reactor. A station blackout caused by the tsunami caused the water temperature in the pool to increase. If all the water in the pool had evaporated, most of the fuel in the pool would have melted down, producing levels of radioactivity so high that recovery would have been impossible. Therefore, pouring water into the pool was one of the most critical and urgent tasks immediately after the accident occurred. A modified concrete pumping track with a camera at the tip of the boom was used for the task and the water was successfully poured. It was then planned to continue this task remotely to reduce the radiation exposure of the workers, and three remote operation systems were developed. Fig.14 shows the entire system and the system configuration of Zousan 3, which consists of a concrete pumping track, an operation car, a monitoring camera car, and a relay station car. The three developed systems are similar, but they were not used in practice since the level of airborne radiation became low enough for workers to operate from the trailer when the systems were prepared.

(a) Remotely controlled backhoe

(b) Stacked containers

(c)Road between reactor building 2 and 3

Fig.13 Removal of debris by the unmanned control system

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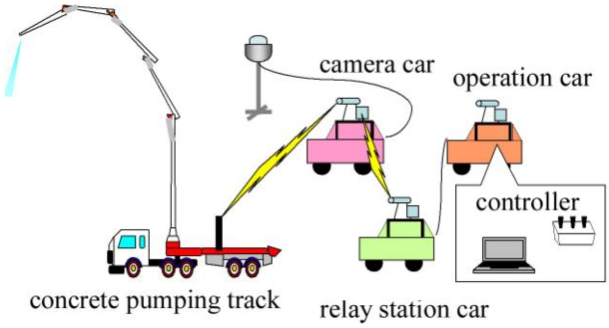
(a) The entire system



(b) Configuration of the system

Fig.14 Remotely controlled concrete pump trailer

3.4 Radiation monitoring

A military robot, TALON, was provided to the Japanese government by DOE-INI on 14 April 2011 (Fig. 15(a)). TALON is equipped with a GPS and a radiation counter and can plot the obtained data on a geometrical map. The robot was expected to be used to monitor the outdoor radiation, but the roads were covered with debris, and the environment to operate the robot was very poor. Therefore, it was considered impossible to use only TALON. On the other hand, JAEA was developing RC-1 (Fig.15(b)), a truck on which a radiation shielding operation box is mounted. The shielding box has an 80-mm-wide steel sheet in front and operators can control the robots from inside of the box. TEPCO and JAEA developed a plan to transport TALON to the sites via RC-1 and tele-operate it from the box. In addition to the shielding box, a gamma-ray camera, laser range finder, thermo camera, radiation counter, and other small items were loaded into RC-1 as shown in Fig. 5.15(c). The gamma-ray camera displayed the intensity of the gamma rays by providing their corresponding colors on a screen, and it was very useful to locate the high-radiation debris around the large equipment hatch of reactor building 3 (Fig.16) and the exhaust air duct of reactor building 1. RC-1 and TALON were used on 5 May 2011. JAEA also developed another gamma-ray camera (γ-eye; Fig.17) that is more reliable than the previous one and a monitoring robot (J-3) that is based on RESQ-A, which was developed just after the disastrous nuclear accident in Tokaimura in 1999. To increase the radiation hardness and reliability, J-3 was remotely controlled via wiring and the motor drivers and the power source were placed in the shielding box. Due to this configuration, the radiation hardness increased 10^6 Gy. The motion range of J-3 was 50 m, which was determined by considering the weight of the cable that had a diameter of 20 mm and the maximum traction force of J-3. J-3 was loaded on to a new truck that had a shielding box and an air conditioner (RC-2), and was used to monitor gamma rays in reactor building 2 on 23 September 2011 (Kawatsuma et al., 2012).

Irradiation was also monitored at sea around the Fukushima Daiichi NPP by an unmanned surface vehicle (USV) (Fig.18), which can be autonomously controlled by using a GPS along a target path consisting of a series of given points on a map. Immediately after the earthquake, there was a lot of debris on the sea surface, and it was almost impossible to control the USV autonomously. Therefore, the USV was autonomously controlled, but the view ahead of the USV was also given to the operator on the ground. If an obstacle was found in the view, the operator sent the control command for collision avoidance to the vehicle. Then, the given command overrides that generated by the USV. To increase the robustness of the control system, four wireless communication systems were implemented (wireless LAN, FOMA, VSAT, and WIDESTAR) in order of priority. The length, width, and height were 6.0 m, 2.3 m, and 0.9 m, respectively, and its weight was 1.8 tons. The maximum velocity was 7 knots/hour and that during monitoring was 3 knots/hour, and the maximum sailing distance was about 100 km. In addition to the GPS compass and wireless communication systems, water samplers, a gamma dosimeter, and an acoustic doppler current profiler (ADCP) were equipped to the USV. TEPCO began operating the USV on 11 November 2011. The USV started at the Fukushima Daini NPP and sampled water at 26 points and measured gamma rays in real time off the coast of the Fukushima Daiichi NPP. The USV was unmanned, the total operation time was 3 hours and 40 min, and the sail distance was 40 km.

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(a) TALON (b) RC-1 (c) RC-1 being loaded with several tools

Fig.15 Irradiation monitoring by TALON

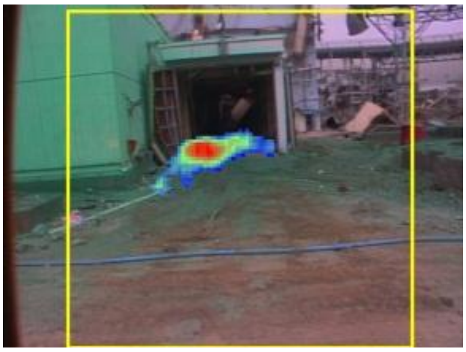

Fig.16 Image obtained by the gamma-ray camera around reactor building 3

(a) Remotely controlled robot J-3 with the γ -eye camera (b) γ -eye camera

Fig.17 Newly developed irradiation monitoring robot J-3

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(a) USV (b) Operation site

Fig.18 Unmanned surface vehicle (USV) used to monitor irradiation

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Fig.19 Packbot

Fig.20 Quince

3.5 Investigation of damage in the reactor buildings

For the monitoring and inspection, two Packbots (Fig.19), which are commercial military robots produced by iRobot Corp., were used to investigate the indoor damage of the nuclear reactor buildings after the middle of April 2011. One robot was controlled as a monitoring robot and captured images of the other robot via its camera, and the other robot was wirelessly controlled by the operator and was used to measure radioactivity, temperature, moisture, and so on. The robots also have a manipulator with (up to) eight degrees of freedom that can be used to open or close doors. These robots obtained valuable data pertaining to the indoor environment, but they were not able to go upstairs due to the steep inclination of the stairs. The rescue robot Quince (Fig.20) was developed by the IRS and began being used in July 2011. The mobile capability of Quince is very high, allowing it to climb stairs. In addition to the main two crawlers embedded in its body, Quince has a unique crawler mechanism that consists of two flippers with crawlers at the front and rear sides, which are similar to arms and legs. Quince is also equipped with a manipulator that has six degrees of freedom and is controlled via wires by operators. Before Quince was introduced to the Fukushima Daiichi NPP, the radiation hardness of the circuits included in the controller, the CCD camera, and the other sensors mounted on Quince were examined by irradiation tests at the Japan Atomic Energy Research Institute (JAEA) and Takasaki Advanced Radiation Research Institute in April 2011. The results showed that the laser range finder and CCD camera become inoperable at 124 Gy and 169 Gy, respectively, but all of the other semiconductors are still operable at 200 Gy, which indicates that Quince can operate for 5 successive days at 100 mSv/h with a safety rating of 10. After all other possible causes of failure were carefully examined, the staff at TEPCO began training to operate Quince in mid-April. On 20 May 2011, TEPCO determined that it was necessary to install a water gauge in the basement of reactor building 2 and to obtain samples of the contaminated water in this location. Quince was extensively modified according to these objectives and tested by TEPCO operators in reactor building 5 of the Fukushima Daiichi NPP, which was not damaged by a tsunami. On 24 June 2011, Quince was employed in reactor building 2 for the given missions, but they were not completed, because the difference in the width of the steps between the drawings of the building (92 cm) and the actual width (70 cm) was too narrow for Quince to turn on the stair landings. On 8 July 2011, Quince reached the second and third floors of reactor building 2 for the first time and monitored the air dose and sampled air dust. The operation screen for this day is shown in Fig.21, and the route taken by Quince is shown in Fig.22. Due to the great success of Quince, the extent of the damages to the buildings was clarified significantly.

Quince was also used to inspect the damaged buildings of Tohoku University in collaboration with a quad rotor helicopter (Pelican) and a rescue robot (Kenaf), which is the base robot of Quince, in July 2011 (Fig.23). A 3D map of the interior of the damaged building was also created (Michael et al., 2012).

3.6 Removal of debris from the reactor buildings

Some robots were used to remove radioactive debris and to clean the floors in the reactor buildings. The robot that was primarily used was a military commercial robot (710 Warrior) (Fig.24(a)) developed by iRobot

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Corp. In June 2011, 710 Warrior began cleaning the reactor buildings indoors. A cleaner is attached to the manipulator tip of 710 Warrior, as shown in Fig.24(b). iRobot Corp. provided two 710 Warriors: one with a heavy manipulator arm, and another with a universal vice with a hose clamp. The robot is a ground vehicle that utilizes tracks rather than wheels. The structure of the chassis consists of a drive mechanism paired with a flipper of the same size, the deck platform, and the base/arm coupling that is connected between the components. The heavy manipulator arm, universal vice, or any other payload can be installed on the deck platform. The chassis length is approximately 89 cm when the flippers are folded and the width is 54 cm (77 cm with flippers). The heavy manipulator arm has two links, but the deck platform, which can be lifted up and down and swivels forward and backward, provides a third link equivalent to an arm and an additional degree of freedom axis. The heavy manipulator arm is capable of lifting and handling approximately 99 kg. With a weight of approximately 200 kg, 710 Warrior has a mobility of over 12 km/h when the heavy arm is installed. It also has a radio and a wired communication mode when using the Operator Control Display Unit (ruggedized laptop PC), and can be operated by a hand controller. The use of 710 Warrior to clean the reactor building entrances was publicized in June 2011. The robot holds the dust collection nozzle and pulls the hose of the cyclone cleaner. It was used to review heavy shield transportation scenarios and to clean interior debris.

Fig.21 Operation panel of Quince

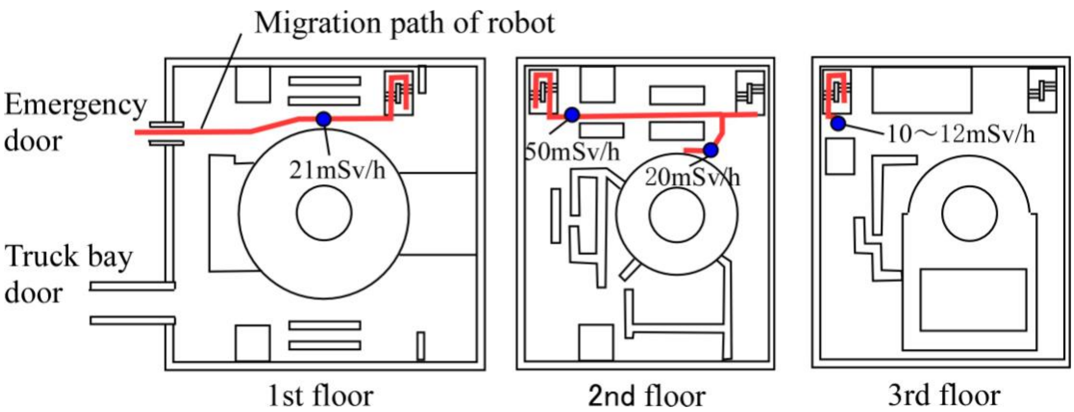

Fig.22 Root for inspecting the damage in reactor building 2 on 8 July 2011

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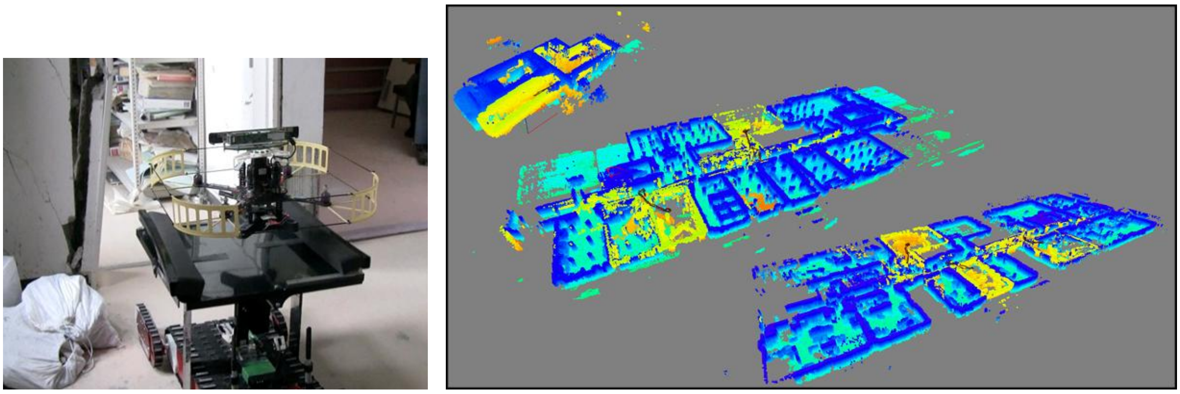

Fig.23 Inspection of a damaged building conducted in collaboration with Quince, Pelican, and Kenaf

(a) 710 Warrior (a) Quince and Pelican (b) 710 Warrior equipped with a cleaner

(http://www.tepco.co.jp/en/news/110311/images/110630_4.jpg)

Fig.24 710 Warrior that was used to clean the floors in the reactor buildings

(a) BOBCAT (b) BROKK

Fig.25 Remotely operated robots used to remove indoor debris

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Fig. 26 Paro in an evacuation center

Three other robots (TALON, BOBCAT and BROKK) (Fig.25) were used to remove debris around the heavy equipment hatch of reactor building 3. BOBCAT is a commercial unmanned construction vehicle developed by QinetiQ. BROKK is a remote controlled demolition robot for nuclear power plants; two BROKKs (BROKK-90 and BROKK330) were used. One was controlled via wires and the other was wirelessly controlled around the hatch.

4. Robot technologies employed at other sites

The therapeutic robots named Paro were employed at almost 70 evacuation centers to provide psychological support to sufferers. Paro is a robot seal developed for animal therapy (Shibata, 2012). Almost 2,000 PAROs have been sold in Japan since 2011 and 30% of them are used in medical and welfare houses. PARO was officially recognized by the Guiness Book of World Records as the most therapeutic robot, and has brought much consolation to sufferers in evacuation centers.

To assist in the reconstruction of daily lives in residential zones, the National Institute of Advanced Industrial Science and Technology (AIST) formed a consortium with corporations and applies life support technologies, such as energy and ICT services to temporary houses, to prevent elderly people from contracting major diseases caused by the lack of movement in Kesennuma.

5. Agenda and proposal for applying robot technologies to disaster sites

5.1 Agenda and proposal of a management system for anti-disaster robots

Along the Sanriku coast, underwater robots were mainly used to search for victims and to inspect infrastructures and the bottom sea surface. However, it should be noted that the number of activities and robots was too few for such a significant disaster. Most of the operators were university staff members and it was very difficult for them to approach the disaster sites due to the debris on the roads. Under such conditions, robots should be used as tools for the missions given by the members of the Self-Defense Forces or rescue teams of the Fire and Disaster Management Agency. The government is strongly encouraged to establish anti-disaster organizations that technically and economically support the operation of anti-disaster robotics technologies and the development of skilled robot operators.

For the Fukushima Daiichi NPP, robots were not initially applicable to the disaster site due to the unexpected severity of the accident and the difficulties of the task environments. The site was contaminated with radiation and had piles of debris. Therefore, both the tele-operation function and the ability to move on debris are required for robots. Professional operators and the robustness of the robots are also essential. However, such robots did not exist in Japan. On the other hand, there are many commercial military robots in the USA that can be easily operated, and it was much easier to introduce such robots to the sites than Japanese prototype robots. This is one reason why many of the robots that were initially used at the Fukushima NPP were from the USA. These facts also reveal the necessity of professional organizations to develop and operate anti-disaster robots.

5.2 Technical agenda and proposal for anti-disaster robots

It was very important that the robots were available for immediate use at the disaster sites. The robots that

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were used along the Sanriku coast had similar features, such as their robustness, portability, easy setup, and usability. These features are very important for anti-disaster robots. To create such robots, in addition to the development of technologies, the spiral improvement of robot technologies through repeated usage by actual operators is essential.

At the Fukushima Daiichi NPP, new objectives for the robots were continuously arising, and much modification was needed to complete their missions. To meet such requirements, robust base machines whose modifications for various missions are easily achievable are essential. A database of the available technical elements, the development of technical elements for an expected disaster or missions, and the coordinators for the developing robots for the given missions are also necessary. In particular, it was made clear that the robots require functions that allow them to access high, narrow, and underwater locations.

6. Conclusions

The Fukushima Daiichi NPP disaster was the first opportunity for most robotics researchers to apply their rescue robots to an actual large-scale disaster in Japan. Activities completed by using robot technologies were reported in this article and many robotics researchers joined various activities, such as damage investigations or recovery operations, and achieved some positive results. On the other hand, many critical issues pertaining to the management of technologies for anti-disaster robots and robots that performed insufficiently were also revealed, but all of the known facts are very valuable to improve the technologies of anti-disaster robots and to apply them to practical use. It is important to learn constructive lessons from as many experiences as possible.

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