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Paper:

Development of an Intersection Module for a Modularized Rail Structure – Implementation of Compliant Mechanisms for a Replacing Task of Movable Parts –

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For decommissioning of the Fukushima Daiichi Nuclear Power Station, we are developing an "automated construction system for a modularized rail structure." The intersection module developed in this study produces structure branches and changes robot attitudes. To maintain module functions, assuming the anticipated malfunctions caused by high-radiation environments, remotely controlled robots are used to replace malfunctioning parts of the module. To facilitate maintenance tasks, small positioning errors must be accommodated. This compliant function can be realized by the maintenance robot or the module. To elucidate effective combinations of the compliant mechanisms, experiments are conducted using prototypes. Experimental results confirm that the compliant mechanism of the robot contributes more efficiently than that of the module. This study is expected to be applied to practical distributed robotic systems because it is necessary to replace malfunction parts as simply as possible if they are replaced by remotely controlled robots.

Keywords: self maintenance, compliant mechanism, disaster response, automated construction, modular robot

1. Introduction

On March 11, 2011, a severe accident, including the damage of nuclear core, occurred at the Fukushima Daiichi Nuclear Power Station. Soon after the accident, existing unmanned construction systems were installed to deal with immediate action [1], and relevant technologies, such as a virtual reality simulator, were developed to advance unmanned construction efficiently [2]. Recently, remotely controlled robots have been working in place of human workers, to clear debris from hydrogen explosions, contaminated substances, and nuclear fuel debris.

In April 2015, for the first time after the accident [a], the interior of the primary containment vessel (PCV) of Unit 1 was investigated using a robot. In the future, working by robots to remove fuel debris from high-radiation environments, such as around of the PCV, is anticipated. However, because of weight restrictions, it is not reasonable to protect robots from high radiation. For example, to protect robot semiconductors from high radiation, lead walls required for attenuation are extremely heavy for robots to move. Accordingly, the development of practical systems that have superior radiation resistance and maintainability is required [3]. To transfer fuels, debris, and materials, robots must move in this high radiation environment (locomote) back and forth repeatedly, which entails an extremely long time for existing robots to complete the removal tasks. Therefore, it is necessary to develop an environment in which operational robots can easily locomote and work.

By applying the concept of construction robotics [4], an "automated construction system of a modularized rail structure" (**Fig. 1**) was proposed by Fukui et al. [5]. In this system, constructor robots construct a modularized rail structure by successively connecting modules, as an environment for robot locomotion and operation. Consequently, the robots can move around efficiently because they locomote on the surface of the structure.

In an earlier study of this system, we demonstrated that the module can be delivered from a transfer robot to a connector robot while allowing positioning errors of robots. The module connecting motion was verified for three robot attitudes [5], and a leg module was developed [6]. In addition, construction planning for this system was proposed in our previous work [7]. **Table 1** summarizes whole tasks for achieving the proposed system. As described herein, we developed an intersection mod-

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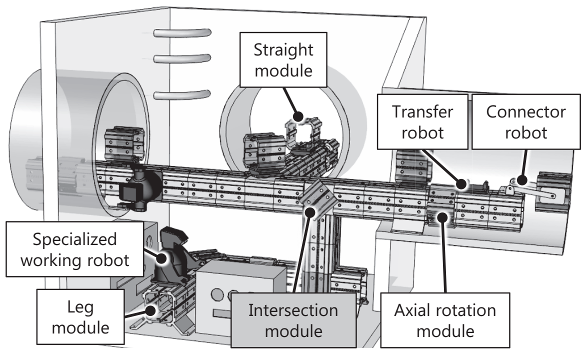

Fig. 1. Conceptual sketch of an "automated construction system of a modularized rail structure."

Table 1. Tasks for realizing the proposed system.

Phase	Task	Components
Concept	Construction	All robots and modules
Construction planning		All robots and modules
Development		Connector robot
		Transfer robot
		Straight module
		Leg module
		Intersection module
		Axial rotation module
	Maintenance	Replacing robot
	Working	Working robot
Maintenance planning	Maintenance	Intersection module Axial rotation module Replacing robot
Working planning	Working	Working robot

☐ Not yet started ☐ Completed ☐ In progress ☐ Focus of this paper

ule that can produce the structure branches and change robots attitudes (**Fig. 2**).

To date, various types of self-reconfigurable and distributed robots have been developed [7–10]. As for technologies utilized in them, high-speed genderless mechanical connection mechanism [11], print-and-fold designs [12], and self assembly with active and passive modules [13] have also been developed. In particular, Lee et al. [14] proposed a reconfigurable magnetic wall-climbing robot and developed the robot system which comprises two modules and a six-degree of freedom (DOF) manipulator, for decommissioning of the nuclear reactor. S. Murata developed "Self-Repairing Mechanical Systems" that restores the original shape if an arbitrary part of the system is cut off [15]. However, if each robot has various actuators, their malfunction risk is expected to be higher.

As in earlier studies, by applying the "Self-Reconfigurable Robots" concept to our system [16], the function of changing the robot attitudes is implemented in some modules [5]: the intersection module has its own actuators in itself to change the robot attitudes. This implementation decreases the total number of actuators in our system [7]. If the rail structure is constructed inside

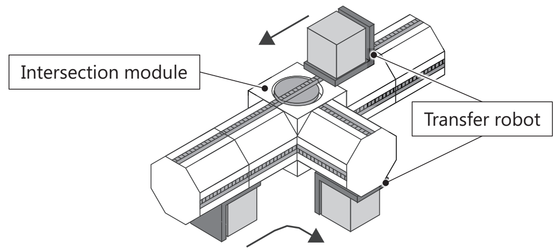

Fig. 2. Conceptual sketch of an intersection module.

a reactor building, then intersection modules will be constantly exposed to high radiation. Therefore, we presume that when an intersection module is out of order, a remotely controlled maintenance robot replaces its defective parts, including actuators. Consequently, intersection modules are operated continually in high radiation environments for long durations.

To accomplish the replacement work using as few actuators and as low power as possible, it is important to minimize the degree of freedom necessary for positioning the defective part. Additionally, it is important to prevent application of undue force by the replacing robot even with a positioning error. In this case, a compliant mechanism is usually installed to either the replacing robot or intersection module. This study investigates the combinations of compliant mechanisms that should be installed to minimize the force necessary for the robot to replace the defective part. Furthermore, we conducted experiments using prototypes and elucidated on the most effective combinations for the remotely-controlling the maintenance robot.

Developing practical distributed robots requires the use of remotely controlled robots to maintain and replace components of a modularized structure. The findings gained from this study are expected to be useful for the development of other distributed robotic systems.

This paper is organized as follows: Section 2 presents technical issues and our approaches. Section 3 describes the intersection module that we developed. Section 4 discusses experiments using prototypes of the intersection module and the replacing robot to evaluate the compliant mechanisms. Section 5 is the conclusion.

2. Technical Issues and our Approaches

2.1. Necessary Functions of the Intersection Module and Basic Design Principles

The main functions of the intersection module are (1) assembling rail structure branches and changing robot attitudes, as well as (2) maintaining functionality in the high radiation environment.

For (1) above, it is necessary to expand the rail structure three-dimensionally in order for working robots to locomote to working area inside the complex terrain. The intersection module requires more than two connecting surfaces to expand the rail structure three-dimensionally.

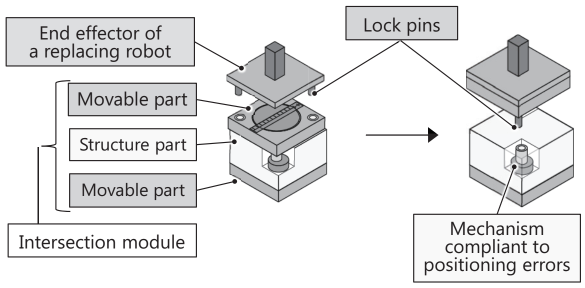

Fig. 3. Components of an intersection module and an end effector of a remote control robot.

Therefore, three connecting surfaces can achieve construction of the structure branches. Changing the robot attitudes can be realized by developing turntables.

For (2) above, functionality must be maintained despite radiation effects, because intersection modules are constantly exposed to high radiation. For example, radiation resistance motors have been developed for the International Thermonuclear Experimental Reactor (ITER) [17]. However, the rail structure will be used for an extremely long time once they are constructed. Therefore, for this study, we designed the intersection module so that its defective parts, including actuators, can be unitized and replaced easily by a remotely controlled robot. The intersection module comprises two movable parts and a structure part to realize basic functions (**Fig. 3**). The robot can replace movable parts of the intersection module. To replace the movable part, an end effector for replacement work firstly removes an existing movable part from an intersection module. Then an end effector holding new movable part installs it into the intersection module.

This series of replacing movable parts requires relative positioning of two kinds: (1) between an end effector for the replacement and the movable part and (2) between the movable part and the structure part. Therefore, a movable part has two kinds of detachable mechanisms: (1) to an end effector for the replacement and (2) to the structure part. Detachable mechanisms must be minimized because the movable part has a turntable to rotate robots and change their attitudes.

For this study, a pin connection mechanism is adopted as the detachable mechanism: a pin with a ball plunger mechanism is inserted and connects to a hole. In related studies, accurate positioning necessary for pin insertion is implemented using a six-axis force sensor [18] and force control have been used [19, 20]. However, because semiconductors are adversely influenced by high-radiation environments, they malfunction [21]. For this reason, it is difficult to use a six-axis force sensor and insert a pin accurately. Some mechanism is necessary to alleviate positioning errors and to realize detachment without a force sensor.

2.2. Related Studies and our Approaches

Whitney analyzed the peg-in-hole task using two-dimensional models and developed the remote center compliance (RCC) mechanism, which shortens the distance between the tip and the pin rotation center [22]. The reaction force from the hole in the pin insertion work is supported by elastic deformation of the RCC mechanism. The positioning error between the pin and the hole is canceled. Herein, it is designated as the "pin flexible method."

Kinoshita et al. and Yamaguchi et al. analyzed the peg-in-hole problem using a compliant mechanism applied to the hole, and demonstrated the effectiveness of the passive correction of the relative positioning error between the pin and the hole [23, 24]. Herein, it is designated as the "hole flexible method."

As explained in the previous section, the intersection module has two kinds of relative positioning in replacing its movable part. Consequently, the movable part requires two kinds of detachable mechanisms. Compliant mechanisms should be installed except to the movable part because the movable part has a turntable. Therefore, a compliant mechanism of the pin flexible method is installed to the end effector of the replacing robot. A mechanism of the hole flexible method is installed to the structure part of the intersection module. Herein, we describe the evaluation of how and what combination of the compliant mechanisms decreases the force/power required by the replacing robot.

We developed prototypes and conducted experiments by making combinations of compliant mechanisms of the pin flexible method and the hole flexible method. The module should be designed to be as simple as possible because numerous intersection modules must be constructed in the real application. We compared the experimentally obtained results with the case in which the compliant mechanism is installed to the end effector. Thereafter we investigate the possibility of simplifying the module.

3. Detailed Design and Implementation of the Intersection Module

Based on the approaches discussed in the previous section, we designed and implemented the intersection module.

3.1. Overview of the Intersection Module

Figure 4 presents an exploded view of the intersection module we developed: three side surfaces are made to connect to achieve rail structure branches. The module has two movable parts with turntables above and below the structure part to facilitate the change of the robot attitudes. The robots can change their attitudes independently on each turntable. Consequently, they can pass each other with no collision. Robots use a rack and pinion mechanism to locomote on the module surface. The turntable has a rack and two rails to support the robots.

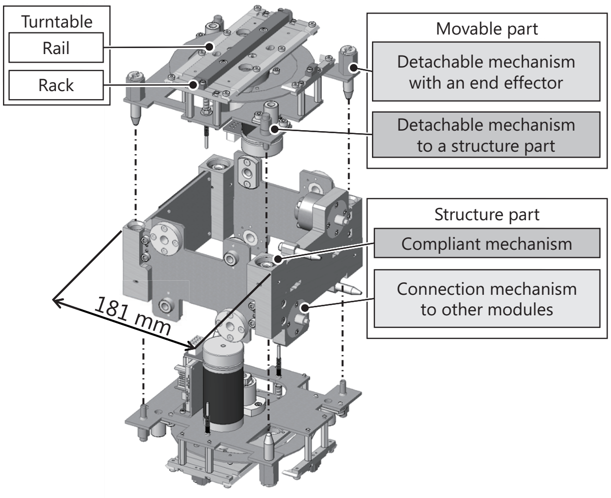

Fig. 4. Exploded view of an intersection module.

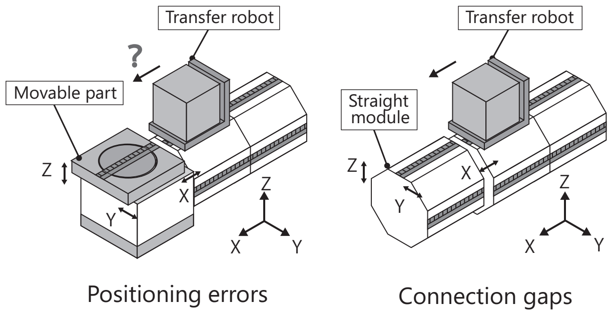

Fig. 5. Conversion between positioning errors of a movable part and connection gaps of straight modules.

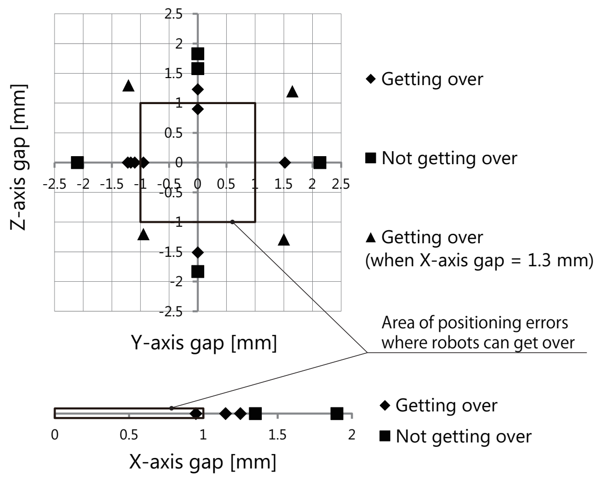

Fig. 6. Preliminary experimental result for allowable positioning errors.

The intersection module comprises two movable parts and a structure part. The structure part has connecting mechanisms to connect to other modules and detachable mechanisms to place the movable part. The movable part has a turntable, the detachable mechanism to an end effector of the replacing robot, and another detachable mechanism to the structure part. In addition, the movable part can be replaced no matter where the turntable stops because the position of the turntable is not unique and unknown when the turntable breaks down. For recognition of the turntable position, mechanical contact switches are used instead of sensors using semiconductor devices to minimize the radiation effects. We designed the detachable mechanism of a structure part to allow the positioning error of the movable part to the structure part so that the movable part can be replaced by the remotely controlled robot.

3.2. Preliminary Experiment: Definition of Required Allowable Positioning Errors

The positioning error of the movable part in relation to the structure part demands the inclusion of a gap separating between the turntable and straight module before the intersection module. We conducted experiments to investigate the range of the positioning errors that the robot can overcome and ride on the turntable.

The robots locomote on the rail structure surface. The translational positioning errors of the movable part are equivalent to the connection gaps of the straight modules, as shown in **Fig. 5**. For this experiment, the straight modules is shifted to the rear module, where it is locked to simulate the positioning errors of the movable part. Under these circumstances, we investigated whether robots can surmount the structure or not. **Fig. 6** shows that the robot can overcome a gap of straight modules set in the directions of the X, Y, and Z axes as shown in **Fig. 5**. Diamond and triangle marks denote the range that the robot can overcome. The experimentally obtained results verified that the transfer robot can overcome an approximately 1.3 mm gap between straight modules in each direction. Therefore, if the positioning error of the movable part stays the inside of the rectangular area on **Fig. 6**, then the transfer robot can surmount it and ride on the turntable with no issues.

3.3. Detailed Design and Implementation of the Compliant Mechanism of the Intersection Module

We designed and implemented a compliant mechanism of the end effector by "the pin flexible method," and that of the intersection module as "the hole flexible mechanism."

For the compliant mechanism of the end effector, a flexible mechanism using four anti-vibration rubbers is developed, in reference to the RCC mechanism. **Fig. 7** presents an overview of an imitated replacing robot that we developed. It simulates a remotely controlled replacing robot and its end effector can be lifted up and down by turning a handle on the top of the robot.

The 15-mm-diameter anti-vibration rubbers are selected from options of 8, 10, 15, and 30 mm. They are

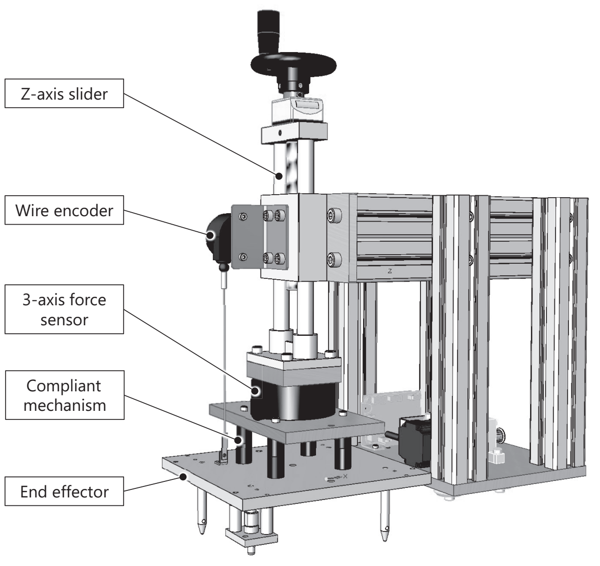

Fig. 7. Overview of an imitated replacing robot.

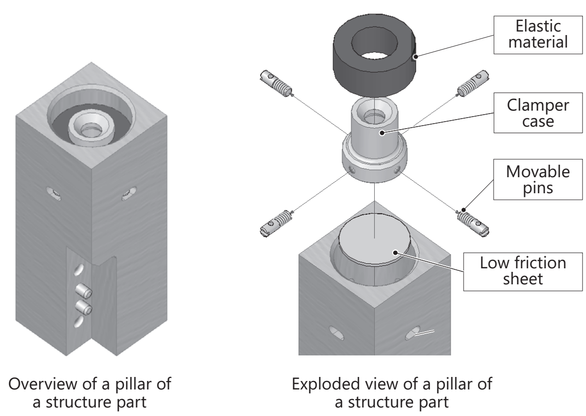

Fig. 8. Compliant mechanism of the intersection module.

flexible and rigid to the degree that the end effector is not deformed by its own weight in the gravity direction, even when the working direction is not the same as that of the gravity. For the compliant mechanism, a three-axis force sensor (WGF-3A-50-5-RG5; WACOH-TECH Inc.) is installed. It can acquire the data of one-axis force and two-axis torque necessary for mounting the end effector. The axis of force is parallel to the mounting direction. The axes of torque are orthogonal to the mounting direction.

The compliant mechanism of the intersection module by the hole flexible method is installed inside a pillar of the structure part. **Fig. 8** depicts an overview and exploded view of the mechanism, which is in the pillar end. Another end has a guide hole for a guide pin of the movable part. The structure part, which has four of the same pillars symmetrically, can receive guide pins and lock pins of the movable part.

The compliant mechanism of the intersection module has two functions: (1) detaching the movable part

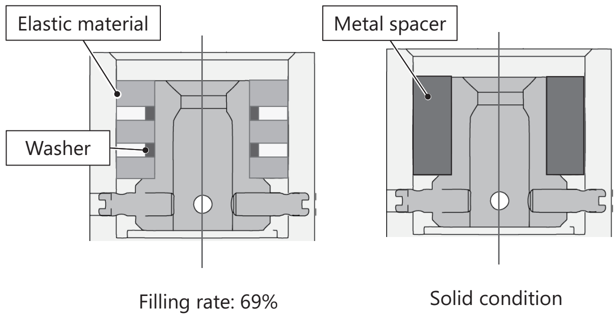

Fig. 9. Filling rate in the compliant mechanism of the intersection module.

and (2) allowing translational positioning errors of the movable part. A pin connection mechanism with a ball plunger is adopted to achieve (1), with a lock pin receptacle installed in the pillar. An elastic material is installed around the receptacle in the pillar because of the restricted space to achieve (2). The elastic material, a silicon rubber sponge (Asker C hardness of 55), is selected because of its elasticity to the extent that it can be deformed and then restored to its default position. The filling rate of the elastic material in the pillar is adjustable by changing the amount of the installed material because the most suitable filling rate of the elastic material for replacing the movable part is unknown. As **Fig. 9** shows, the filling rate can be chosen as 100%, 76.9%, or 69.2% by combining the elastic material and metal bushings. Additionally, it is possible to cancel the compliant mechanism in the intersection module by installing metal spacers.

The guide hole diameter of the pillar is 2 mm larger than that of the pin of the movable part. Therefore, the structure part can allow, a maximum of 1.0 mm of translational positioning error of the movable part.

3.4. Replacement Flow of the Movable Part of the Intersection Module

Replacing the movable part of the intersection module comprises four phases: (A) mounting the end effector, (B) removing the movable part, (C) mounting the movable part, and (D) removing the end effector. **Fig. 10** shows the flow of the movable part replacement by the replacing robot.

(A) Mounting the end effector

1. The replacing robot stops when the end effector is on top of the intersection module.
2. The end effector descends vertically. Its rough guide pins are inserted into the movable part. The end effector positions the movable part.
3. The end effector stops descending. Its lock pins are inserted into the movable part.

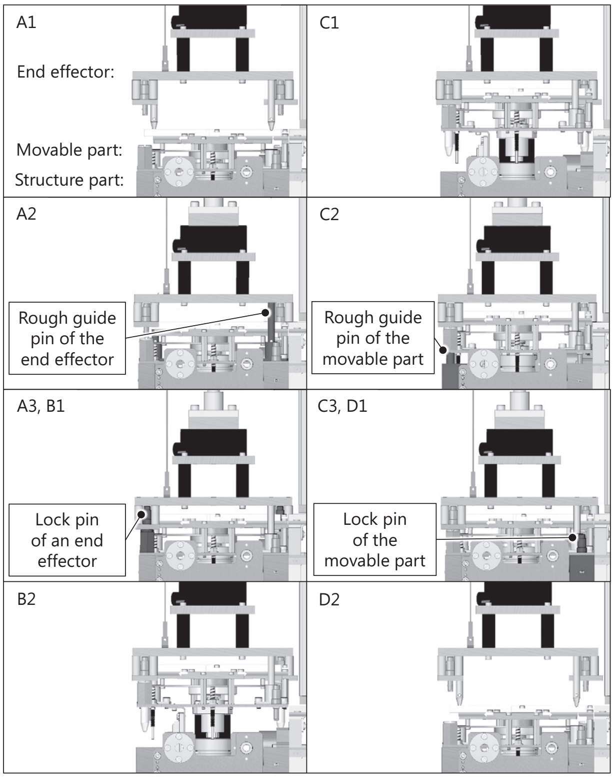

Fig. 10. Sequential snapshots of the replacement motion for the movable part of the intersection module using the end effector.

(B) Removing the movable part

1. The lock pins lock the movable part and lock pins of the movable part for the structure part are unlocked.

2. The end effector ascends. The movable part is removed from the structure part.

(C) Mounting the movable part

1. The replacing robot with a new movable part stops when the end effector is on top of the intersection module.

2. The end effector descends vertically. Rough guide pins of the new movable part are inserted into the structure part. The new movable part positions the structure part.

3. The end effector stops descending. Lock pins of new movable part are inserted into the structure part.

(D) Removing the end effector

1. The lock pins of the new movable part lock the structure part and lock pins of the end effector for new movable part are unlocked.

2. The end effector ascends. It is then removed from the new movable part.

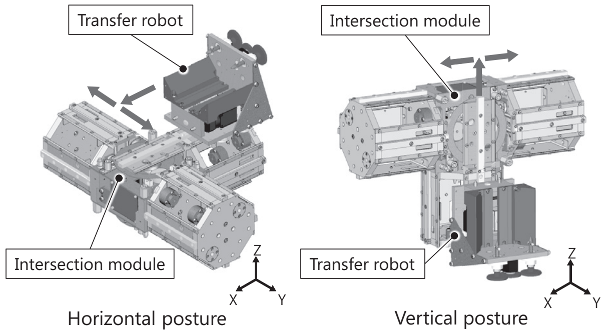

Fig. 11. Two postures for changing the transfer robot's attitudes.

4. Experiments to Evaluate the Intersection Module Performance

Using the intersection module and the replacing robot, we conducted experiments of changing transfer robot attitudes and the replacement of the movable part, assuming the use of a remotely controlled robot.

4.1. Experiment of Changing the Transfer Robot Attitudes

4.1.1. Objective of the Experiment

It is verified that the intersection module can change the robot attitudes by means of its turntable. Thereafter, the rail structure can expand two-dimensionally by constructing the module.

4.1.2. Experiment Methods

The transfer robot rides into the intersection module. The turntable rotates the robot and changes its attitude. The robot gets out of the module. The experiment is conducted in the two postures shown in **Fig. 11**.

4.1.3. Results and Discussion

Figure 12 presents the sequential snapshots of the transfer robot's right turning in the horizontal posture. **Fig. 13** shows that in the vertical posture.

Both right and left turnings are realized in each posture. Therefore, results show that constructing the intersection module can produce the rail structure branches and change attitudes of the transfer robot using the turntable.

4.2. Experiment of Movable Part Replacement Assuming a Remotely Controlled Robot

4.2.1. Objective of the Experiment

As for the compliant mechanism in the intersection module, deformation of the elastic material allows positioning errors of the movable part and restores its default position. In this experiment, the elastic material filling rate is changed. The movable part is replaced by the replacing robot at each filling rate. Results reflect the influence of the compliant mechanisms for the force/power necessary for the replacing robot.

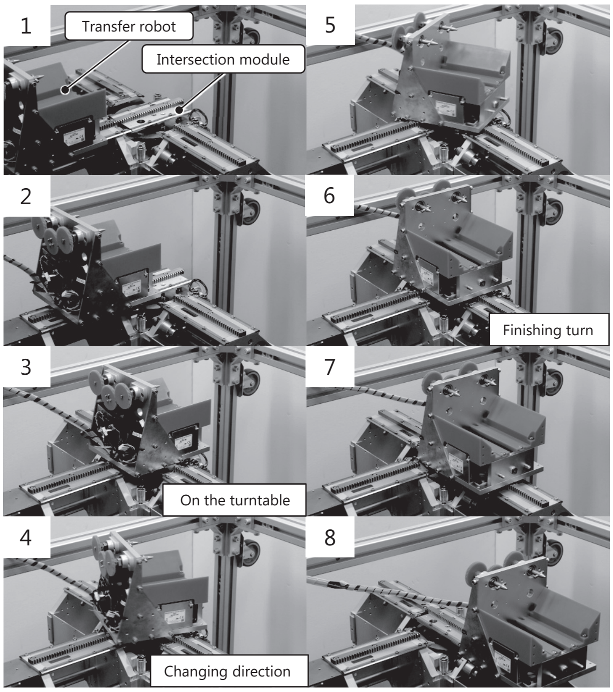

Fig. 12. Sequential snapshots showing changes of the transfer robot attitude in the horizontal posture.

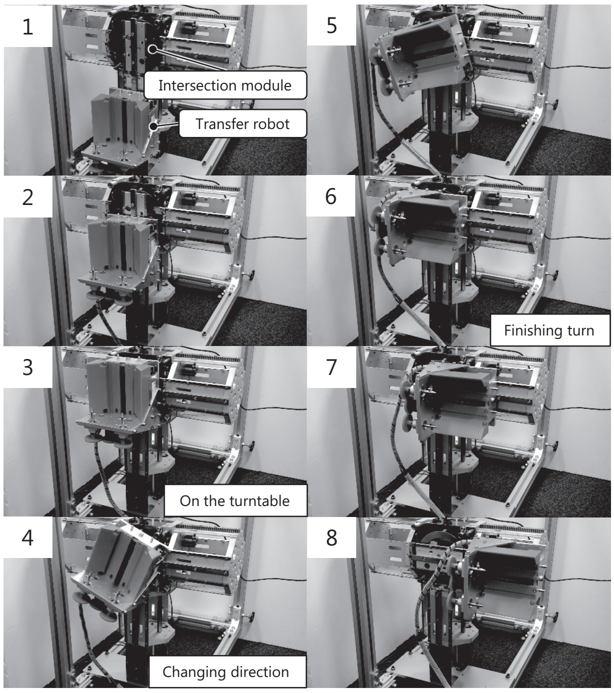

Fig. 13. Sequential snapshots showing changes of the transfer robot attitude in the vertical posture.

4.2.2. Experimental Configurations

We combined the compliant mechanisms of the end effector and the intersection module. **Fig. 14** presents an overview of the experimental equipment. Thereafter, we investigated the effects of decreasing the force necessary to mount the end effector. Regarding the compliant mechanism of the intersection module, the elastic material filling rate is adjusted to 100%, 76.9%, and 69.2%. In each configuration, the movable part is replaced by the imitated replacing robot, and the three-axis force sensor in the end effector measures the vertical force and orthogonal two-axis torque. The wire encoder measures the end effector height.

The maximum force is measured in (A) mounting the end effector as Section 3.4 describes because the force required in that phase (A) is the largest among those in the preliminary experiment. In the mounting task, the greatest force is acquired when the pin is inserted completely into the hole because the pin position is displaced against that of the hole. However, in the removal task, only the weight of pin-side components is necessary because the inserted pin is pulled out. In addition, mounting the movable part can allow the pin positioning error against the hole by smaller deformation of the compliant mechanism of the end effector, because of the length between the rotation center of the mechanism and the pin tip.

In this experiment, the end effector is mounted when its initial position is displaced 1.0 mm against the movable part. When an actual remotely controlled replacing robot mounts the end effector to the movable part, it will apply the force to the end effector continuously until the mount-

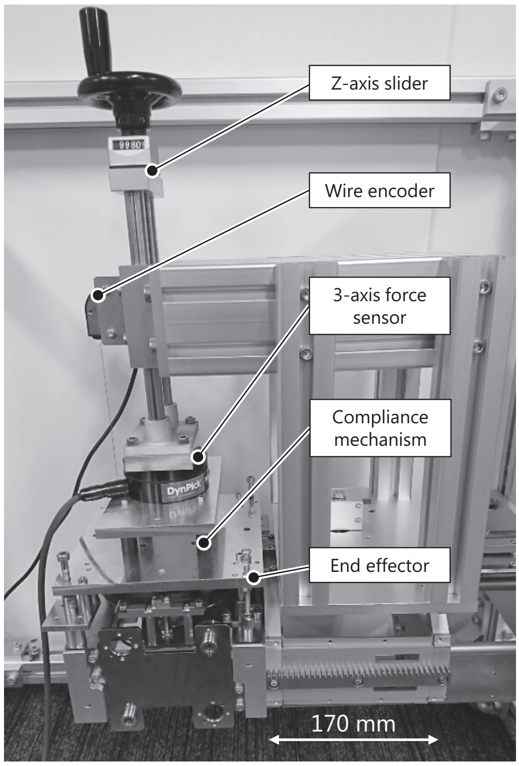

Fig. 14. Experimental equipment for replacing the movable part by the imitated replacing robot.

Table 2. Experimental configurations.

Configuration	Compliant mechanism in the end effector	Compliant mechanism in the intersection module
NN	None	None
EN	Installed	None
E100	Installed	Installed: filling rate 100%
E77	Installed	Installed: filling rate 77%
E69	Installed	Installed: filling rate 69%

ing is completed. In a similar manner, mounting of the end effector is imitated by turning the Z-axis slider handle continuously. **Table 2** presents the five experimental configurations. Ten trials were conducted except for the configuration NN. With the configuration NN, the number of trials is three, because the force sensor always indicates its limit as 62.2 N.

4.2.3. Results and Discussion

Figure 15 shows relationships between the length of the end effector insertion and the Z-axis force and X-axis and Y-axis torque for each experimental configuration, which are smoothed by considering the moving average before and after ten samples. **Fig. 16** presents the maximum force and standard deviation acquired through experimentation.

The result depicted in **Fig. 16** reveals that the compliant mechanism in the end effector reduces the force required for mounting the end effector. However, irrespective of the filling rate, the force reduced by the compliant mechanism in the module is substantially less than that of the mechanism of the end effector. It is inferred that the mechanism of the end effector can allow sufficient positioning errors because its mechanism has elasticity in the translational and rotational directions, whereas that of the module has elasticity only in the translational direction. A force approximately 40 N necessary for the end effector installation is sufficient for a linear actuator that will be used to develop a remote-controlled replacing robot.

Additionally, **Fig. 15** shows that the mechanism of the end effector decreases the two-axis torque orthogonal to mounting the end effector. Therefore, considering the deterioration of the organic elastic material that results from constant exposure to high radiation, only the compliant mechanism of the end effector is available for the replacement of the movable part and the intersection module can be developed in a simpler way without installing the compliant mechanism. If the compliant mechanism is not installed in the intersection module, designing taper guide holes for guide pins of the end effector and the movable part becomes essential to replace the movable part with positioning on the structure part.

5. Conclusions

For the long-term decommissioning of the Fukushima Daiichi Nuclear Power Station, the use of remotely controlled robots is anticipated. We are developing an "automated construction system for a modularized rail structure," which is an environment that facilitates robot locomotion and operation constructed by the robots' successive connection of rail structure modules.

For this study, we developed an intersection module that produces rail structure branches and changes robot attitudes, which is intended to reveal the effective design required to maintain the functions in preparation of the anticipated malfunctions. The intersection module that we developed has two replaceable movable parts and a structure part. Key features of this research are compliant mechanisms installed at the end effector and the structure part of the module, which allow the positioning error of the movable part against the structure part in the replacement task.

We developed prototypes of the intersection module and the imitated replacing robot, which revealed the following findings obtained through experimentation:

- A robot which locomotes on the surface of the rail structure can change its attitude at an intersection module constructed as part of the rail structure.
- The compliant mechanism of the end effector in a replacement task, assuming a remotely controlled robot, accommodates the positioning error of a movable part and decreases the necessary force for the replacing robot.
- The decrease in the force because of the compliant mechanism of the intersection module is extremely small because the mechanism accommodates only the translational positioning error.

For practical distributed robotic systems under the assumption of component malfunctions, it is important to design replacement components to overcome the anticipated malfunctions. If the malfunctioned part is replaced by the remotely controlled robot, then it is necessary to replace that part in the simplest manner possible. This study reveals that the force necessary for the replacement task is sufficiently decreased by the installation of the compliant mechanism only at the end effector of the replacing robot.

Future works will include remotely conducted replacement work and verification that the lower force requirement facilitates the replacement task.

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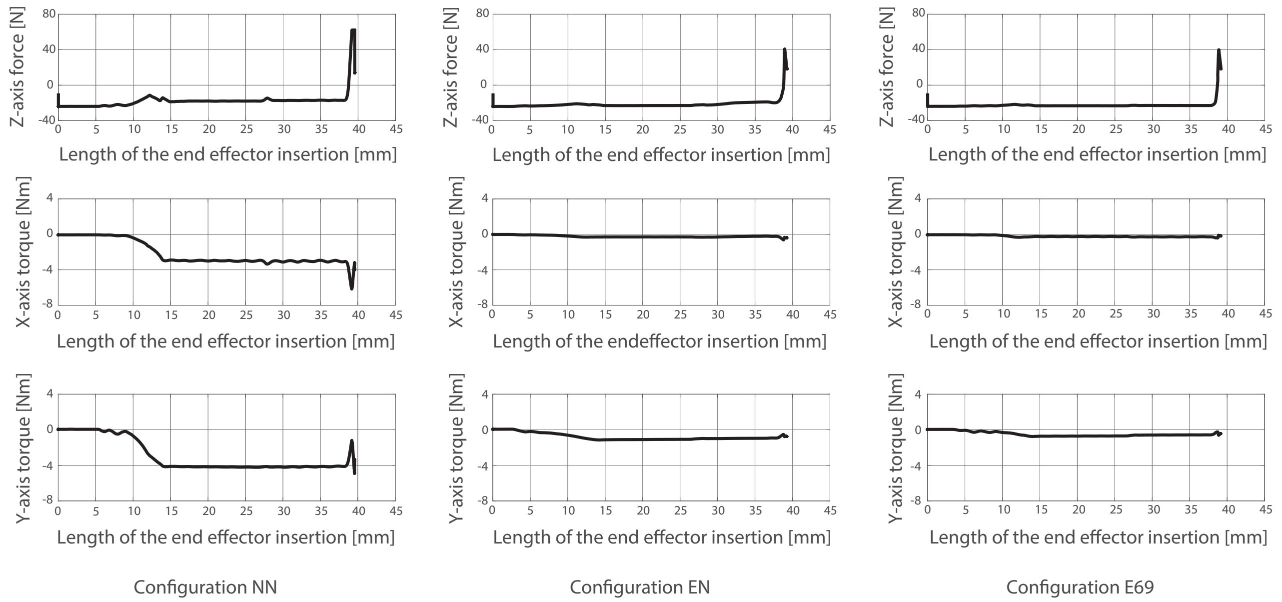

Fig. 15. Relationships between the length of the end effector insertion and Z-axis force, and X-axis and Y-axis torques in mounting the end effector under the configuration NN, EN, and E69.

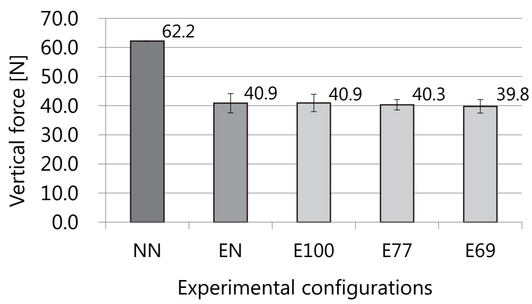

Fig. 16. Relationships between experimental configurations and vertical force in mounting the end effector.

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