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Unitization for portability of emergency response surveillance robot system: experiences and lessons learned from the deployment of the JAEA-3 emergency response robot at the Fukushima Daiichi Nuclear Power Plants

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Abstract

It was cleared that transportability of emergency response robots system had been very important. Therefore, RESQ series robots, which were developed by Japan Atomic Energy Research Institute (present, Japan Atomic Energy Agency: JAEA), were installed or stored in containers for easy transportation to the accident site. After Fukushima Daiichi NPPs' accidents occurred, JAEA modified a RESQ-A robot in order to meet the situation of the accidents with consideration of transportation. However, actual situation was beyond the anticipation, and unitization was required to deploy JAEA-3 robot to Fukushima daiichi NPPs. The actual confused situation was many rubble were scattered and temporary cables and hoses were constructed in the reactor buildings, so that reconnaissance robots should be conveyed by operators through limited route, should be reassembled in short time. JAEA modified again in order to unitize JAEA-3 robot system in Fukushima daiichi NPPs. It was lesson learned that emergency response robot system needed to be unitized for increase of portability, and that "Unitization policy for emergency response robot system" was developed.

Keywords: Fukushima, NPP accident, Emergency response, Robot system, Unitization, Unitization policy

Background

Development of nuclear emergency response robots after the JCO criticality accident

The JCO criticality accident occurred on September 30, 1999 when technicians making nuclear fuel using unapproved processes, poured too much around 20% enriched uranium nitrate into a precipitation tank. Stopping the criticality subjected workers to higher than normally approved radiation doses and it was recognized that nuclear emergency response robots were needed to respond to future accidents.

Three organizations developed nuclear emergency response robots: Nuclear Safety Technology Center, Japan Atomic Energy Research Institute [JAERI, now reorganized to Japan Atomic Energy Agency, (JAEA)], and Manufacturing Science and Technology Center (MSTC). The Nuclear Safety Technology Center developed the Monirobo-A and Monirobo-B for outdoors reconnaissance [1]. JAERI developed the RESQ series robots which included two RESQ-A, a RESQ-B, a RESQ-C, and a RaBOT for indoors reconnaissance [2, 3]. MSTC developed the SMERT-K, SMERT-M, SWAN, MARS-A, MARS-T, and MENHIR robots for indoor tasks [4, 5].

It was also recognized that it is important that the nuclear response robots can be immediately transported to the accident site. The outdoor reconnaissance robots were designed to be stored in a transport and control vehicle. The transport and control vehicle delivers the robots to the site and the robots are controlled from inside the vehicle. The indoor reconnaissance and task robots were designed to be stored and transported

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in containers. For the indoor reconnaissance and task robots there were additional containers for storage and transportation of the control systems. The containers were also designed to be the operator stations. For example, a RESQ system consisted of two containers (Fig. 1) with the two RESQ-A (Fig. 2), the RESQ-B (Fig. 3), the RESQ-C (Fig. 4), the robot controls, and accessory items. The list of accessory items included two diesel generators (Fig. 5). It was expected that the containerized systems could be delivered to the accident site as soon as trucks, trailers, and drivers could be arranged.

JAEA's response to the Fukushima accident using nuclear emergency response robots

When the accidents at the Fukushima Daiichi Nuclear Power Plants (NPPs) occurred on March 11, 2011, the RESQ series robots were not mission ready. Due to lack of budget, the robots which were still stored in their

Fig. 1 Container for RESQ robots

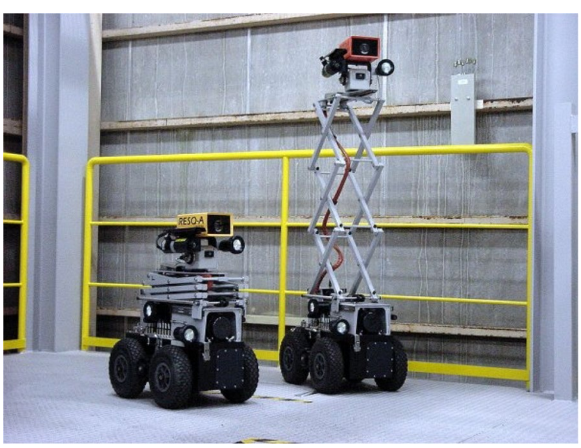

Fig. 2 RESQ-A robots

Fig. 3 RESQ-B robot

Fig. 4 RESQ-C robot

Fig. 5 Diesel drive electric generator

containers were not maintained and there were no trained operators. The RaBOT robot had been abandoned. JAEA contacted the original manufacturer of the robot for help getting the RESQ robots operational. The original manufacturer was unable to support the need because their facilities had also been damaged by the earthquake and the original engineering was not accessible. In addition, the original engineer was no longer with the company and since the RESQ robots were over 10 years old, some components in the robots were no longer available. After the initial inability to get RESQ robots operational it became apparent that the RESQ robots would not have been suitable for the conditions at Fukushima.

In order to support the emergency efforts at Fukushima, JAEA decided to modify the RESQ robots and a Brokk-40 robot which they also owned. The Brokk-40 was modified to the JAEA-1 robot by adding a blade for moving concrete rubble created by the hydrogen explosions. The blade was to be used to clear the way for small reconnaissance robots. To decontaminate floors in the reactor buildings, JAEA repaired and modified one RESQ-A robot to the JAEA-2. The main modification on JAEA-2 was a water sprayer. To detect hot spots on reactor building floors, the second RESQ-A was repaired and modified to the JAEA-3. The main modification on JAEA-3 was a gamma ray imaging and measurement device called Gamma Eye. JAEA also built robot control and transport vehicles RC-1 and RC-2. Each RC transports a robot and accessory components including a shielded operation box, area camera, radiation dose meter, a smaller gasoline drive generator, and so on [6, 7] (Figs. 6, 7).

Fig. 6 JAEA-3 robot equipped with gamma imaging and measurement device

Fig. 7 Trial results of gamma imaging and measuring device

Preparation of the JAEA-3 robot system

The JAEA-3 Robot system was prepared and which system consisted of JAEA-3 robot, the newly developed Gamma Eye, and accessory components. The mission of the system was planned to find out the hot spot on the floor or wall of reactor buildings. Gamma Eye was designed to be remotely operated and to be small and light enough for small reconnaissance robots like JAEA-3. Other modifications on the JAEA-3 robot were done to increase radiation resistance and to waterproof JAEA-3 for water spray decontamination. To increase the radiation resistance of JAEA-3, electronic circuits like servo drives were moved from the robot and into the controller. Long cables connect the controller to JAEA-3. Moving electronic components from the robot to the robot controller increased the radiation resistance of JAEA-3 robot by more than an order of ten thousand Sievert. High pressure water spray was planned for decontamination of the robot itself and the robot was required to be waterproof. However the rubber cables and tires were expected to be difficult to decontaminate with high pressurize water, because small pores on the surface of the rubber would trap small particles of radioactive Cesium. Alternative tires and cables were prepared for use during maintenance to reduce radiation dose to the technicians. The alternative cable for maintenance was short, which made it easier to handle during maintenance.

The RC-2 was a tracked vehicle with: a remotely operated lift for robot deployment, a shielded operation BOX for reducing operators' radiation exposure during robot operations, an area camera for easy robot operation, dose rate meter, a smaller gasoline generator with 100 VAC output, a 6 MPa water spray and so on. All components were installed or stored on the RC-2, to assure transportability of the JAEA-3 robot and accessory components.

The modification and preparation was started at the beginning of May 2011, and was completed near the end of May, and ready to deploy to unit 2 of the Fukushima Daiichi NPPs.

Unitizing and deployment of the JAEA-3 robot

Actual situation and requirements for deployment at Fukushima Daiichi Nuclear Power Plants

During the modification of a RESQ-A robot to JAEA-3 robot, knowledge of the actual situation at Fukushima Daiichi NPPs improved. The following observations drove new requirements:

- The radiation level was so high the JAEA-3 operator would be exposed to, too much radiation if the robot control vehicle RC-2 is used in the truck-lock of unit 2 of the Fukushima Daiichi NPPs.
- In order to deploy JAEA-3 robot to survey for hot spots using Gamma Eye in unit 2 of the Fukushima Daiichi NPPs, operators would have to carry robot and accessory components from the turbine building to the reactor building.
- There is a long corridor the from turbine building to reactor building where there were temporary cables and hoses that were used to stabilize and cool the reactor cores. A temporary walkway covered the cables and hoses and let operators walk over the cables and hoses.
- The smallest opening was 700 mm wide × 700 mm high.
- The floor of the turbine building was contaminated and components temporarily put on the floor while being transported through the building would become contaminated.
- The turbine building did not have sufficient ventilation for an internal combustion engine to be run inside the building.
- Operations, including carrying units, disassembly, and reassembly, would require operators and technicians to be in a radiation protection suit with full face mask for 3–4 h.
- Disassembly and reassembly requiring special operator's skill or tools would require more time that operators and technicians need to be in radiation protective gear.
- A deployed robot would become contaminated.

Unitization policy for the JAEA-3 robot system

The requirements for the JAEA-3 robot system became clearer and it was decided that the system should be unitized to make it portable, with the following constraints:

- Unitization should be completed in 1 month.
- Support would not be available from the maker.
- It would be difficult to procure special parts.
- Each unit should weigh less than 25 or 35 kg, so that one operator could carry it.
- Each unit should be smaller than 400 mm depth, 600 mm width and 1000 mm high, to allow the unit to be carried through the 700 mm wide × 1000 mm high opening.
- Each unit should fit on a three-wheel-carrier (Fig. 8) to limit the contamination of the unit and to make the units easier to carry and back pack.
- Each unit should be assembled with waterproof connectors and without special tools.

Units of the JAEA-3 robot system

Unit 1

Consists of the area camera, a camera tripod, and a cable from the camera to the controller. JAEA-3 did not have a robot mounted camera, but the operator could watch JAEA-3 on the area camera while viewing the output of Gamma Eye. After the robot operational test, the operator could operate the robot using the area camera.

Unit 2

Consists of the man–machine interface (or control station) components which includes: a joystick for robot operation, PC for control of Gamma Eye, and a monitor for the area camera. All these fit on a three wheel carrier for easy portability (Fig. 9).

In addition, servo drives for the motors of the JAEA-3 robot were also located inside the control station. It was difficult to find servo drives compatible with the motors from the RESQ-A robot. Many servo drive suppliers were affected by the earthquake and tsunami and were unable to provide servo drives to JAEA. Sawamura Denki Corporation was able to supply servo drives which were almost completely compatible with the

Fig. 8 Three wheel carrier

Fig. 9 Controller, unit 2

JAEA-3 motors. These servo drives had low radiation resistance and it was decided the servo drives should be located in unit 2.

Unit 3

Unit 3 was a 50 m cable to connect the robot and the controller. A single cable with all the conductors could not be manufactured in the short time frame. Several cables were tied together and covered by heat-shrink tube.

Unit 4

Unit-4 was a battery module instead of the gasoline generator to supply power. The battery module was rated for the motor surge currents, could be easily recharged, and powered the Gamma Eye and area cameras.

Unit 4 was the same type of lead-acid battery that is used in cars and an inverter to convert 12 VDC to 100 VAC. All equipment was designed for 100 VAC.

Unit 0: JAEA-3 robot equipped with Gamma Eye

The most difficult equipment to unitize was the JAEA-3 robot equipped with the Gamma Eye, gamma ray imaging and measuring device.

One option was to disassemble Gamma Eye from JAEA-3 and then reassemble the Gamma Eye to the robot. Reassembly would require making mechanical and electrical connections and then precisely aligning and adjusting Gamma Eye, while wearing one cotton glove and three rubber glove for radioactive contamination control. This is very difficult and would potentially expose the operators to high radiation doses.

The second option is not to disassemble the Gamma Eye from the JAEA-3 robot. The JAEA-3 with the Gamma Eye weighs around 70 kg and is twice the unitized weight goal of 25–35 kg. Despite the weight, this option was chosen because of the benefits of lowering radiation doses. Because of the weight, it was also decided that two operators would carry the unit. Grips were added to JAEA-3 for two operators to hold. Testing showed that there was a possibility of an operators' hand slipping. If one person loses their grip on the robot, their end of the robot could fall and the other operator could be injured by the suddenly shifting load. To prevent the robot from falling if an operator loses their grip, shoulder belts were added (Fig. 10).

The end result was that the original JAEA-3 system was divided into units 1, 2, 3, 4 and unit 0 (Figs. 11, 12) and Table 1.

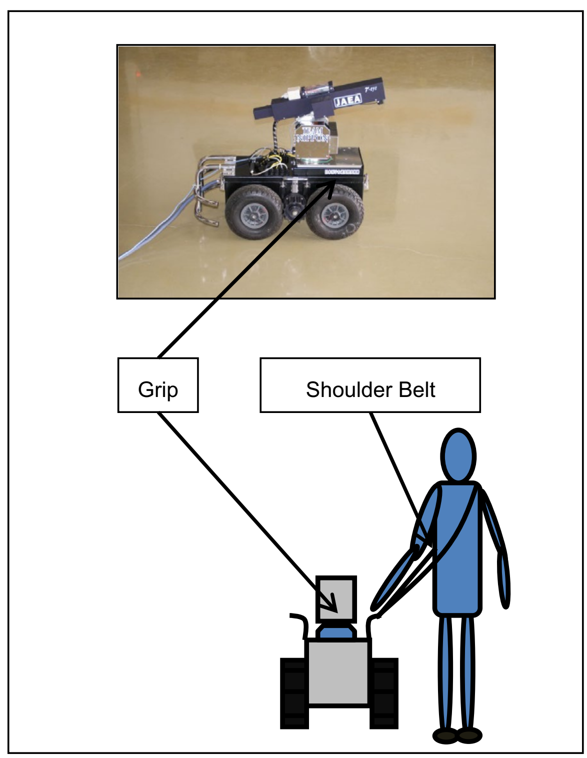

Fig. 10 Added grips and removal shoulder belt

Deployment of the JAEA-3 robot system

The JAEA-3 robot system was deployed in unit 2 of the Fukushima Daiichi NPPs on Sep 23rd 2011, with assistance from a Packbot robot instead of the Unit 1, area camera (Fig. 13) [8–10]. The purpose of the deployment was to find hot spots which were major gamma ray sources. JAEA-3 robot found that the block-out, a part of bio-shielding of primary containment vessel of unit-2, was uniformly releasing high levels of gamma rays. The block-out is concrete blocks piled and fixed by mortar without reinforcing steel rod, in order for easy access in the case of trouble.

By dividing the JAEA-3 robot system to five units, it was possible for operators to carry the units and deploy the robot.

Table 1 Contents of each unit

Unit no.	Contents	Remarks
0	JAEA-3 robot	Equipped with "Gamma Eye"
1	Area camera	Picture as shown in unit 2 on monitor
2	Controller	Includes servo divers, camera control units and monitors and PC for gamma camera
3	Cable	Consists of multi-line cable, a twisted pair cable and a stainless steel wire
4	Battery module	Consists of two 12 V lead acid batteries and DC/AC inverter

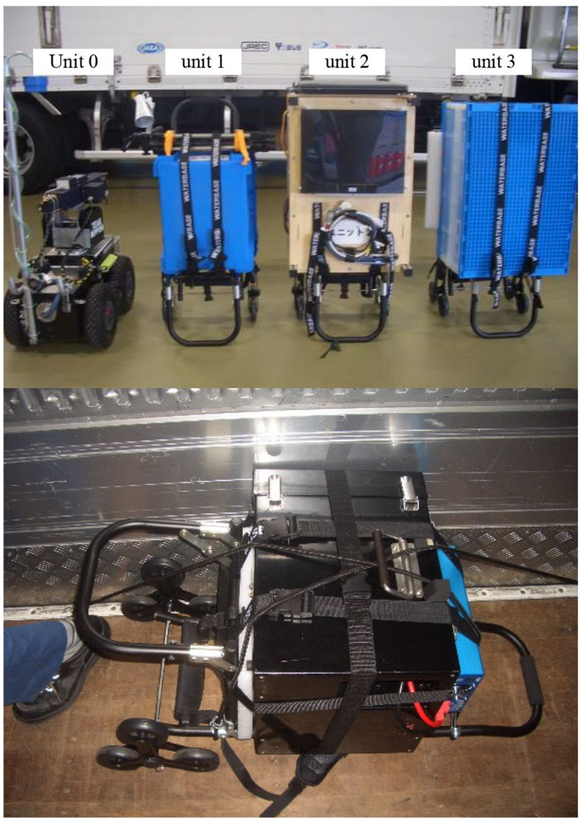

Fig. 11 Unit 0, 1, 2, 3 and 4

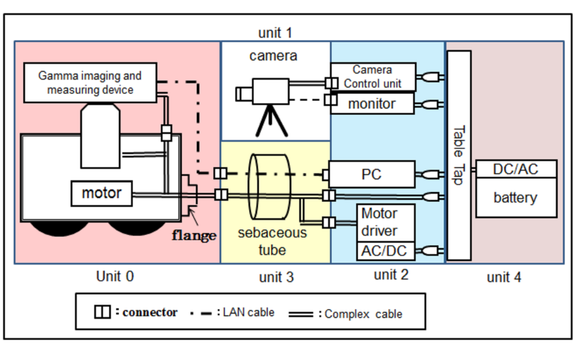

Fig. 12 JAEA-3 robot system

Fig. 13 JAEA-3 robot being deployed in unit 2

Lessons learned

Importance of portability of nuclear emergency response robots

As mentioned above, it had been recognized that transportability to an accident site was important. Portability of the robot which allows operators to carry the robot system into buildings for deployment is also recognized as important.

Emergency response robots and the process for deploying the robots should be considered as a system. The system should consider storage in a robot control vehicle in order to allow immediate transportation to an accident site. By unitizing the system into units that can be carried by one or two operators the emergency response team can bypass obstacles like debris and stairs to deploy the robot deep inside a building.

Development of a general unitization policy for portability of nuclear emergency response robot systems

Using the experience of unitizing JAEA-3 for transportability and portability, a general policy of unitization for portability of nuclear emergency response robot systems has been developed. This policy should be considered when developing emergency response robot systems for use in environments with high radiation and contamination.

1. Divide the robot system including the robot itself and accessory components into units weighing less than 25–35 kg, so that each unit could be carried by a single operator.
2. Sometimes a unit weight of 35 kg or less is not possible. For unit weights of 35–70 kg, add hand holds and carry straps to allow two people to carry the unit. For unit weights over 70 kg, additional solutions should be evaluated.
3. Limit contamination of each unit to make decontamination of the units easier. For example, units could be transported on a cart, so that contamination is limited to the cart wheels.
4. To minimize radiation dose to maintenance personnel, remove contaminated components that are not easily decontaminated. For example, temporarily replace the robot cable and wheels.
5. Units should be easy to reassemble without special tools. For example, tool free connectors could be used.
6. Avoid build-to-order parts or custom-made parts. Store common parts like tool free and waterproof connectors, so that operators can modify or optimize the system quickly.

Perspectives

The unitization policy would help the robot emergency response team immediately deploy a robot system in response to a nuclear emergency.

Authors' contributions

SK carried out the total engineering of the dividing and designed the dividing except video system, participated in the sequence alignment and drafted the manuscript. RM carried out designed and participated in the dividing of video system, HA conceived of the study, and participated in its design and coordination and helped to draft the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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References

1. Nuclear Safety Technology Center (2009) Anti-disaster monitoring robot, Leaflet (In Japanese)
2. Kobayashi T et al (2001) Development of robots for nuclear accident in Japan Atomic Energy Research Institute (1). Development of remote surveillance squad. J Robot Soc Japan 19(6):706–709 **(In Japanese)**
3. Shibanuma K (2001) Development of rescue robot at JAERI—part 2 development of radiation-proof robot. J Robot Soc Japan 19(6):710–713 **(In Japanese)**
4. ManoT et al (2001) Development of robotic system for nuclear facility emergency preparedness. J Robot Soc Japan 19(6):714–721 **(In Japanese)**
5. Manufacturing Science and Technology Center (1999) Fisical year result report on nuclear disaster assistance system developing project, 2011 (In Japanese)
6. Kawatsuma S et al (2012) JAEA Robotics' emergency response to Fukushima-daiichi accident—summary and lessons learned-, The seventeenth International Symposium on Artificial Life and Robotics 2012 (AROB 17th 2012), Oita, Japan, p 19–21
7. Fukushima M et al (2012) Radiological emergency response to Fukushima Daiichi Accident; Teleoperation and robotics of JAEA. Proceedings of American Nuclear Society embedded topical on decommissioning, decontamination and reutilization (DD&R 2012)
8. http://photo.tepco.co.jp/date/2011/201109-j/110928-01j.html
9. Kawatsuma S et al (2012) Emergency response by robots to Fukushima-Daiichi accident; summary and lessons learned. Ind Robot Int J 39(5):428–435
10. Kawatsuma S et al (2013) Reconstruction of JAEA robots for the Fukushima NPP accidents emergency response—unitizing for conveyance and reassembly at the confused area by accidents -", ROBOMEC2013, Tsukuba, Japan