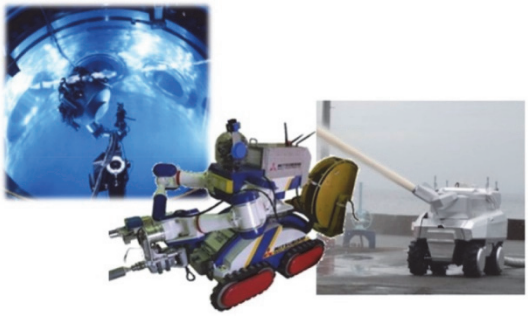
Development of Robots for Nuclear Power Plants and Their Application to New Fields



JUN FUJITA[*1] DAISUKE SODA[*2]
CHOTARO MURATA[*3] HIROYUKI TSUHARI[*3]

Since the start of the operation of nuclear power plants, Mitsubishi Heavy Industries, Ltd. (MHI) has contributed to their stable operation through the development and operation of various different types of robots for maintenance work on the major plant equipment. In the aftermath of the Fukushima Daiichi Accident, as a step toward its swift containment and safe decommissioning, we have been working hard to meet the needs of society with our robot technologies. This report introduces the progress of our robot development in the nuclear power field with some of the actual robots MHI has innovated, together with related technologies and current attempts to apply these efforts in fields other than nuclear energy, taking advantage of our strength in the robot technologies we have accumulated so far.

1. Introduction

The progress of our robot development in the nuclear power field started with the operation of nuclear power plants (**Figure 1**). In nuclear power plants, various types of maintenance work such as inspections, repairs and replacements are carried out on a regular basis with scheduled shutdowns of the plants to maintain their stable operation. Such works are conducted in environments that are highly radioactive, extremely narrow, underwater, etc., which workers cannot easily access. In order to manage such works in an efficient and safe manner, it is absolutely necessary to introduce robots that can carry out these tasks instead of humans. MHI has been working on the development of such robots since the 1970s.

Maintenance work at nuclear power plants may require not only adaptation to the special environments described above, but also the development of new robots in a short amount of time so that the work can be carried out as planned. Accordingly, as a key technology that would meet this need, we created the “Multi-joint manipulator” which can be commonly used in various different types of maintenance work. We have been refining this technology through multiple upgrades while utilizing it in numerous actual maintenance activities (Chapter 2).

In the aftermath of the Fukushima Daiichi Accident in 2011, what is expected of robots has increased further. At accident sites or in disaster-hit areas, robots with excellent mobility and remote operability would be highly desired. MHI has been developing highly versatile mobile robots with exceptional travelling performance while applying the manipulator technology we have developed for power plant maintenance work. Furthermore, in order to enhance remote operability in unknown environments, MHI has acquired “navigation assistance technology based on environmental recognition” as a new key technology. We plan to effectively utilize these technologies in the decommissioning work, which will begin in earnest from now on (Chapter 3).

As described so far, MHI has been accumulating technologies and cultivating human resources that will enable us to develop and design from scratch new robots suitable to meet the need for various types of work in extreme environments, through our robot development in the

*1 Chief Staff Manager, Nuclear Plant Component Designing Department, Nuclear Energy Systems, Mitsubishi Heavy Industries, Ltd.
*2 Deputy Director, Nuclear Plant Component Designing Department, Nuclear Energy Systems, Mitsubishi Heavy Industries, Ltd.
*3 Nuclear Plant Component Designing Department, Nuclear Energy Systems, Mitsubishi Heavy Industries, Ltd.

nuclear energy field, which is one of the strengths of our robot technologies. We will continue to aggressively take on the challenge of new fields and projects by acquiring cutting-edge technologies in a timely manner on top of our own technologies and experience accumulated so far, while aiming to contribute further to the nuclear energy field (Chapter 4).

This report introduces our robots developed for the nuclear energy field together with related technologies as the progress of our robot development, as well as some recent projects we have worked on toward our business expansion to new fields.

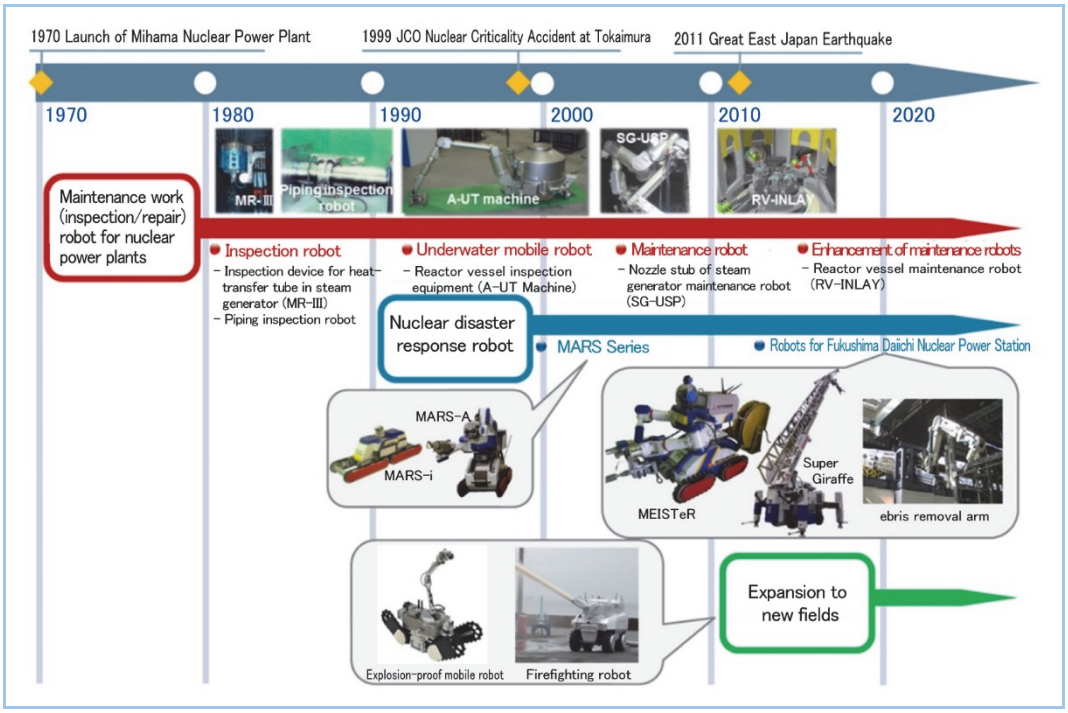


Figure 1 Progress of robot development

2. Efforts in the development of robots for maintenance work at nuclear power plants (Accumulation of technologies)[1][2]

Since PWR (Pressurized Water Reactor) nuclear power plants started operating, MHI has accumulated and refined its robot technologies in the nuclear power field through the development and operation of various different types of robots for maintenance work required for major plant equipment, while contributing to stable plant operation (**Figure 2**).

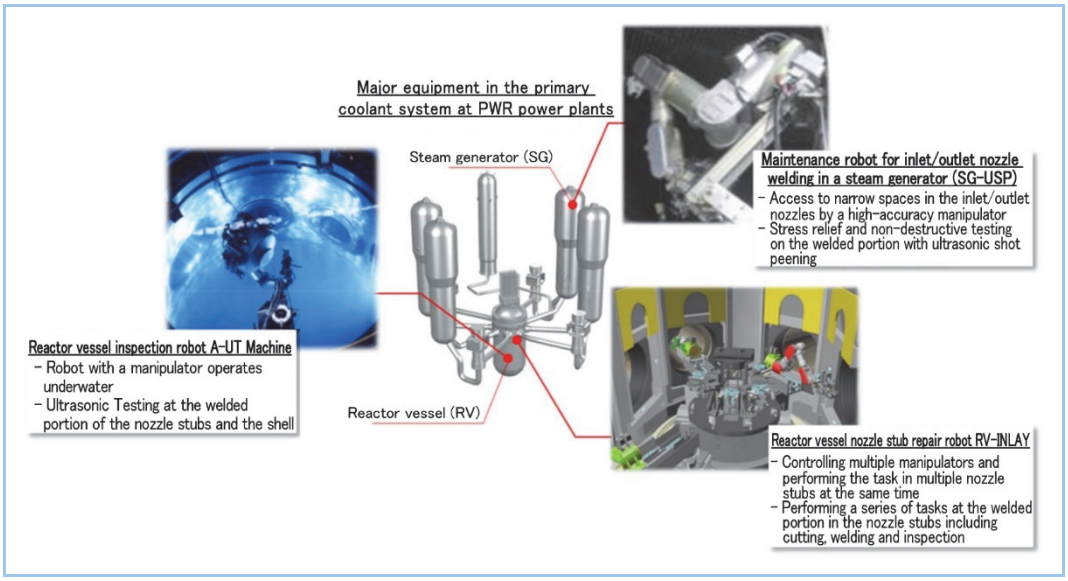


Figure 2 Maintenance of major equipment in PWR nuclear power plants (Major manipulator usage examples)

In maintenance work (inspections, repairs and replacements) at nuclear power plants, it is necessary to guide sensors and tools to respective locations depending on the purpose in various extreme environments that are highly radioactive, extremely narrow, underwater, etc. Since the equipment that requires maintenance and its surrounding environment vary greatly, each required task would need a special robot. However, the development period can be shortened, and the reliability of robots can be improved by standardizing the tool-guiding mechanism. Accordingly, MHI has developed a manipulator which is capable of delicate movements just like human arms and hands, which is positioned as a key technology and is utilized in a wide range of robots. This chapter will introduce our multi-joint manipulator, which is used extensively in many robots for maintenance work at nuclear power plants, as well as some of the actual robots equipped with it.

2.1 Multi-joint manipulator (Our signature key technology)

The features of the multi-joint manipulator include (1) providing relatively small robots with a wide range of motion and a high degree of flexibility and (2) allowing a flexible motion design with control software. It is versatile enough to be used in various different types of maintenance work if tools necessary for individual tasks are developed.

The requirements for utilizing the manipulator in maintenance work at nuclear power plants and some of our efforts to satisfy them are listed below.

(1) Radiation resistance is necessary
- Using a radiation-proof resolver in the angle detector at the joints and selecting materials with high radiation resistance for the resin utilized in the robot, such as the wire covering and insulating material
- Accurately understanding the service life for the individual components taking into account the deterioration due to radiation and utilizing the optimum shielding structure for each robot

(2) Reduction in size and weight is necessary, taking into consideration carry-in and carry-out from narrow locations
- The motor at the joints uses tailor-made windings customized specifically for individual robots and their needs (rated output/ instantaneous output), and is designed to release heat directly by standardizing the motor case and main body of the robot.
- Since installing as many commercially available servo drivers as required would inevitably increase the size of the robot, MHI developed an original integrated multi-axis motor driver.

(3) A level of operation accuracy similar to or higher than human workers is necessary.
- MHI developed all control algorithms and software for individual joints.

These efforts are different from those for general commercial industries and form the foundation of our robot development, which is applicable to nuclear power plants, a very special environment. With these technologies brought together, we have created a 7-axis multi-joint manipulator applicable as a common technology to maintenance work robots at nuclear power plants (**Figure 3**).

Number of axes	7
Overall length/weight	1317 [mm] ／ 40 [kg]
Maximum arm tip load	10 [kgf]
Actuator	AC servo motor
Repetitive positioning accuracy	0.1 [mm]
Angle sensor	Resolver (Absolute angle)
Radiation resistance	Cumulative dose 106 [Gy]
Environment resistance	Drip-proof IP54 (Waterproof IP67 is also available.)

Figure 3 Multi-joint manipulator

Some of the actual maintenance work robots utilizing this manipulator are introduced below.

2.2 Reactor vessel inspection robot (A-UT Machine)

This is a robot detector for ultrasonic testing (UT) and eddy-current testing (ECT) at the welded portions of a reactor vessel (RV), which is one of the main components at a PWR power plant (**Figure 4**). In order to mitigate the impact of radiation emitted from the RV, the inspection must be conducted with the RV filled with water. Accordingly, the robot is made fully waterproof and its structure has a manipulator attached on an underwater-operable dolly (Underwater dolly) that can move around freely underwater with the propulsion from the thruster (propeller) (**Figure 5**). The flaw inspection is conducted by an inspection tool attached at the tip of the manipulator where the tool can be easily removed, reattached or replaced underwater without it being lifted out of the water. Two units of the A-UT Machine can be operated at the same time, which contributes to the shortening of the inspection period.

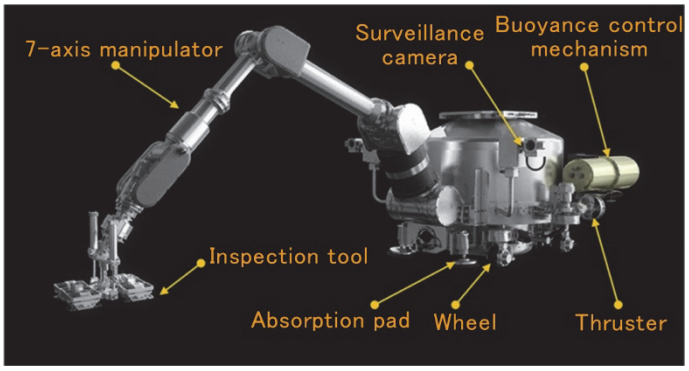


Figure 4 A-UT Machine

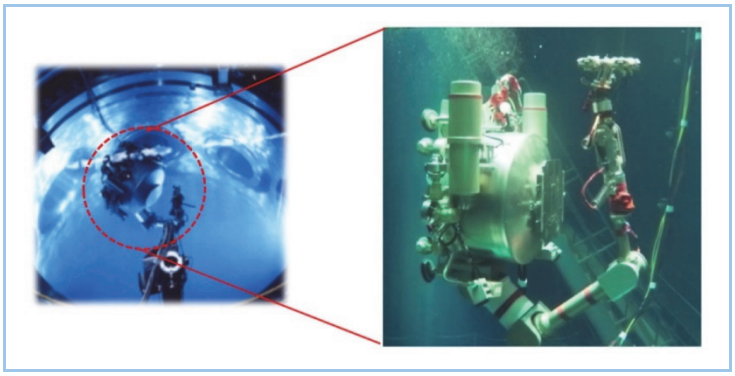


Figure 5 A-UT Machine performing RV inspection while navigating underwater

The A-UT Machine was first launched in 1995, and it has had a total of 46 applications so far with many refinements and adjustments along the way. It was recognized by the Japan Society of Maintenology as the first Maintenance Heritage (*1), which they newly established in 2020.

(*1) Maintenance Heritage: Defined as “a maintenance technology-related heritage in history, as well as a cultural heritage of humanity”

2.3 Reactor vessel nozzle stub repair robot (RV-INLAY) (3)

The welded joints between RV nozzle stubs and the primary coolant pipes (Nickel-base alloy 600) have a risk of Primary Water Stress Corrosion Cracking (PWSCC). Therefore, this robot is used in a material-improving process where the surface of welded portions is cut and overlay welding is performed with Nickel-base alloy 690, which has excellent PWSCC resistance (**Figure 6**). This robot performs multiple tasks including groove shape measurements before overlay welding, welding itself and the non-destructive testing of the welded portions, using a manipulator in the highly radioactive environment in the RV. Since its introduction, this robot has successfully replaced humans in most tasks.

Its system configuration and general operation procedure are described as follows.

- A platform with the manipulator and tool magazine attached is installed inside the RV.
- The manipulator base moves on the platform along the circumference and positions the manipulator in front of the nozzle stub in which the work will be performed.
- The manipulator selects and equips the necessary tool among various tools for work loaded

in the tool magazine placed in the center of the platform.

- The manipulator and its base are navigated to perform the required tasks at the welded portion in the nozzle stub.

Depending on the number of plant loops (the nozzle stubs which require the work), multiple manipulators can be attached, which can work on multiple nozzle stubs at the same time, changing the tools they hold at the tip as they go, contributing greatly to the shortening of the work period. The manipulator is highly controlled so that it doesn't make contact with other units during tool changing and all of the movements performed in the nozzle stubs, and it is fully remote-controlled as well, which makes it a groundbreaking invention.

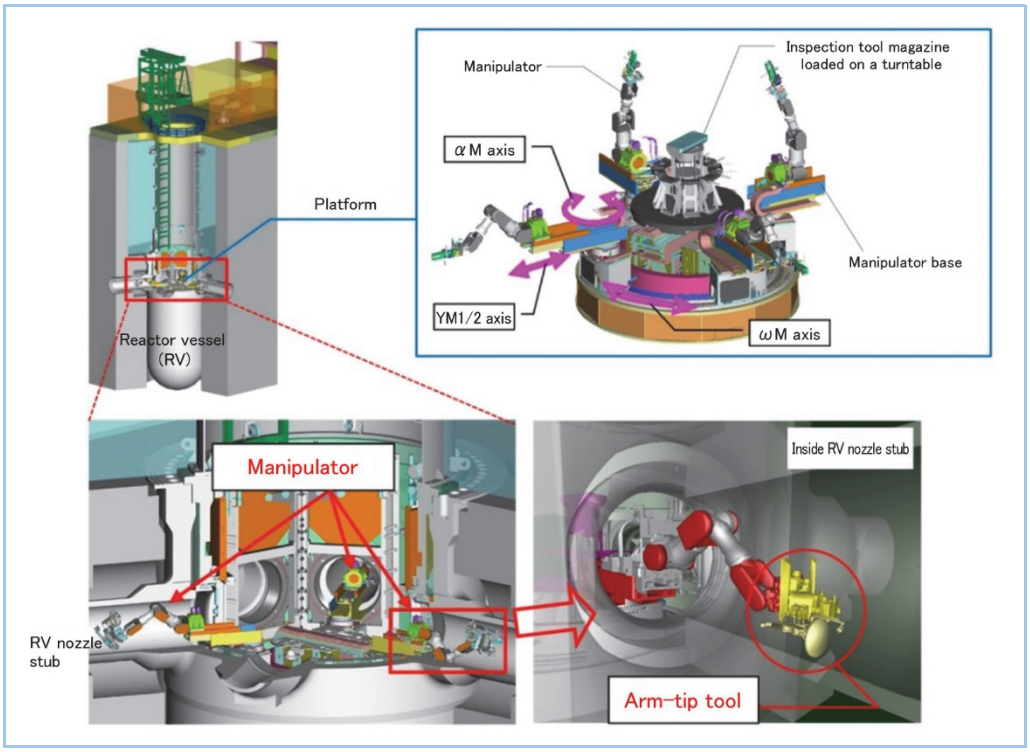


Figure 6 Reactor vessel nozzle stub repair robot

2.4 Maintenance/inspection robot for nozzle stub of inlet/outlet nozzle welding in steam generator (SG-USP)

This robot performs a stress-relief process called Ultrasonic Shot Peening (USP), which is a process to apply a compressive stress on a metallic surface by applying a physical force with a small ball continuously hitting it, as well as non-destructive testing, as part of the measures against deterioration caused by aging at the welded portion between the inlet/outlet nozzle of the SG, which is a unique component required at PWR power plants, and the primary coolant pipe. The SG channel is an environment that requires robots to do the work, as humans cannot stay there for a long time due to the high dose of radiation. This robot is structured to have a manipulator attached on a mobile base that hangs from the tube sheet on the ceiling of the SG channel (**Figure 7**). As it is necessary to install this robot through a narrow manhole in the channel, the manipulator is made small and light, and can be split into 2 pieces. The manipulator base and both pieces of the manipulator are all easy to mechanically and electrically detach. Such a structure and method are applied so that the robot can be installed piece by piece on the tube sheet near the manhole from outside the channel. For inspection, the manipulator base is moved around on the tube sheet for access to the portion subject to inspection. Accordingly, human workers never have to go in the high-radiation channel in any of the processes ranging from installation to inspection and removal.

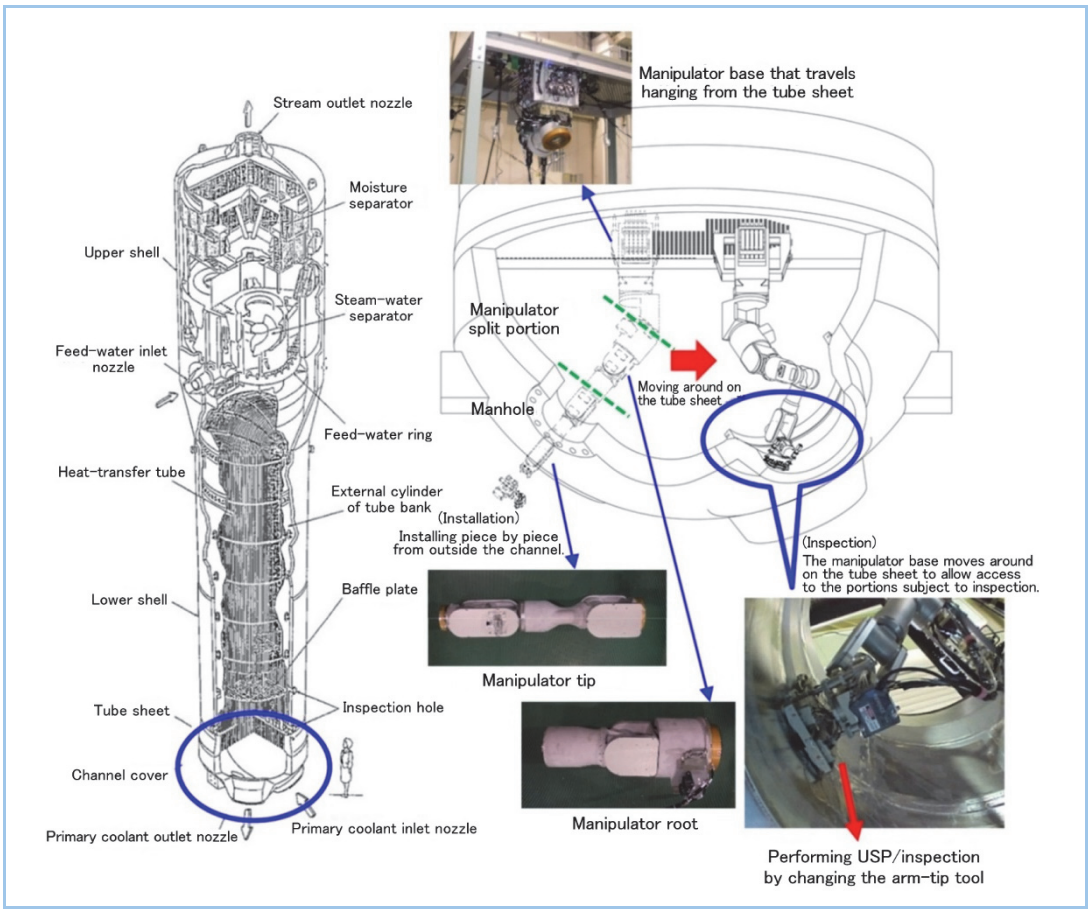


Figure 7 Maintenance/inspection robot for inlet/outlet nozzle stub welding in Steam Generator

3. Development of nuclear disaster response robot (Expansion of technologies)

At the time of the JCO Nuclear Criticality Accident at Tokaimura in 1999, the need for robots for nuclear accident/disaster response attracted broad attention. After the Fukushima Daiichi Accident in 2011, robots became an essential technology and the need for their development surged rapidly. Accident/disaster sites require not only the assumed tasks, but also various general works depending on the situation (opening doors, operating levers, cutting handrails, etc.) Therefore, MHI's highly mobile and flexible manipulator based on our experience acquired in robot development for maintenance work at nuclear power plants would be extremely effective. Meanwhile, since the area which is off-limits to humans at accident/disaster sites would grow, the robots are expected to have high mobility and remote operability. MHI has developed highly versatile and mobile robots with excellent traveling performance that will also be applicable to the Fukushima Daiichi Accident, while also applying manipulator technology acquired through maintenance work at power plants.

This chapter will introduce some of the robots and "navigation assistance technology based on environmental recognition," which we have acquired as a new key technology for increased remote operability necessary at unknown accident/disaster sites that would differ greatly from ordinary power plants.

3.1 High-place work robot for nuclear disaster response (Super Giraffe)[4]

After the Fukushima Daiichi Accident, NEDO announced a robot development project [*2] which was expected to perform some tasks such as valve operation at accident/disaster sites in high places by remote control. MHI joined this project and developed Super Giraffe (**Figure 8**). It utilizes 4-wheel drive and a 4-wheel steering system for the drive system and has great mobility, which makes it capable of moving sideways and diagonally as well as circling on the spot, not just going back and forth. Its special features include a ladder-like lift mechanism that can extend up to 8 meters in height. It can perform tasks in high places with the manipulator attached at the tip of the ladder. A large-capacity lithium-ion battery for electric cars is mounted as the power source, and it

can be operated remotely for about 5 hours.

(*2) This robot was developed in the "Research and Development Project for Unmanned System Used for Disaster Recovery" commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

3.2 Two-arm robot for nuclear disaster response (MEISTeR)

This mobile robot is equipped with two manipulators for work so that various works can be performed by remote control in place of human. As part of the work required after the Fukushima Daiichi Accident, it was necessary to cut out the concrete floor in a cylindrical shape and bring it back in order to examine the contamination inside the building (core sampling). What exactly was going on inside the building was hardly known due to the high dose of radiation, and it was necessary to perform the required tasks using robots instead of humans. MHI remodeled a nuclear disaster response robot, developed for the JCO Nuclear Criticality Accident at Tokaimura in 1999, for the required tasks, and brought it to Fukushima Daiichi Nuclear Power Station. The new robot is called MEISTeR (**Figure 9**).

MEISTeR is a two-armed robot with two manipulators moving just like human arms. It is highly versatile and capable of performing various tasks by a combination of multiple tools mounted on both manipulators. It has four drive crawlers that detect bumps and slopes on the driving surface, and features high mobility which allows it to travel on rough roads or even to go up and down stairs by automatically adjusting the position of its upper body to maintain its balance.

MHI brought MEISTeR to the building in which debris were scattered after the Fukushima Daiichi Accident and successfully performed core sampling by full remote control for the first time in the world (**Figure 10**).

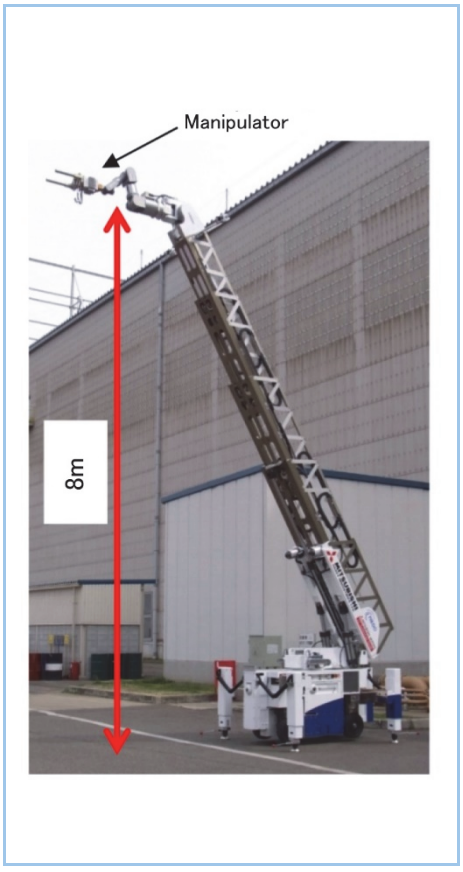


Figure 8 High-place work robot Super Giraffe

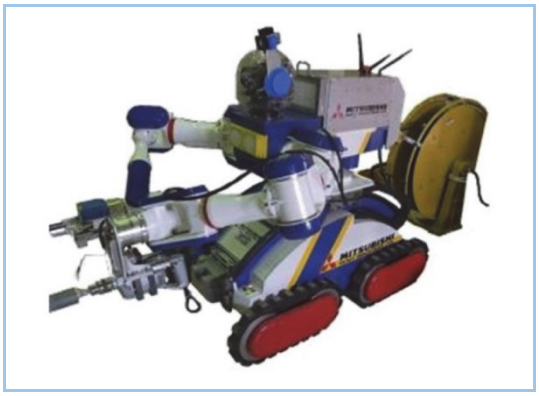


Figure 9 Two-arm robot MEISTeR

Figure 10 Core sampling performed by MEISTeR

3.3 Navigation assistance technology based on environmental recognition (New key technology)

When an accident or a disaster happens, the situation at the site quickly turns into an unknown environment that is totally different from ordinary times. Under the circumstances where the surrounding environment including passages, walls and road surfaces are unknown, it is not easy to send a robot to its destination and to perform tasks by remote control, which would cause a

growing burden on the operator and an increase in the work period. In order to address these issues, MHI developed a navigation assistance technology that will recognize the robot's surrounding environment and effectively convey the information to the operator in real time.

When remotely controlling a robot based solely on the images taken using its built-in camera (the images that the operator can see from the robot at its eye level), it is difficult to see the depth or have a sense of distance in the surroundings. Even when there are multiple built-in cameras available, in order to understand the surroundings all around the robot, it is necessary to look at multiple sets of images, which would create a great burden on the operator and might possibly lead to grave danger such as a collision with an obstacle or a fall from a height caused by a minor error in judgement.

In order to address this concern, we included in the robot a virtual bird's-eye technology where we combine multiple sets of images from the cameras mounted on the front, back and both sides of the robot. This technology corrects the images for projection on the ground and sends them to the operator in real time (**Figure 11**). This allows the operator to have a panoramic view of his or her surroundings as if he or she was looking down on the robot from above. Although this technology was being utilized in some passenger vehicles at the time [5], it had never been applied to a robot. Therefore, we have created algorithms that will perform image correction easily depending on the types of cameras and where they are placed, which varies with individual robots.

We also included in the robot a technology that will measure its surroundings with a 3D distance sensor (LiDAR) and display the real-time results as the robot moves around. This enables the operator to understand the robot's surroundings as three dimensional environmental information in real time (**Figure 12**).

By combining the above navigation assistance technology based on environmental recognition with the conventional camera images, we have successfully conveyed accurate information about the robot's surroundings at the site to the operator and have significantly improved the robot's remote operability (**Figure 13**).

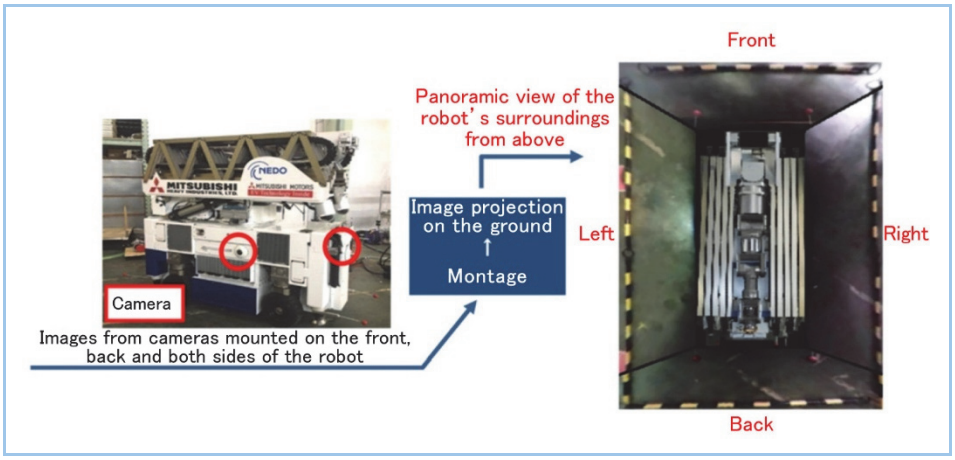


Figure 11 Virtual bird's-eye view technology

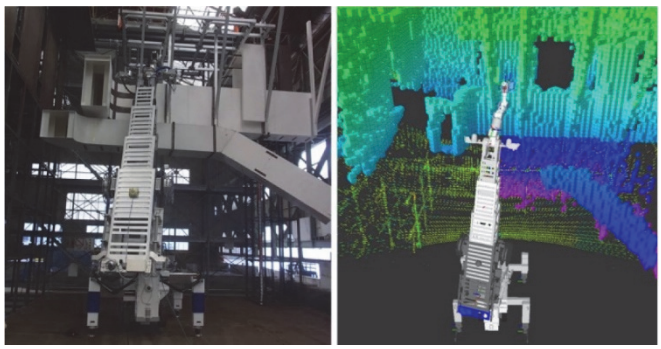


Figure 12 Information about the surrounding environment provided by LiDAR

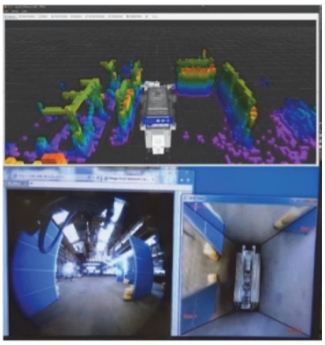


Figure 13 Combined camera images using the navigation assistance technology

4. Taking advantage of our strengths in the robot technologies developed through nuclear power projects (Expansion to new fields)

So far, we have introduced some of the robot technologies we have accumulated through maintenance work and disaster response at nuclear power plants, as well as the actual robots we have developed. Our strengths in the robot technologies which we have developed through multiple projects in the nuclear energy field are as follows.

- Capable of handling extreme environments that are off-limits to humans
  MHI is able to develop robots which can be used in various severe environments such as radiation, narrow spaces, underwater, rough roads, uneven grounds, etc.
- Highly flexible “customized design” is available.
  MHI is capable of a wide range of customized designs by bringing together the design/development engineers in mechanical, electrical and software fields, and creating parts and components which are not commercially available, as well as developing original control algorithms.
- “Comprehensive ability” as a nuclear power plant manufacturer
  MHI exercises its comprehensive ability to perform extremely difficult engineering work with high quality by having robot engineers, plant/equipment designers, maintenance engineers and device operators all work together.

We are committed to continue to refine our technologies and experience accumulated so far, and to constantly acquire cutting-edge technologies in a timely manner in order to contribute further to the development of the nuclear power field. There are also some fields other than nuclear power field, including disaster response, disaster mitigation and anti-terrorism measures, where our strengths in robot technologies would be extremely useful. We intend to try to expand our business aggressively into these new fields and projects. This chapter will introduce our latest models of explosion-proof mobile robot and firefighting robot, as well as the “autonomous control technology” that we are working on at the moment in order to acquire and improve expertise in our robot development.

4.1 Explosion-proof mobile robot [6] [7] [8] [9]

In petroleum gas plants, chemical plants and accident sites in tunnels, where there is a risk of explosion due to the generation of flammable gases, explosion-proof equipment is the only technology that can be used. MHI developed a robot for collecting information in such environments, which was certified as an explosion-proof model of mobile robot for the first time in Japan (**Figure 14**, left). We utilized a pressurized-enclosure explosion-proof structure where the internal pressure is kept higher than the atmosphere at all times so that no flammable gases outside the robot can enter. After innovating this land-mobile explosion-proof robot, MHI is now working on the development of the next-generation explosion-proof mobile robot equipped with a manipulator (Figure 14, right), by adding an explosion-proof design to existing mobile models and securing the technology that will provide a high level of travel performance achieved by its lighter body. Research and development is currently underway where we will add autonomous drive control technology to this explosion-proof model, aiming to achieve unmanned patrol inspection in offshore oil fields, petroleum gas plants, etc.

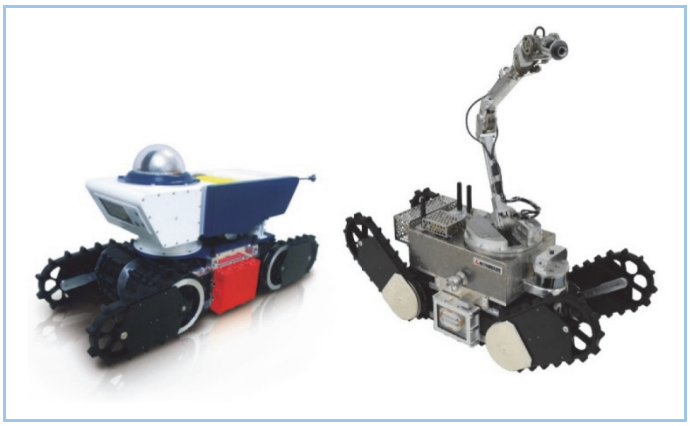


Figure 14 Explosion-proof mobile robot

4.2 Firefighting robot [10]

A tank fire in a petrochemical complex is an extraordinary disaster which can affect a large area and is difficult to extinguish. The major issues include the extensive radiant heat from the flames and the high risk of explosion, making the area virtually inaccessible to humans. Under these circumstances, there are great expectations for robots to perform firefighting, cooling and other required tasks instead of human firefighters. Accordingly, the Fire and Disaster Management Agency, the Ministry of Internal Affairs and Communications, sought participants for a 5-year project for robot system development(*3). MHI took part in this project and developed a water cannon robot and a hose extension robot.

The water cannon robot (**Figure 15**) is capable of being remotely controlled as well as autonomously driving to a location designated on a map with a mobile dolly equipped with a water cannon with an available water flow of 4000L/min at 1MPa pressure and a water discharge range of approximately 70 meters. The hose extension robot (**Figure 16**) lays a 150A fire hose (weighing 2 kg per unit length) up to 300 meters, which is capable of water conveyance of 4000L/min, from a water source such as a water pump or fire hydrant, to the water cannon robot. Just like the water cannon robot, remote control and autonomous driving functions are available. It also has a similar dolly and radiant heat resistance. Both robots are designed to withstand 20 kW/m^2 of radiant heat as part of features to resist to the radiant heat from the flames at an accident site.

This robot was deployed to the Ichihara Fire Department, Chiba Prefecture, in 2019 for verification purposes. The firefighters are practicing operating the robot on a daily basis so that it would be ready to be dispatched at all times in the case of an emergency. We plan to upgrade it by improving the maintainability and operability based on the needs of the people on the frontline who are engaged in actual operation.

(*3) This robot system is the outcome of “Research and Development of Firefighting Robots for Energy and Industrial Infrastructure-related Fires” conducted by the National Research Institute of Fire and Disaster, the Fire and Disaster Management Agency. MHI was in charge of the water cannon robot and hose extension robot, which this system consists of, as well as the entire system design.

Figure 15 Water cannon robot

Figure 16 Hose extension robot
(Left : Driving autonomously to the scene of the fire with a water cannon robot)
(Right : Laying a hose toward the water source after arrival at the scene of the fire)

4.3 Development of autonomous control technology

MHI is working on the development of autonomous control technology for robots as represented by autonomous driving as one of the new technologies requiring no remote control by an operator. The explosion-proof mobile robot and firefighting robot are equipped with sensors required for autonomous control, such as LiDAR and IMU (Inertial Measurement Unit), as well as GPS in the firefighting robot, which allow the robots to identify their own locations by inverse calculation (estimated self-location) in which they compare the information about the surrounding environment (electronic map) in the data that was acquired and saved beforehand with the actual measurements conducted by the sensors. The development of algorithms that determine the optimum route from the current location to the destination and their motion control programs has enabled the technology to allow the robots to travel automatically to the locations designated on the map (**Figure 17**). MHI aims to improve the accuracy in the robot's autonomous motions by further advancing this technology.

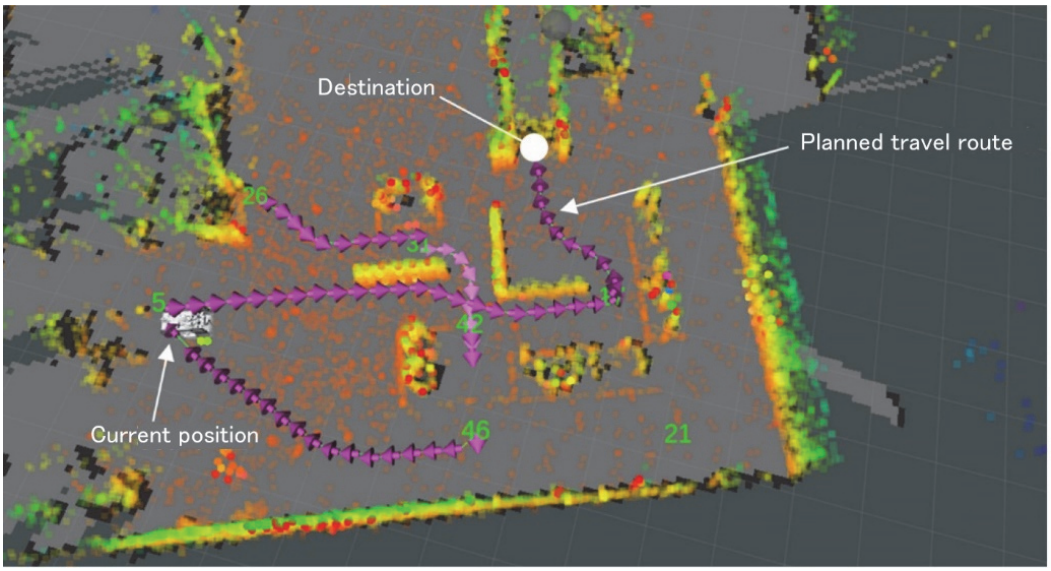


Figure 17 Self-position estimation by autonomous traveling and route determination to destination

5. Conclusion

MHI has contributed to the stable operation of nuclear power plants through the development of multiple robots for maintenance work at the plants while accumulating various different types of robot technologies. We have also worked on the development of robots for nuclear accident/disaster response and have expanded the range of application of our technologies. As the need for robots in special environments is expected to increase not only in the nuclear power field, we intend to support Japan's critical infrastructure with our robot technologies that can address diverse needs, while taking advantage of our strengths in a wide range of industrial fields and expertise and acquiring various cutting-edge technologies.

References

(1) Jun Fujita et al., Application of Manipulator Type Robot to Plant Maintenance. (Japanese title translated into English), Japan Society of Maintenology, 6th Academic lecture proceedings, C-4-2, (2009)
(2) Kohata Yukifumi et al., lant Maintenance Technology Using Manipulator Type Robot , Japan Society of Maintenology. (Japanese title translated into English), 7th Academic lecture proceedings, A-5-8, (2010)
(3) Noriaki Shimonabe et al., Advanced INLAY system for reactor vessel inlet/outlet nozzles. (Japanese title translated into English), Journal of the Robotics Society of Japan , Journal of the Robotics Society of Japan, Vol.30 No.1, pp.47～48, (2012）
(4) Jun Fujita et al., The Development of Robot System “Super Giraffe” for Unmanned Operation on Disaster, Journal of the Robotics Society of Japan, Vol.32 No.2, pp.148～150, (2014）
(5) Intelligent Around View Monitor, Nissan Motor Co., Ltd., https://www.nissan-global.com/JP/TECHNOLOGY/OVERVIEW/iavm.html
(6) Koji Shukutani et al., Development of Explosion-proof Autonomous Plant Operation Robot for Petrochemical Plants, Mitsubishi Heavy Industries Technical Review Vol.55 No.4 (2018)
(7) Ken Onishi et al., Development of the inspection robot to Operate in the Presence of Flammable Gases. (Japanese title translated into English), Robotics Society of Japan, Academic lecture proceedings, 1Y3-03 (2016)
(8) Ken Onishi et al., Development of the Explosion-Proof Mobile Robot. (Japanese title translated into English), Robotics Society of Japan, Robotics Society of Japan, Academic lecture proceedings, 1E3-04 (2017)
(9) Ken Onishi et al., Application of the Explosion-Proof Mobile Robot to Automatic Patrol Plant Check. (Japanese title translated into English), Robotics Society of Japan, Academic lecture proceedings, 3F3-08 （2018）
(10) Jun Fujita et al., Development of firefighting robot system applicable to petroleum complex fires, The Japan Society of Mechanical Engineers, The Robotics and Mechatronics Conference 2020 proceedings, 2A1-A02, (2020)