

# Development of High-Access Survey Robot for TEPCO's Fukushima Daiichi Nuclear Power Station

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## ABSTRACT

A high-access survey robot system was developed to acquire images, doses of radiation, temperature, and humidity in locations high above the floor inside the reactor building at Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Station, where there is a high level of on-site demand for this capability.

This robot system has a crawler-type high-place work cart modified for remote operation and is equipped with an arm having 11 joints that can reach to a height of seven meters. It is also able to insert the arm tip deep into narrow spaces at locations high above the floor. The mechanical and electrical systems were developed according to requirements formulated using information brought from the site. An operating interface was also developed to reduce the burden of remote operation. Functionality assessments were carried out by endurance testing with a mock-up as well as by proving tests conducted in a reactor building at Hamaoka Nuclear Power Station, a physical environment that closely resembles the one in the Fukushima Daiichi Nuclear Power Station.

This robot performed missions twice in Unit 2 Reactor Building, on June 18 and July 23, 2013, and once in Unit 3 Reactor Building, on May 13, 2014, for a total of three missions. It acquired doses of radiation, which had not been available before then, from the upper areas inside the reactor building, as well as images from the vicinity of the primary containment vessel. It also acquired data on the geometry inside the reactor building that will contribute to various upcoming tasks involved in decommissioning of the reactor.

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## 1. Introduction

The Great East Japan Earthquake of March 11, 2011 was accompanied by an accident at the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Station (hereafter referred to as 1F). Since that time, there have been numerous hopeful calls for Honda to send in a robot on-site. There has also been a strong desire in-house to contribute somehow to improvement of the current state of affairs.

Given this background, Honda joined with the National Institute of Advanced Industrial Science and Technology (AIST) and Tokyo Electric Power Company (TEPCO) in June of the same year to start a three-party survey of on-site application of robot technology.

At that time, the situation inside the reactor building was still largely undetermined, so it was necessary first of all to carry out a survey of the interior circumstances. Initial surveys of the interior were, in fact, performed by compact robots about one meter in length. Packbot<sup>(1)</sup>, for instance, made a survey of the ground floor of the reactor building, and led the way for other robots. Quince<sup>(2)</sup> climbed the stairs to the second and third floors and performed surveys

there and of the operating floor above. Survey Runner<sup>(3)</sup> performed a survey of basement floors. As a result, the state of affairs and radiation doses in the reactor building up to 1-1.5 m high above the floor were determined.

With these compact robots, however, it was difficult to survey areas near the ceiling (locations high above the floor) on the first floor. These were areas inferred to be contributing a large proportion of the air dose in the reactor building. Locations high above the floor in the reactor building contain a complex maze of piping, ducts, cable racks, and other such potential obstacles that make surveys even more difficult to carry out.

The Honda team therefore developed a high-access survey robot capable of reaching to a height of seven meters as well as reaching deep inside narrow places to measure radiation, temperature, and humidity, and to acquire imagery. Figure 1 shows the high-access survey robot. On the left is the robot in driving posture and on the right its higher extended posture for surveying high locations.

This robot is made up of a high place work cart and a survey arm for which AIST and Honda were respectively in charge of development.

In following sections, this paper will relate the

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development of the high-access survey robot, with a focus on the survey arm developed by Honda. It will describe how the requirements for the robot were determined, how the information for determining them was obtained under circumstances that did not allow direct entry to the 1F site, how a robot that would definitely be able to operate in the reactor building was developed, and how the robot was used in actual missions.

## 2. On-Site Circumstances

### 2.1. Survey Location

1F has nuclear reactor Units 1 to 6. Apart from Units 5 and 6, which avoided damage, surveys of reactor building interiors for the other reactors, Units 1 to 4, have been proceeding since the accident. These surveys are crucial for the planning and efficient implementation of future reactor decommissioning work. The first floor of these reactor buildings is where the robot is slated to perform surveys.

A cross-sectional view of a Boiling-Water Reactor (BWR) building of the same type as 1F is shown in Fig. 2, and a top view of it in Fig. 3. In the center of these is the Primary Containment Vessel (PCV), with various facilities and equipment installed around it. The developed robot is intended to perform surveys on the ground floor and in particular of the upper part of the Traversing Incore Probe (TIP) room, the upper part of the personnel access airlock

room, and the catwalks in the vicinity of the PCV shown in Fig. 3. All of these locations are constricted spaces containing multiple pipes and are difficult to access.

### 2.2. On-Site Circumstances and Requests Regarding the Robot

#### 2.2.1. Requests regarding the robot

Discussions with TEPCO showed the on-site need for a robot described as follows;

- (1) Capable of acquiring radiation dose, temperature and humidity data, and imagery from narrow spaces at high locations;
- (2) Be introduced on-site as quickly as possible;
- (3) Able to perform as many surveys as possible during one mission;
- (4) Possess a high level of operability;
- (5) Able to be operated by personnel wearing layers of protective clothing and gloves;
- (6) Able to perform its missions even during light rain;

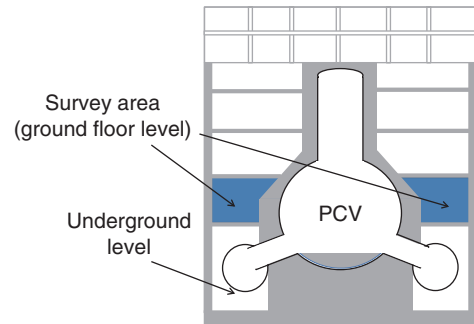


Fig. 2 Cross-section view of BWR reactor building



Fig. 1 High-Access Survey Robot  
The driving posture (left) and higher posture (right)

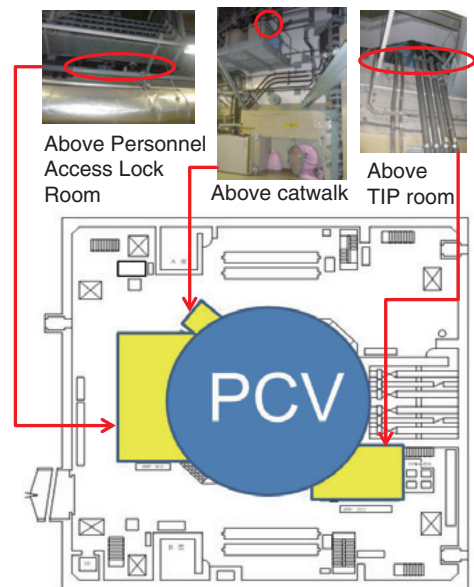


Fig. 3 Top view of BWR reactor building of ground floor  
The survey target areas are filled with yellow.  
(Images provided by Chubu Electric Power Co., Inc.)

- (7) Definitely able to make its way back out of the reactor building;
- (8) Will not damage facilities inside the reactor building; and
- (9) Able to repeat operation for at least 16 missions.

### 2.2.2. On-site circumstances

The circumstances in front of the reactor building, where the robot begins its movement, and inside the building, are as follows.

- (1) There are locations with high-dose radiation in front of and inside the reactor building, and people cannot remain at those locations for extended periods of time.
- (2) In front of the reactor building, there are differences in level where there are steel plates, uneven terrain where there is some gravel and so on.
- (3) Inside the reactor building, facilities may have been damaged at some locations and there are no accurate pictures that show on-site conditions.
- (4) Inside the reactor building, there are places where water drips down and there are puddles of water.
- (5) In the upper part of passageways inside the reactor building there is temporary piping, work platforms and scaffolding, and ducts installed at a height of about two meters, as shown by the red arrow in Fig. 4. Work materials and equipment are also located on the floor along the sides of passageways.
- (6) Survey locations are high above the floor, and survey work can be particularly difficult where such locations are constricted and convoluted due to piping and other obstructions.
- (7) There is airborne radioactive material inside the reactor building.

These on-site conditions and requests were made into requirements in the various areas of mechanical systems, electrical systems, and operating interface. Design and development of the robot system were carried out accordingly.



Fig. 4 Inside reactor building (Image provided by TEPCO)

Table 1 Specification of high-access survey robot

|                      |                        |                                                            |
|----------------------|------------------------|------------------------------------------------------------|
| Entire robot         | Length                 | 1.8 m                                                      |
|                      | Width                  | 0.8 m                                                      |
|                      | Minimum height         | 1.8 m (when driving)                                       |
|                      | Maximum height         | 7.0 m                                                      |
|                      | Weight                 | 1.1 t                                                      |
|                      | Operating time         | 5 hours                                                    |
| High place work cart | Maximum velocity       | 2 km/h                                                     |
|                      | Maximum incline        | 15 degrees (back and forth)<br>20 degrees (right and left) |
|                      | Maximum bumping height | 60 mm                                                      |
| Survey arm robot     | Length                 | 1.7 m                                                      |
|                      | DOF                    | 11 (except parallel link)                                  |

## 3. High-Access Survey Robot

### 3.1. System Overview

The developed robot system is a high place work cart modified to enable remote operation and is equipped with a survey arm having 11 degrees of freedom. Table 1 shows the main specifications.

The length, width, and height in these specifications were decided according to the on-site passageway conditions described in section 2.2.2.

Figure 5 shows the sensors installed on the robot. For data acquisition purposes, the tip of the arm has a camera, dosimeter, thermo-hygrometer, and other such instruments. In order to enable passage through narrow spaces, the cart is equipped with cameras to show the area around the cart, cameras to check for obstacles to the upper part of the cart, Laser Range Finders (LRF) attached to the cart and to the tip of the arm, and other such equipment.

### 3.2. Operating Procedure

As shown in Fig. 6, the robot is operated over a wired LAN using a remote operation device (the operation PC) in the important anti-seismic building.

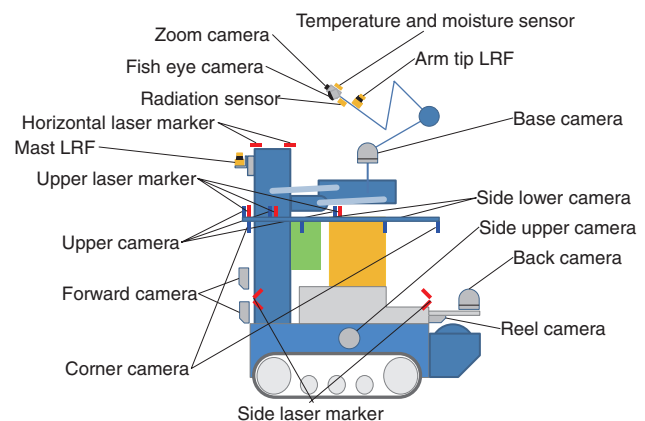


Fig. 5 Robot sensors

The LAN extends to the switching hub in front of the reactor building. The robot is transported by truck from the robot warehouse to the front of the reactor building, where the optical fiber cable installed on the robot is attached to the switching hub. Travel from there to the survey locations inside the reactor building and back, and the survey activity, are performed by means of the operation PC. When the surveys have ended and the robot exits the reactor building, it will be disconnected from the LAN and returned by truck to the robot warehouse. Communications will all be conducted through wired connections, except during emergencies. This is to avoid the risk that radio communication will be interrupted and to make certain that the robot will return.

At a survey location, the robot will be instructed to extend its mast and move its survey arm to acquire data on the survey location. The data is transmitted to the operation PC in real time.

Work sessions are anticipated to be completed within five hours.

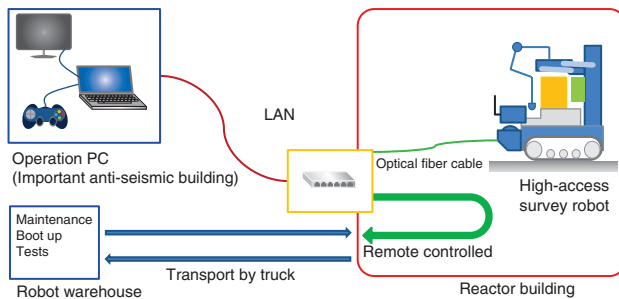


Fig. 6 Use case of robot

#### 4. High Place Work Cart

A commercially available aerial work platform was used as a base for development in order to send in the robot as quickly as possible. The high place work cart has a low center of gravity in the first place, and the weight of the lower portion was further increased and the cart was given sufficient width, even where narrow, to assure stability. Its maximum travel speed is 2 km/h with a maximum bumping height of 60 mm. The cart was also equipped with cameras: two each were installed front and back, eight pointing downward around the periphery of the cart, and two on the sides pointing upward. The cart width is indicated using laser markers and LED lights to enable movement through narrow passageways in building areas where there is no illumination.

The optical fiber cable used for communication allowed for movement to a distance of 400 m when paid out from its reel. While the robot is moving, any excess length that occurs in the optical fiber cable could cause it to break if it becomes tangled with itself or caught on the body of the robot or on something in the environment. This is avoided by exercising control to maintain tension in the cable.

#### 5. Survey Arm

A compact, highly reliable arm system was developed within a short time by maximizing the use of ASIMO<sup>(4)</sup> technology that had a record of results.

##### 5.1. Mechanical System

The main requirements for the robot's mechanical system, based on sections 2.2.1 and 2.2.2, are as follows.

- Requirement 1 That it not interact with upper obstacles while the robot is traveling
- Requirement 2 That the mast not interact with obstacles at high locations when being raised and lowered, and that the arm can be brought close to survey objects
- Requirement 3 That the tip of the arm can be inserted deep into narrow spaces
- Requirement 4 That it not break down under rainfall when traveling outdoors or under dripping water when indoors
- Requirement 5 That it allows decontamination of adhered radioactive substances
- Requirement 6 That it be capable of operating for extended periods of time

Development was conducted on the basis of the above requirements.

Specifically, requirements 1 and 2 were satisfied by development of the arm transfer mechanism. Requirement 3 was satisfied by the articulated arm. Requirements 4 and 5 were addressed by development of dustproofing and drip-resistant functionality.

In order to satisfy requirement 6, reductions in electric power consumption were achieved by using the frame structure and configuration as well as technology for the motor and reduction gears that were cultivated during ASIMO development.

The arm transfer mechanism, articulated arm, and dustproofing and drip-resistant functionality will be explained in detail in the following sections.

##### 5.1.1. Arm transfer mechanism

Given requirement 1, the developed robot needs to limit its total height while traveling. The aerial work platform used as a base, however, had a total height of 1.73 m, so that when the arm was mounted on top of it, the total height exceeded two meters, which would interact with upper obstacles. It would be desirable, therefore, to locate the arm on the periphery of the mast while the cart is traveling. On the other hand, it would be desirable to locate the arm on top of the mast while surveying due to requirement 2, so as to minimize the lift up area while the mast is being raised and lowered, and to meet the requirement that the arm be brought close to the survey object.

An arm transfer mechanism that uses a parallelogram link mechanism was therefore designed. As shown in Fig. 7, lowering the arm and folding it away while the cart is

traveling reduces the total height, and moving the arm onto the top of the mast while elevating it reduces the lift up area so that the arm can approach closely to the survey object.

These measures kept the robot compact while traveling, with a total height of 1.8 m. While surveying, it can rise through a high, narrow area of just 0.7 m square and reach a total height of 7.0 m.

### 5.1.2. Articulated arm

Given requirement 3, avoiding obstacles while approaching closely to the survey object necessitates an articulated arm. An articulated arm with normal redundancy typically has seven joints, which adds one axis as a redundant degree of freedom to the basic six axes that determine the position and attitude of the robot arm-end. Since the developed arm here will be inserted deep into a narrow spaces while avoiding obstacles, three more axes were added as redundant degrees of freedom, with another added to the arm-end to use in changing the attitude of sensors and cameras installed on the arm-end. This makes for an articulated arm with a total of 11 axes of motion.

The robot's axes were configured (Fig. 8) so as to shorten the computation time required for control of the arm. The base, shoulder, and wrist were therefore each given three orthogonal axes. A particular effort was made to allow a large angle of available motion on the Z-axis in the shoulder region as well as to take the feasibility of having three orthogonal axes into account. As a result, the axes were placed in the order Z, Y, and X from the base.

In order to avoid obstacles and to approach closely to the survey object for investigation, the arm tip is equipped with an LRF to observe conditions at the insertion point and around the arm tip and check for obstacles. There is a zoom-lens camera to look in the direction of the arm tip and a fisheye-lens camera to view the arm-tip periphery. There are also a dosimeter to measure radioactivity, a thermo-hygrometer, and a six-axis force sensor (6AF) for contact sensing mounted on the wrist and on the base. An inertial sensor to detect attitude is also mounted on the base, as are

two dome cameras to observe the periphery when the arm is being raised and lowered and when it is being inserted.

As stated in item (8) of section 2.2.1, two base axes, one shoulder axis, one elbow axis, and the arm transfer mechanism are equipped with brakes so that the robot will not damage equipment or facilities if power to the drivetrain is interrupted. These brakes enable the robot to maintain its attitude. Details will be given in section 5.3.2.

### 5.1.3. Dustproofing and drip-resistant functionality

Requirement 4 necessitates drip-resistant functionality while requirement 5 necessitates shapes that can be easily decontaminated and/or dustproofing functionality.

As shown in Fig. 9, a cover that encompasses the entire arm was developed. The reason for this was that an articulated arm may be subjected to penetration by water from every direction. Also, since the arm has many component parts that have complex shapes, making it

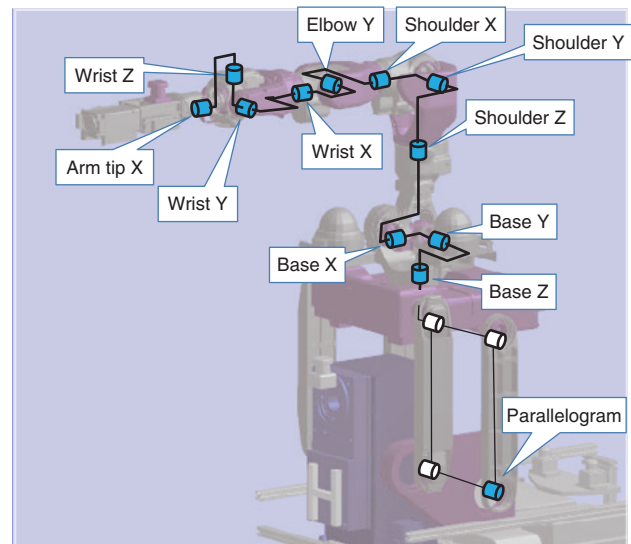


Fig. 8 Joint configuration of arm

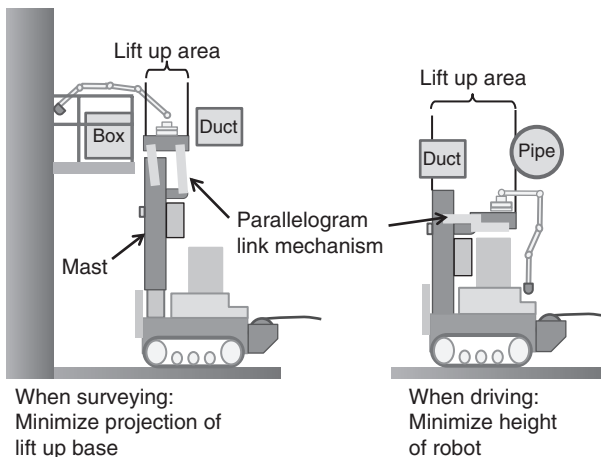


Fig. 7 Arm transfer mechanism



Fig. 9 Cover for arm  
Four arrows indicate holding points

drip-resistant and capable of decontamination by wiping is difficult. Development used cloth bonded to a water-resistant film with water pressure resistance to 20,000 mm H<sub>2</sub>O and further took the following matters into consideration.

(1) It can readily be changed.

If large amounts of radioactive material adhere to the cover, the robot will be decontaminated by changing the cover. In order to reduce the amount of radiation exposure by workers when this is done, it is necessary for the cover to be changeable in a short time. In order to avoid catching or damaging the cover, corners in the robot arm are rounded or have resin covers attached to give it a smoother shape.

(2) It does not obstruct movements of the arm.

The developed arm has numerous joints and a wide range of movement. Therefore, a tight cover that closely follows the contours of the arm would subject the 6AF and drivetrain to the load generated by the stretching or twisting of the cover. On the other hand, a loose cover could become jammed in the joints or catch on objects in the environment. In either case, the arm movement would be affected and the cover itself could be damaged. Many prototypes were therefore created and repeatedly tested, and the outcome was a water-resistant cloth with 130% stretchability that is held in place at four locations, as shown by the red arrows in Fig. 9. This realized a cover that does not obstruct arm movement.

Item (1) above was confirmed by a worker who performed the operation in a short time during operational training. Results for item (2) above will be described in section 7, on reliability testing.

Drip-resistant construction will be discussed next. Drip-resistant functionality was realized for electrical equipment, such as sensors, batteries, switches, and charging connectors, and for the arm transfer mechanism by covering them in a shape that facilitates decontamination. The battery compartment, for example, is subject to penetration by water from above, and also must allow airflow and passage of wiring, so its drip-resistant functionality was achieved through a labyrinth structure and drainage structures.

A waterproof cover that covers the entire robot was also prepared to protect the robot from rainfall while being transported outdoors by truck.

## 5.2. Electrical Systems

In order to respond to demand for early on-site introduction of the robot, it was necessary to develop it within a short period of time. For this reason, highly reliable hardware and firmware that had a track record from use in ASIMO were also used in electrical systems as a base for development of control systems for the 11-axis articulated arm and arm transfer mechanism. In addition, new functionalities were developed such as external environment recognition, power source systems for the purpose of extended operation, dustproofing, and drip-resistance of printed circuit boards (PCB).

### 5.2.1. Control system

When the arm is being inserted into a narrow space, it is essential to have compliance control to allow contact with the environment so that operation errors or other such reasons do not result in damaging facilities or equipment caused by the arm interacting inside the reactor building. For that purpose, it was necessary to obtain data of forces applied to the arm and the angles of the joints in real time, and to drive the joints accordingly. The distributed control system developed for ASIMO was therefore applied to this robot. Data from the 6AF and inertial sensor located at the wrist and base of the arm, as well as from the joint encoders, are used to transmit control commands to the various motor drivers in real time.

### 5.2.2. Sensor systems

As shown in section 5.1.2, the developed robot possesses multiple external environment sensors for acquiring various data on the environment in narrow spaces at high locations. That sensor data must be transmitted to the operation PC in real time. It is also desirable to allow for the addition of new sensors as needed to meet further on-site needs. This led to the selection of sensors possessing USB or LAN interfaces that are scalable by means of hubs.

Selection of the dosimeter also involved the following special conditions:

- (1) Should possess an on-site record of performance;
- (2) Should be capable of acquiring data in real time; and
- (3) Should be capable of directionality for the purpose of estimating radiation source locations.

The dosimeter satisfying given conditions (1) and (2) above transmits data using infrared communication. The infrared receptor located at the arm tip, however, was subject to being influenced by the LRF and other such optical equipment, and a shield was therefore installed.

Satisfying condition (3) above, however, would ordinarily involve not shielding the dosimeter so that it can measure air doses of radioactivity. The dosimeter was therefore given directionality by attaching a lead cover that can be used to shield the five faces other than the measurement face of the dosimeter when necessary for identifying a radiation source. Identification of radiation sources was further enabled by changing the attitude of the arm tip.

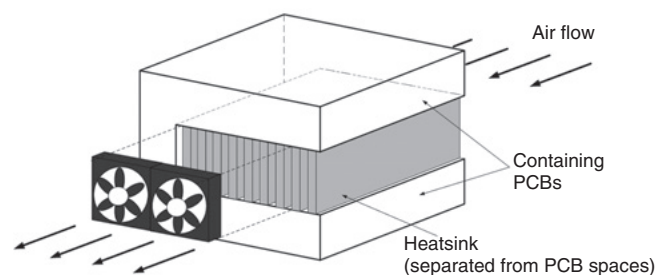


Fig. 10 Enclosure for electric devices

### 5.2.3. Power source systems

Based on section 3.2, since the developed robot must be able to operate for five hours, batteries developed for ASIMO were installed.

A new system was also developed for recharging batteries after a mission has ended. This allows multiple batteries to be recharged on-board, thereby reducing the amount of radiation to which workers are exposed.

This system uses a constant-voltage constant-current method in order to protect against over-charging. In the constant-voltage charging region close to a fully charged state, the amount of charge per unit time diminishes. However, if the interval to the next mission is not sufficient to fully recharge, more efficient recharging is required. Rather than fully recharging each individual battery, therefore, it was decided to switch batteries that need recharging at fixed time intervals so that all the batteries can be recharged rapidly in a constant-current region where charging is efficient.

### 5.2.4. Printed circuit board design for cooling, dustproofing, and drip resistance

It is necessary to assure the drip resistance of electrical components during operation outdoors and inside a building where water leakage may occur. Meanwhile, the system as a whole generates several hundred watts of heat, necessitating achievement of a balance between drip resistance and cooling performance, under the following constraints.

- (1) Due to external heat discharge and cable layout, it is desirable to distribute electrical components to the various arm link locations. The drip-resistant cover described in section 5.1.3, however, makes it difficult to discharge heat from the arm into the air.
- (2) The use of air-cooling is likely to draw radioactive substances into the robot interior, which would be difficult to decontaminate by wiping or other such methods. Therefore, the method of blowing air against the PCBs cannot be used.
- (3) The cooling apparatus must not hinder movement of the arm and should be of a size that allows for a smaller lift up area when the mast is raised and lowered.

In order to satisfy above constraints (1) to (3), a compact enclosure was developed that could concentrate the PCBs in one location in a size (200×280×300 mm) that could be positioned on the rear surface of the mast. As shown in Fig. 10, the enclosure is hollow and has a heatsink located in the hollow portion, separated from the interior portion of the enclosure where the PCBs are housed. Heat simulation was used to arrange the PCBs in a layout that would transfer the quantity of heat in the enclosure to the heatsink and keep the device temperature of each PCB within the rated range. A fan attached to the exterior was then used to cool the heatsink.

## 5.3. High Reliability Design

Given the requests in section 2.2.1, the developed robot

had the following specific requirements.

- (1) It must not damage facilities or equipment inside the reactor building.
- (2) It must definitely make its way back out without becoming stuck.

With regard to item (1) above, measures were taken to deal with the problem in the hardware that controls the survey arm at a point when the arm has been inserted into a narrow space. Fail-safes used in ASIMO were employed so that the arm would maintain its attitude without moving, depending on the problem, or a process would function to shut off the drive power, thereby preventing damage to equipment, facilities, or the robot itself.

With regard to item (2), in the unlikely event that the robot becomes stuck, the high levels of radioactivity inside the reactor building would make it difficult for workers to recover the robot. The developed robot is also relatively large and would interfere with future reactor decommissioning if unable to return. The reasons preventing its return were therefore analyzed and recovering procedures were prepared, together with multiple emergency detour procedures in the event that a system cannot be recovered. These procedures were built into the robot systems, increasing reliability. Some representative functions are described below.

### 5.3.1. Remote rebooting function

A rebooting device was developed to restore arm systems from the operation PC. This is intended to enable the robot to return even if control software deadlock occurs, or a CPU or other such component hangs, or another such system problem occurs.

As shown in Fig. 11, the connection between Hub1 and Hub2 passes inside the mast, so there is a possibility that the cable could be severed when the mast is raised or lowered. A separate communication line was therefore installed to transmit a reboot command by way of the cart controller. This establishes dual system redundancy for the reboot procedure and thus increases reliability.

### 5.3.2. Joint brake function

If the arm system experiences an abnormality while

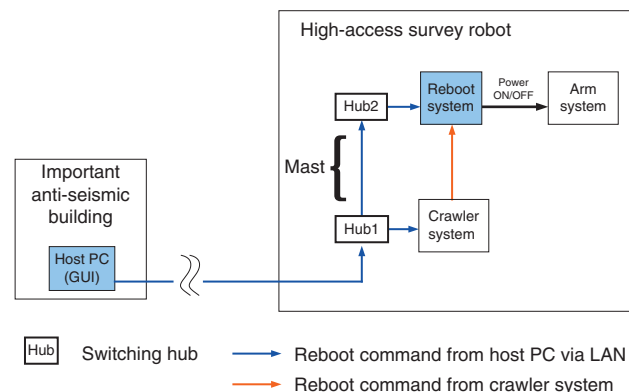


Fig. 11 Remote rebooting system

performing a survey at a location high above the floor, a reboot of the system as described in the preceding section could be considered. If this course is taken, the drive power source for the arm will also be cut off. Depending on the arm's posture, its own weight may cause the joint to move, interacting with equipment or facilities inside the reactor building. Consequently, non-excitation actuating brakes were installed on those joints that could experience a significant change of position due to the arm's own weight when drive power is not being supplied. This enables the arm to maintain its posture in those conditions.

In the unlikely event of a fatal abnormality that prevents recovery of the arm system even when the remote rebooting function is used, the cart will have to be operated to return with the arm held in position. It is conceivable, however, that with joints held in position by brakes, the arm might catch on equipment or facilities inside the reactor building. Taking this into consideration, dual systems were put in place so that the brakes on individual joints could be released not only by the arm system, but also remotely through the cart system.

### 5.3.3. Functionality for radio communication with rescue robot

The developed robot moves while paying out optical fiber cable. There is a possibility, therefore, that repeated bending at corners and other such actions may cause attenuation of the light intensity, or the cable may catch on some sharp object and be severed, terminating communication. Dual systems were therefore established so that both wired and wireless means of communication are available. Should communication by optical fiber cable fail, a rescue robot equipped with a radio is dispatched to the site to restore communication by radio.

Considering that the wired LAN connection between the arm system and cart system could also be broken, or that the radio equipment could malfunction, separate radio equipment was also installed in the arm and in the cart. The robot radio was configured with different Service Set Identifiers (SSID) on the arm and on the cart. The rescue robot can switch the SSID, thus realizing dual system redundancy.

## 6. Operating Interface

The developed robot is used in an environment where people cannot remain for extended periods. Consequently, sufficient training cannot be given in advance, and responses to unanticipated on-site circumstances may be required. The actions involved in inserting the arm into a narrow space that includes piping, ducts, and so on in a high place may also cause contact with the environment, resulting in damage. For these reasons, precise operation is required, and a Graphical User Interface (GUI) with a high level of operability was developed. Operation of the robot takes place remotely from an important anti-seismic

building so as to minimize the operator's exposure to radiation. However, it may become necessary to operate the robot from a location near the reactor buildings if, for example, communication through the wired LAN between the important anti-seismic building and the switching hub in front of the reactor building, as shown in Fig. 6, is interrupted. At these times the robot will have to be operated by personnel wearing layers of protective clothing and gloves. In order to enable operation under these circumstances, it was decided against using a keyboard, opting for a mouse for arm operation and a gamepad for cart operation. This configuration allows operations to be separated into parts, thereby preventing operating errors by dividing up the objects of actions.

Feedback on the operating experience and other such factors was obtained from the actual operators during use so that the developed GUI could be given additional functionality and enhancements to make the interface intuitively understandable, less tiring, and less likely to produce errors. Figure 12 shows the arm operating screen in the developed GUI. The arm operating screen shows the arm position in animated form at the center of the screen. The camera displays are on the left side of the screen, and the controls for operating the arm are arranged on the right side of the screen.

The status of the arm and the cart are also displayed in icon form at the bottom of the screen where they can be instantly comprehended.

### 6.1. Methods for Representing the Environment to Operators

The goal of the developed robot is to perform surveys in narrow spaces through operation from a remote location. For that purpose, the surrounding environment is made known to the operator by presenting camera-acquired imagery. Camera imagery may omit depth information,

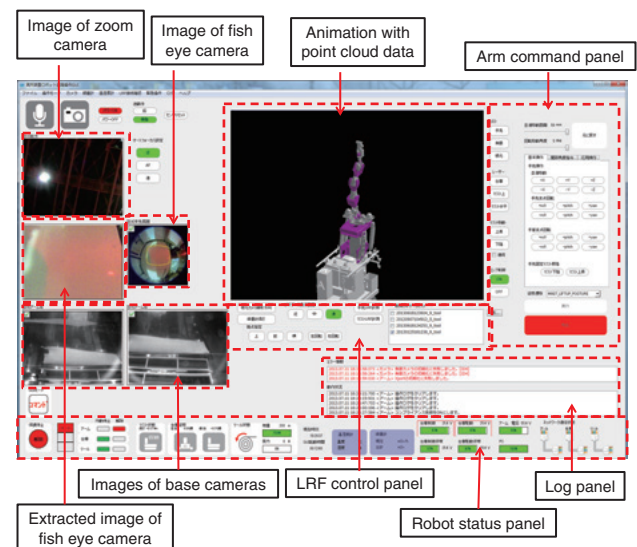


Fig. 12 GUI tab for survey arm

however, leaving the operator unable to judge the positional relationship between the arm and the environment. Then, when the arm is moved, it may come into contact with the environment.

On the arm operation screen, the camera imagery is presented only for the purpose of checking the presence and attributes of objects in the periphery. For ascertaining the positional relationship with the environment, the LRF installed on the arm tip is used. This LRF is a line-type two-dimensional scanner, and by rotating the arm tip, it can be used to acquire three-dimensional scanning data that is presented as point cloud data. A point cloud is a cluster of points that represents a three-dimensional position estimated from the data on position, attitude, and distance of an LRF when it is scanning an object. Presenting this information superimposed on the animated image in the center of the screen allows the positional relationship of the arm and an object to be checked from various points of view. Figure 13 (a)-(f) shows images of the environment presented to the operator following a scan.

Figure 13 (a) is a photograph taken of the robot exterior for reference. What the operator needs to check here is the positional relationship of the arm and the two bars shown inside red ovals. Imagery from the cameras installed on the robot, however, does not allow a grasp of positional relationships between the robot and the environment. As shown in Fig. 13 (b), (c), (d), and (e), therefore, the perspective of the animation depicting the point cloud and the robot is changed. The distances to the two bars can be determined from Fig. 13 (c) and (d). There can be cases, as shown in Fig. 13 (e), where the point cloud in the area being checked overlaps the depth dimension of the image that the operator wants to see, so that the area cannot be checked. When this happens, the press of a button in the GUI can erase the parts of the point cloud display that are distant from the robot. This eliminates the overlap on the depth dimension so that the system can display an image like that in Fig. 13 (f), from which the operator can easily check the distance.

### 6.2. Arm Movement Simulation Display

Arm operation involves checking the animation shown at the center of the screen in Fig. 12 while issuing

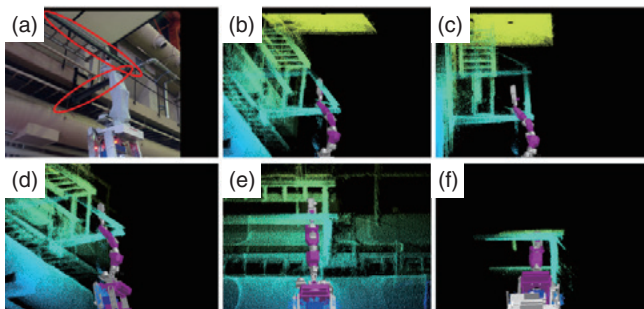


Fig. 13 Check minimal distances between robot and environment utilizing point cloud data

commands for the arm tip position and amounts of positional movement. Ordinarily the arm will be displayed as on the left side of Fig. 14. When the desired amount of movement is entered by the GUI, however, the intermediate postures are superimposed onto the display shown on the right side. In this way, the kind of movement the arm will make is simulated internally by the GUI and displayed, together with transitional positions during the movement, before the movement command is issued. The operator can therefore check in advance whether there will be any contact with the environment represented by the point cloud, as described in section 6.1, and so even operations in narrow spaces can be carried out with a sense of security.

### 6.3. Synchronized Movement of the Arm and Mast

In order to keep the arm from coming into contact with the environment when being inserted into a narrow space, it is necessary to perform mast elevating operations linked to arm operations. For example, when entering a narrow space laterally as shown in Fig. 15 (a), raising the mast while moving the arm into the narrow space allows the arm access deep inside the space. As it happens, the mast elevating function of the developed robot is a repurposing of the hydraulic lift on the cart, which is not capable of accurate movement instructions or synchronized movement. What is done, therefore, is to raise the mast as shown in Fig. 15 (b) for a unit of time. The amount it was raised is then measured, and the arm is moved vertically by an amount that will cancel out the amount the arm was raised by the mast movement. After this operation has been repeated a number of times, the arm will be

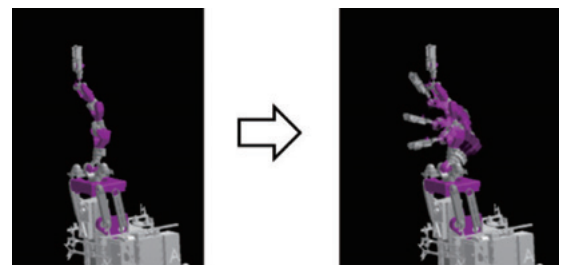


Fig. 14 Preview of arm movement

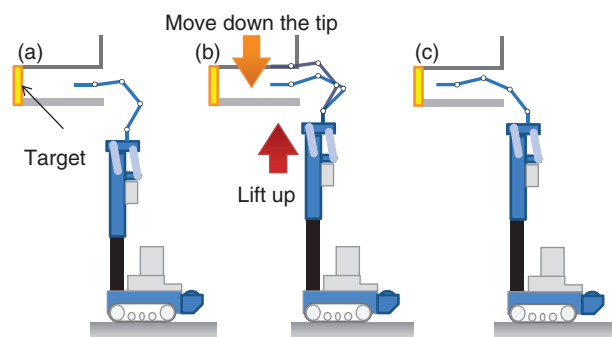


Fig. 15 Synchronization mast and arm movement

moved into the space as shown in Fig. 15 (c). As there is a possibility of contact with the environment when this is done, the amount the mast will be raised at one time is limited to about 10 mm. Since the amount the mast is raised is limited, this operation will have to be performed a number of times. However, the movement of raising the mast and then canceling out that amount by moving the arm can be configured as a single operation so that contact with the environment is avoided while mitigating the burden on the operator.

## 7. Reliability Testing

Reliability requirements were determined from the on-site environment and number of times of robot operation. The number of times of robot operation cited in section 2.2 was multiplied by a safety factor of 5 to arrive at 80 times of operation as the endurance requirement. The number of hours per mission is five hours. Reliability testing consists of endurance testing and environmental testing. The requirements are shown in Table 2.

As to radiation resistance, no actual testing was conducted because it was decided to suspend use of the robot when exposure exceeds a cumulative 20 Sv. This is following “the basic conceptual approach for assessment and management of radiation resistance in general-purpose heavy machinery and robots.”<sup>(5)</sup>

### 7.1. Endurance Testing

#### 7.1.1. Endurance testing of electrical functions

For the new functions developed for use with this robot, the number of times they would be used in each mission was estimated and endurance testing of each function was carried out. In the case of the brake function, for example, it was confirmed that the switching devices that control brake operation would not malfunction under the surge voltage generated when multiple brakes were controlled simultaneously.

#### 7.1.2. Operating endurance testing

The arm joints were repeatedly made to move to the limit of their working range to confirm their endurance performance in mechanical terms. Confirmation was also made of matters such as that the cable would not be severed or broken by being dragged or bent, that the drip-resistant cover would not tear and that its elasticity presented no issues.

### 7.2. Environmental Testing

#### 7.2.1. Heat cycle test

Electrical components were housed in the compact enclosure described in section 5.2.4 and a temperature sweep test was conducted at 0-40°C for 30 cycles of eight hours. During and after the test, it was confirmed that there were no problems with actuator driving or with any electrical functions.

Table 2 Test conditions

| Test               |                     | Condition                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|--------------------|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Endurance test     | Electrical function | <ul style="list-style-type: none"> <li>Brake control, LED control and rebooting</li> <li>Charge and discharge of battery</li> </ul>                                                                                                                                                                                                                                                                                                                                               |
|                    | Mechanical function | <ul style="list-style-type: none"> <li>Repetitive movement to all working range : 40 h</li> <li>Parallelogram link mechanism : 400 cycle</li> </ul>                                                                                                                                                                                                                                                                                                                               |
| Environmental test | Heat cycle test     | <ul style="list-style-type: none"> <li>0 to 40°C</li> <li>30 cycle (8 h/cycle)</li> <li>Transition               <ul style="list-style-type: none"> <li>(a) 0 to 40°C : 2 h</li> <li>(b) 40°C constant : 2 h</li> <li>(c) 40 to 0°C : 2 h</li> <li>(d) 0°C constant : 2 h</li> </ul> </li> </ul>                                                                                                                                                                                  |
|                    | Hygrothermal test   | <ul style="list-style-type: none"> <li>Temperature: -10 to 40°C</li> <li>Humidity: Less than 90%</li> <li>1 cycle</li> <li>Transition               <ul style="list-style-type: none"> <li>(a) 5°C, 80%</li> <li>(b) 20°C, 31%</li> <li>(c) 0°C (Humidity uncontrollable)</li> <li>(d) 30°C, 80%</li> <li>(e) -10°C (Humidity uncontrollable)</li> <li>- Waiting for heating up of arm system (40 min)</li> <li>- Reboot arm system</li> <li>(f) 40°C, 90%</li> </ul> </li> </ul> |
|                    | Vibration test      | <ul style="list-style-type: none"> <li>Acceleration : Less than 5 G</li> <li>Vibration : 10 to 500 Hz</li> <li>11 min log sweeping</li> <li>30 h</li> </ul>                                                                                                                                                                                                                                                                                                                       |
|                    | Rainfall test       | <ul style="list-style-type: none"> <li>10 mm/h, 25 min (without wind)</li> <li>10 mm/h, 10 min (with wind)</li> </ul>                                                                                                                                                                                                                                                                                                                                                             |

#### 7.2.2. Hygrothermal testing

Since the robot may be operated in winter, the system is required to start at -10°C. The robot was therefore placed inside the hygrothermal test apparatus and put through one cycle of the test pattern shown in Table 2. It was confirmed that acquisition of sensor data on the environment, control of the arm, and control of the cart does not have any problems.

#### 7.2.3. Vibration testing

Conditions when the robot travels inside the reactor building and when it is transported by truck were envisioned and then vibration requirements were determined. Robot travel conditions inside the reactor building were determined from travel data acquired from another robot operating inside the reactor building and truck transport conditions were based on data acquired during actual transportation by truck. According to this data, the vibration condition was set at 5 G. With vibration testing of independent electrical systems and of the robot arm conducted under those conditions, it was confirmed that no screw loosening or other such mechanical defects occurred, and that there were no issues in operation of the system as a whole.

#### 7.2.4. Rainfall testing

After workers unload the robot from a truck near the reactor building, the robot enters the reactor building under its own power, controlled by remote operation. It is conceivable that the robot could be affected by rain during that time. Taking the time required for the work and self-propelled travel into account, the rain exposure was set at 5 mm/h of rain for 20 minutes. Rainfall testing was conducted accordingly. Before testing, water submersion indicator

stickers were applied to locations where drip-resistance is necessary, and it was confirmed after testing that no water infiltration had occurred at any of those locations.

## 8. Field Testing

The robot systems were put through actions similar to those on an actual mission in a location resembling the actual use environment. System functions were assessed, and then functions for addition as well as points for improvement were identified.

The field testing was conducted at Unit 2 of Hamaoka Nuclear Power Station of Chubu Electric Power Co., Inc. This facility ceased commercial operation in 2009, it is approximately the same age as Units 1 to 4 at 1F, and it was constructed in a similar physical configuration.

Figure 16 shows scenes of the field testing. The photograph at the upper left shows the personnel access airlock room, the one on the upper right shows a penetration section on a catwalk, and the two on the bottom show the survey being conducted in the TIP room.

This field testing revealed the existence of a number of issues relating to the arm, as follows.

For example, there is limited space in front of the TIP room, and it was found that when the arm was moved from the driving posture shown in Fig. 7 to a higher extended posture, it would collide with facility features. The space required for this posture transition was therefore made smaller by breaking down the intermediate postures between driving posture and higher extended posture into smaller increments.

It was also found that operating the robot took more time than was initially anticipated. The overall mission time was therefore reduced by various means. When the arm is inserted into a narrow location, for example, the commands used to insert it are reversed in sequence by using the undo command to withdraw the arm. For another example, when

scanning with the LRF, the rotation of the arm tip was made faster to reduce the time taken in scanning.

## 9. Missions

Missions at 1F were conducted twice at Unit 2 and once at Unit 3.

### 9.1. Overview of Mission at Unit 2 Reactor

The mission at Unit 2 was made up of two steps. Figure 17 shows the areas where the robot conducted surveys for this mission and the postures taken by the robot while surveying for each step.

In the first step, the robot carried out an overall survey of the west side of the upper part of the ground floor of the reactor building. It made radiation dose and other measurements and acquired imagery.

In the second step, the robot arm was inserted into a narrow place for the purpose of acquiring imagery in the vicinity of a penetration on the southwest side of the PCV.

### 9.2. Results of Mission at Unit 2 Reactor

As a result, it was found that the radiation at locations high above the floor, where measurements previously could not be made, was 7-18 mSv/h and did not significantly differ from the radiation at lower locations. No damage to facilities or equipment was found near the ceiling in areas where the survey was conducted.

Some of the images acquired in the second step, which took place on July 23, 2013, are shown in Fig. 18<sup>(7)</sup> and Fig. 19<sup>(7)</sup>.

The imagery resulting from the survey did not reveal any damage to facilities or equipment in the upper part of the personnel access airlock room. The surface of the PCV wall could not be examined in detail, but there are large numbers of pipes, ducts, and cables on the upper part of the PCV, and the existence of narrow spaces was confirmed.

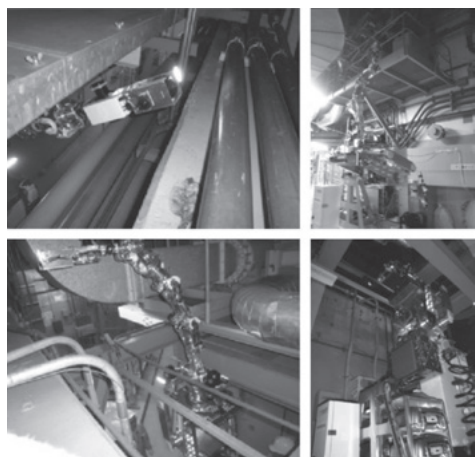


Fig. 16 Experiments in Hamaoka Nuclear Power Station (Images provided by Chubu Electric Power Co., Inc.)

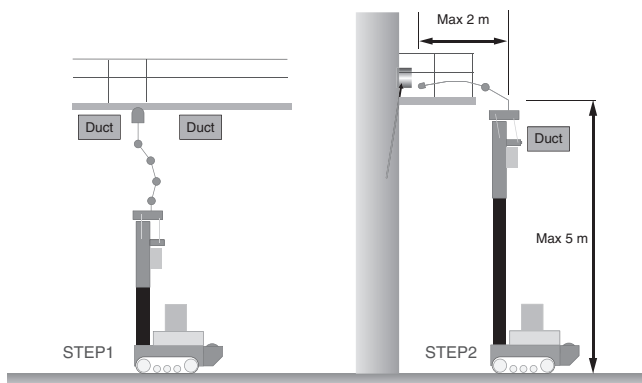


Fig. 17 Robot postures when robot surveying in missions  
The left shows the step 1 and the right shows the step 2.

### 9.3. Mission at Unit 3 Reactor

The mission at Unit 3 Reactor took place on May 13, 2014. With a view to surveys inside the PCV, measurements were made of air dose, of the shapes of objects that would interfere with work, and of other such elements at a height of 2.4 m in the vicinity of the PCV penetration, which is to be used for the survey. The on-site radiation at the measurement points was a maximum of 98.3 mSv/h.

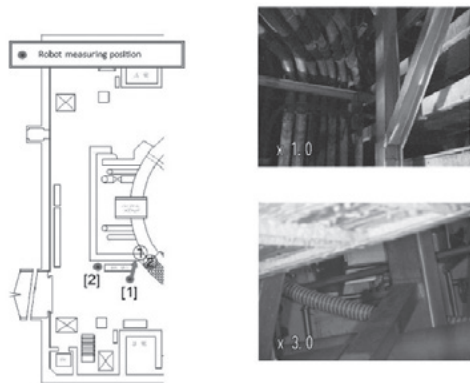


Fig. 18 Result of mission 2 (Provided by TEPCO)  
The pictures show the images of ① and ② from [1], respectively.

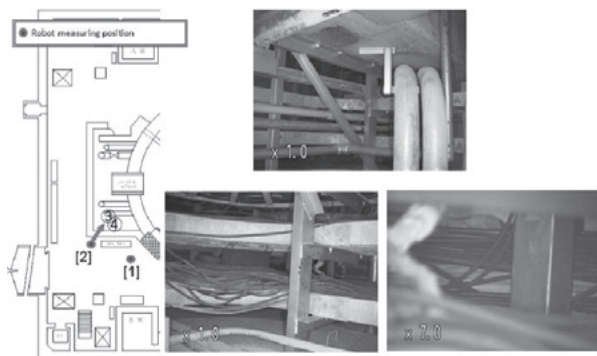


Fig. 19 Result of mission 2 (Provided by TEPCO)  
The top and bottom left pictures show the images of ③ and ④ from [2], respectively. The bottom right picture enlarges the image of the bottom left.

## 10. Conclusion

A highly reliable high-access survey robot system was developed to carry out surveys in narrow spaces at high locations. Its purpose is to contribute to the work of dealing with the accident at TEPCO's Fukushima Daiichi Nuclear Power Station.

In the limited time available for development, a system capable of actual use was developed to carry out surveys of the Fukushima Daiichi Nuclear Power Station reactor

building, where people are unable to enter and remain for extended periods of time. Use was made of existing systems in order to achieve the capability.

For that purpose, a detailed survey was made of on-site conditions and on-site needs regarding robots were ascertained. Development was carried out on the basis of requirements formulated accordingly. Reliability testing was then used to confirm the requirements, and tests were also carried out in an environment resembling that on-site. Problem areas in the system as a whole were revealed in this way and measures were taken to address them.

During the three missions that were conducted, imagery and radiation data were successfully obtained on locations high above the floor of the first story of the reactor building, where conditions had not been ascertained up to that point.

It was also confirmed that three-dimensional data inside the reactor building could be obtained from the point cloud used to operate the robot. This data is also slated to be employed in various upcoming tasks involved in reactor decommissioning.

The developed robot is slated for continuing use at TEPCO's Fukushima Daiichi Nuclear Power Station to conduct radiation surveys and to acquire three-dimensional data on the reactor building interior.

## Acknowledgements

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## Reference

- (1) <http://www.irobot.com/en/us/robots/defense/packbot.aspx>
- (2) Nagatani, K., Kiribayashi, S., Okada, Y., Otake, K., Yoshida, K., Tadokoro, S., Nishimura, T., Yoshida, T., Koyanagi, E., Fukushima, M., Kawatsuma, S.: Emergency response to the nuclear accident at the Fukushima Daiichi nuclear power plants using mobile rescue robots, *Journal of Field Robotics*, Vol. 30, Issue 1 (2013)
- (3) [http://www.topy.co.jp/files/default/News\\_Release\\_survey\\_runner\\_F\\_1\\_.pdf](http://www.topy.co.jp/files/default/News_Release_survey_runner_F_1_.pdf), 2012/3/6
- (4) Shigemi, S., Kawaguchi, Y., Yoshiike T., Kawabe, K., Ogawa, N.: Development of New ASIMO, *Honda R&D Technical Review*, Vol. 18, No. 1, p. 38-44
- (5) <http://roboticstaskforce.wordpress.com/2011/05/20110427-rcpt-radiation.pdf>, (2011) (in Japanese)
- (6) Yokoi, K., Kato, S., Yamanobe, N., Yoon, W-K., Morikawa, Y., Ogure, T., Shigemi, S., Matsumoto, T.: Koshochosayo Robottoshisutemuno Kaihatsu, THE 31st ANNUAL CONFERENCE OF THE ROBOTICS SOCIETY OF JAPAN (2013) (in Japanese)

(7) [http://www.tepco.co.jp/nu/fukushima-np/handouts/2013/images/handouts\\_130724\\_06-j.pdf](http://www.tepco.co.jp/nu/fukushima-np/handouts/2013/images/handouts_130724_06-j.pdf)

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