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Elastic Telescopic Arm Extension/Contraction Mechanism using a Helically Grooved Flexible Conduit

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Abstract— **Thin and long-reach arms are effective for the decommissioning of the Fukushima Daiichi Nuclear Power Plant, particularly for measuring in-vessel structures and removing fuel debris. Currently, there is a need for an arm that can investigate the bottom of the reactor pressure vessel by attaching a vertically extending arm equipped with investigation equipment to the tip of a horizontally extending long-reach arm. Telescopic arms are expected to provide a high extension-to-contraction ratio, reduce the installation space of the arm, and enable entry into narrow spaces and wide-area observation. In this paper, we propose an extension/contraction mechanism that uses a helically grooved flexible conduit as a feed screw. Using the proposed mechanism, the conduit is fed into an elastically bendable arm, and a prototype that can extend/contract up to 8.6 m is developed. The fundamental performance of the elastic telescopic arm was evaluated through experiments in which the arm was extended/contracted horizontally (0 deg), tilted (45 deg), and upward (90 deg), payload experiments, and an external environment interference experiment.**

I. INTRODUCTION

To expedite the decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Plant, it is crucial to understand the condition of structures and fuel debris inside the Primary Containment Vessel (PCV) and Reactor Pressure Vessel (RPV). Currently, long-reach arms that can enter the inside of PCV and the bottom of RPV through the access hole called X-6 penetration are under development [1]–[3]. There is also a need for technology to attach an extensible arm equipped with investigation equipment such as cameras and ultrasonic sensors to the tip of the long-reach arm, thereby enabling the investigation of the bottom of the RPV (Fig. 1). Such an extensible arm should be thin and highly extendable in order to pass through the hole that is believed to have opened in the bottom of the RPV due to the meltdown, and have a certain amount of payload to carry investigation equipment.

Therefore, the development of arms with a telescopic structure, which has a large extension-to-contraction ratio and can be lengthened, is currently underway. A telescopic structure consists of pipes of different diameters that nest within each other and extend/contract like a fishing rod. Endo et al. attached a CFRP telescopic arm with a wire-driven linear motion mechanism at the tip of a 10-m-long-coupled tendon-driven articulated manipulator [1], extending it vertically upward to 2.8 m, resulting in an arm with a total length of about 13.7 m [4]. This arm has a structure similar to that seen on fire truck ladders and has a large payload because the tip load is supported by rope tension. However, each pipe is about 1.5 m long, and pulleys must be placed between the pipes, making it difficult to reduce the segment length and the diameter. On the other hand, the International Research Institute for Nuclear Decommissioning (IRID) has developed a pneumatically driven telescopic arm with a total of 14 stages, 1.0 m in contraction and 7.3 m in extension [5]. Nonetheless, this arm is difficult to extend while tilted due to the pneumatic seal, and its high stiffness makes it less adaptable when in contact with an unknown environment. Moreover, the total time required for the extension/contraction is about 6,000 sec, which is time-consuming.

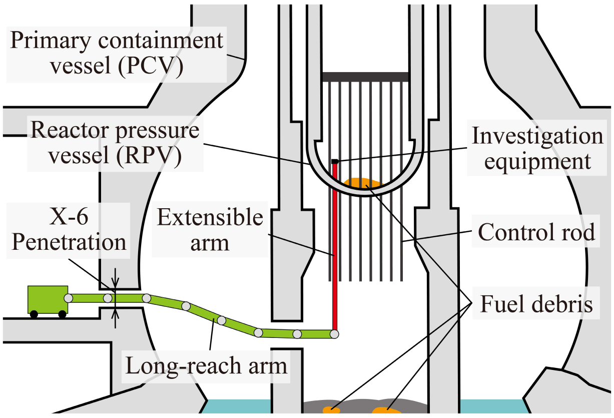

Fig. 1. Planned robotic RPV investigation in Fukushima Daiichi Nuclear Power Plant.

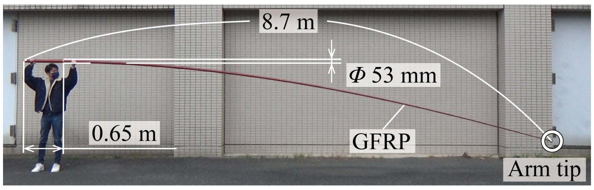

Fig. 2. A commercially available cable towing arm（DRXF-10000, DENSAN）.

From such backgrounds, we have been utilizing a commercially available cable towing arm as an elastic telescopic arm (ETA), as shown in Fig. 2. This arm uses Glass Fiber Reinforced Plastic (GFRP) for the pipes. It has a high extension-

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to-contraction ratio and a compact structure with a length of 0.65 m when contracted, 8.7 m when extended, a maximum diameter of 53 mm, and a mass of 1.8 kg, making it an elastic arm that can be deformed by external force or its own weight. We have developed arm extension/contraction and bending mechanisms using the ETAs [6]. However, the conventional extension/contraction mechanism uses a complex constraint mechanism inside the arm to extend the pipe one by one, and the sliding friction increases as the length and the payload increase, preventing the mechanism from being driven. The maximum extension length was limited to 3.6 m.

In order to increase the maximum extension length and the payload capacity, our research objectives in this paper are to propose a new extension/contraction mechanism for the ETA, and experimentally evaluate the effectiveness of the proposed mechanism by hardware experiments. As for the extension/contraction mechanism, we have focused on a helically grooved flexible conduit (hereinafter called conduit), which is used to protect water pipes, camera stands, electric cables, and optical fibers. We propose a method to extend/contract an arm by pushing/pulling a conduit into the arm. Since the conduit is simply pushed or pulled into the arm, there is no need for a complex mechanism inside the arm, and a lightweight and compact arm can be achieved. In this paper, we also develop prototypes with the proposed extension/contraction mechanisms and experimentally demonstrate the effectiveness of the ETA by conducting experiments in which the ETA is extended/contracted horizontally (0 deg), tilted (45 deg), and upward (90 deg), payload experiments, and an external environment interference experiment.

II. PROPOSAL OF EXTENSION/CONTRACTION MECHANISMS USING A CONDUIT

A conduit is a structure that can flexibly bend when a force over a threshold is applied, but maintains its shape when the force is less than the threshold. The conduit is characterized by its extremely high cyclic bending strength and its ability to save space when stored by bending.

Morphable Beam Device [7] and Flexible Feed Screw [8] have been proposed for research on robots using flexible and bendable rods. Nakanishi et al. proposed a robotic system using a morphable beam that uses the beam as extendable arms and legs [7]. The proposed system is equipped with a beam shaper and a reel mechanism at the tip of the beam. The beam shaper allows the system to bend and move at a desired position. However, the generating force at the hand tip is not discussed because the system is based on the space structure. Matsuura et al. proposed an extendable continuum robot arm using a flexible screw that has many moving plates along an elastic feed screw and deploys each plate to a certain contactable area [8], but the experimental verification is about 1 m in size and it would be difficult to scale up for decommissioning work.

On the other hand, Fujioka et al. conducted an extension experiment in which a conduit was fed into the ETA [9]. In this experiment, two rubber rollers were used to sandwich the conduit and feed it into the ETA by friction between the rollers and the conduit. However, when the pipe diameter was increased, the axial force of the conduit was not transmitted in the direction of the arm extension, and the arm could be extended only about 4 m. One of the reasons is that the high flexibility of the conduit causes the conduit to be helical inside the arm and press against the inner wall of the arm, generating a large frictional force between the arm and the conduit. The larger the inner diameter of the pipe, the smaller the pitch of the helix due to the torsion of the conduit, which increases the amount of contact and friction, preventing extension. Since the helix of the conduit inside the ETA is a problem for arm-lengthening, the following two methods can be considered to solve this problem.

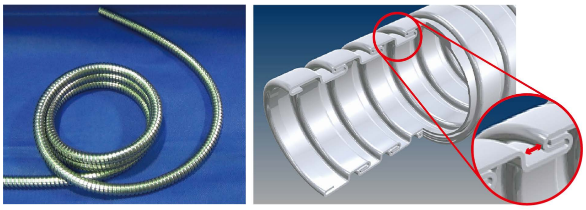

(a) Overview (b) Cross section

Fig. 3. Helically grooved flexible conduit（Semi-inter tube, HAGITEC Co., Ltd.）.

1) Make the diameter of the conduit larger with respect to the pipe diameter
2) Suppress rotation of the conduit around the longitudinal axis

In this paper, we propose two extension/contraction mechanisms, 1) as method 1 and 2) as method 2.

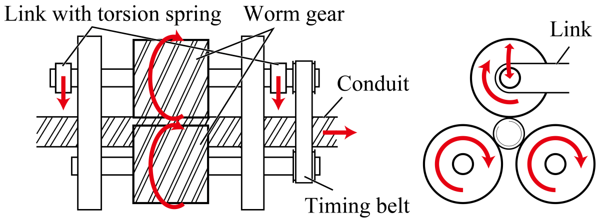
A. *Helically grooved flexible conduit*

Fig. 3 indicates the conduit used in this study. It has an S-shaped cross-section of stainless steel interlocked as shown in Fig. 3 (b). It is resistant to lateral pressure, torsion, tension, and repeated bending, and is also flexible. Additionally, the conduit is hollow, allowing energy supply to the arm tip by inserting electric wires and pneumatic tubes through it. Because the conduit requires the same length as the arm, high flexibility is essential for ease of storage. We use a flexible conduit with a bend radius of about 65 mm.

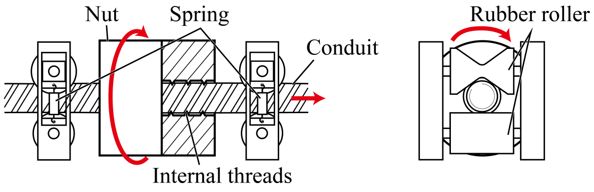
B. *Method 1*

If the outer diameter of the conduit is too small compared to the pipe diameter, extension is prevented by the helical deformation of the conduit inside the arm, so the outer diameter of the conduit should be larger according to the pipe diameter to increase the thrust force in the longitudinal direction.

Therefore, we propose an extension/contraction mechanism that can feed a conduit with different diameters (Fig. 4 (a)). This mechanism synchronously rotates three worm gears with teeth that fit into the helical groove of the conduit, and one of the worm gears is movable to enable feeding of the conduit even if the conduit diameter changes. Three worm gears are driven and synchronized by timing belts,



(a) Method 1



(b) Method 2

Fig. 4. Proposed extension/contraction mechanisms.

and one of them is constantly pressed against the conduit by torsion springs mounted on links, which are thought to allow the conduit with different diameters to be fed by moving passively even if the conduit diameter changes.

C. Method 2

Another method to prevent the conduit from deforming the conduit inside the arm is to suppress the rotation of the conduit around the longitudinal axis. When the conduit is fed as a feed screw, if the conduit is not suppressed around the axis, the conduit itself rotates, causing it to be helical inside the arm or the arm to rotate together with the conduit.

Therefore, we propose an extension/contraction mechanism that can feed a conduit by a feed screw equipped with a mechanism to suppress the rotation of the conduit (Fig. 4 (b)). This mechanism rotates a nut with internal threads that fit into the helical groove of the conduit, and a rotation suppression mechanism in front and behind the nut suppresses the rotation of the conduit around the longitudinal axis while the conduit is fed. Rotation of the conduit can be suppressed by using a flat rubber roller and a V-shaped grooved rubber roller, which presses against the conduit at three points by spring force.

III. DEVELOPMENT OF PROTOTYPES

We define Method 1 as a worm gear type extension/contraction mechanism and Method 2 as a feed screw type extension/contraction mechanism and developed prototypes.

A. Development of worm gear type extension/contraction mechanism

Fig. 5 indicates the prototype worm gear extension/contraction mechanism. The rotation of the motor synchronously rotates three worm gears with teeth that fit into the helical groove of the conduit through gears and timing belts. The shaft of one of the worm gears is supported by torsion springs mounted on links, which passively change the position of the shaft as the conduit's outer diameter changes, thus allowing it to fit into larger conduits. The motor is a power tool motor (MM-26EH, Nippo Denki Co., Ltd.) and has a max power output of 90 W. The worm gears were fabricated by a 3D printer (G-ZERO, Gutenberg Co., Ltd.) using a potassium titanate fiber-reinforced material (POTICON, Otsuka Chemical Co., Ltd.) with high sliding properties, and were designed to be able to feed a conduit with different diameters by connecting 14.9 mm and 24.1 mm conduits with a connector as shown in Fig. 5.

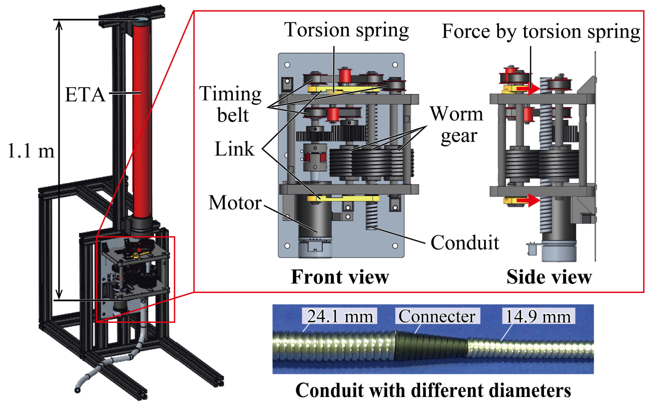


Fig. 5. Worm gear type extension/contraction mechanism.

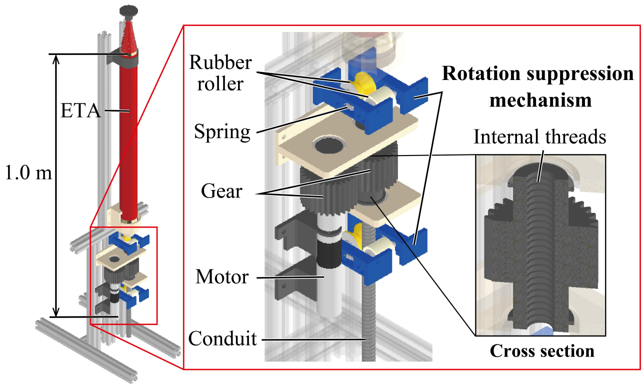


Fig. 6. Feed screw type extension/contraction mechanism.

B. Development of feed screw type extension/contraction mechanism

Fig. 6 indicates the prototype worm gear type extension/contraction mechanism. A gear with internal threads that fit into the helical groove of the conduit is rotated by the rotation of the motor. The conduit is fed through two rotation suppression mechanisms and a gear with internal threads by attaching a rotation suppression mechanism to the front and behind the gear. The rotation suppression mechanism is designed to suppress conduit rotation by pressing the conduit at three points with the spring force, using a flat rubber roller and a V-shaped grooved rubber roller that can be free to rotate. The motor is the same as the worm gear type extension/contraction mechanism. The gears were fabricated by a 3D printer (Onyx One, Markforged Inc.) using short carbon fiber reinforced nylon (Onyx, Markforged Inc.).

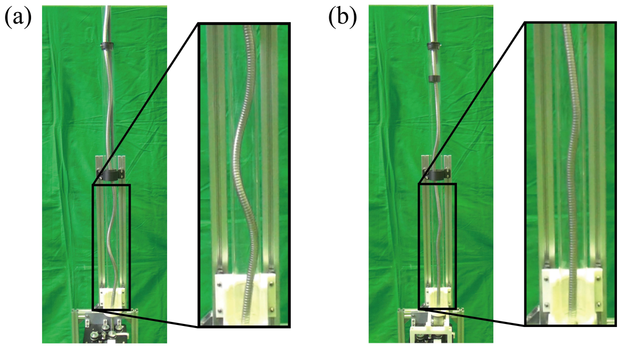


Fig. 7. Results of extension experiment with and without rotation suppression mechanism. (a) Without rotation suppression mechanism. (b) With rotation suppression mechanism.

IV. DRIVING EXPERIMENTS OF PROTOTYPES

Using developed prototypes, we conducted driving experiments of each extension/contraction mechanism by extending the ETA upward.

A. Driving experiment of worm gear type extension/contraction mechanism

After confirming that the conduit with different diameters could be fed using the worm gear type extension/contraction mechanism shown in Fig. 5, the conduit was fed into the ETA and an attempt was made to extend the ETA upward. As a result, the ETA could be extended to a height of more than 7 m and then contracted. However, the larger the diameter of the conduit, the heavier the mass and the larger the torque on the motor, and the conduit and worm gears slipped and disengaged, making it difficult for thrust force to be transmitted. Because the rotation of the conduit is not fixed, friction between the conduit and worm gears causes the conduit to torsion around the longitudinal axis and the arm tip to whirl. In addition, the conduit tangles in front of the lower rotation suppression mechanism, requiring hand adjustment.

B. Driving experiment of feed screw type extension/contraction mechanism

First, we attempted to extend the conduit into an acrylic pipe to see if the rotation of the conduit could be suppressed with or without the rotation suppression mechanism shown in Fig. 6. The rotation of the conduit was visualized by applying tape to the pipe. Fig. 7 indicates the results of extension experiments with and without the developed rotation suppression mechanism. As a result of the experiments, it was confirmed that in the case of no rotation suppression (Fig. 7 (a)), the conduit is fed while contacting the inner wall of the pipe in a helical shape, but in the case of rotation suppression (Fig. 7 (b)), the conduit extends in a linear shape without contacting the inner wall of the pipe in a helical shape and is fed to contact the pipe due to buckling repeatedly. It was also confirmed that the rotation of the conduit could be considerably suppressed compared to the case without the rotation suppression mechanism.

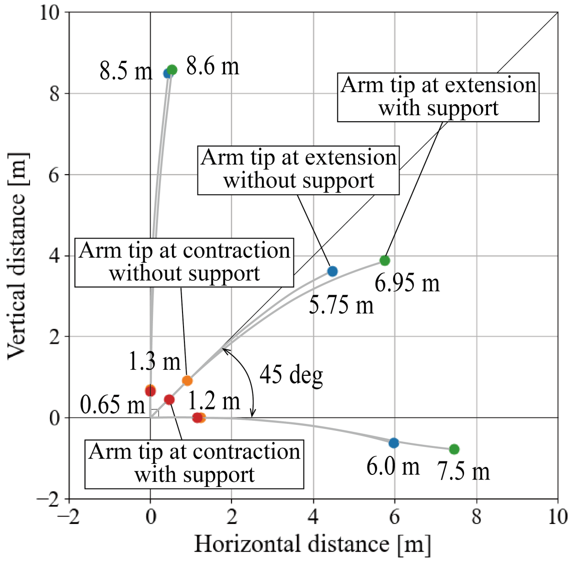


Fig. 8. Results of extension/contraction experiments.

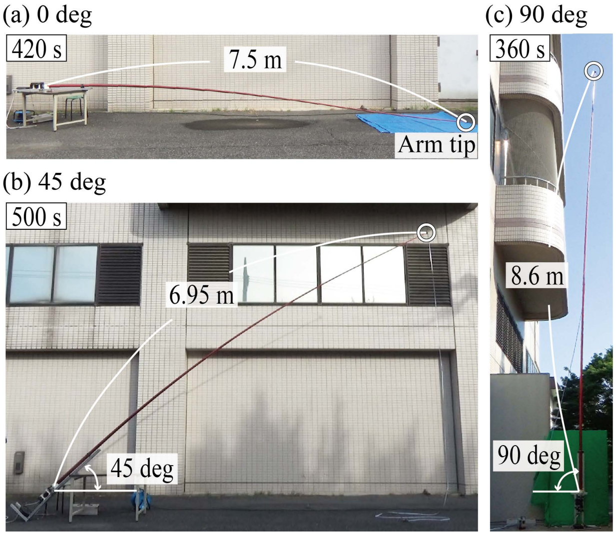


Fig. 9. Extension results when supported by hand. The upper left number indicates extension time.

Next, the ETA was extended upward with the feed screw extension/contraction mechanism. As a result, the ETA could be extended to a height of about 7.4 m and then contracted. In the driving experiment, the conduit was only about 8.5 m long and the arm could only be extended to about 7.4 m, but a further extension could be achieved if the conduit is longer.

C. Comparison between worm gear type and feed screw type extension/contraction mechanism

Although friction between the conduit and worm gears causes the conduit to torsion around the longitudinal axis and the arm tip to whirl in the worm gear type extension/contraction mechanism, it is thought that the rotation and torsion of the conduit can be suppressed by applying the rotation suppression mechanism as well as the feed screw type extension/contraction mechanism. On the other hand, the feed screw type extension/contraction mechanism consists of fewer gears and other parts than the worm gear type extension/contraction mechanism and is considered to be more compact and lightweight, making it easier to integrate with long-reach arms. Furthermore, because the number of internal threads between the conduit and the gear inside is large, the mechanism is expected to be able to withstand a large compressive force without the conduit slipping through due to an increase in the mass of the conduit or investigation equipment attached to the tip of the ETA. Therefore, the feed screw type extension/contraction mechanism was adopted in the next section.

V. PERFORMANCE EXPERIMENTS OF THE ETA BY FEED SCREW TYPE EXTENSION/CONTRACTION MECHANISM

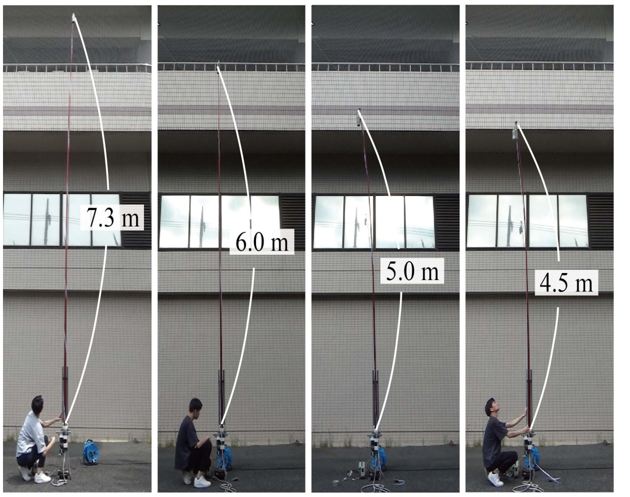
We conducted three-directional extension/contraction experiments, payload experiments, and an external environment interference experiment using the feed screw type extension/contraction mechanism (diameter of the conduit: approx. 14.0 mm).

A. Three-directional extension/contraction experiments

In investigating the inside of the RPV, the arm can be extended/contracted not only upward but also in multiple directions to avoid obstructions and observe a wide area.

We therefore conducted experiments in which the arm was extended horizontally (0 deg), tilted (45 deg), and upward (90 deg), and then contracted. The conduit tip and the arm tip are fixed through a rope, and the gear is reversed and the conduit is fed back, resulting in contraction. In the ETA, the pipes are not pushed out one by one from the tip side due to friction between the pipes, resulting in non-uniform extension. For this reason, we define the case in which the pipes are supported by hand so that they are extended one by one from the tip side as ”with support” and the case in which they are not supported as ”without support”. In this study, the pipe was extended/contracted three times in each of the three directions without and with support, and the arm lengths were measured with a tape measure.

Fig. 8 and Fig. 9 indicate the experimental results. Fig. 8 indicates the arm tip position at the maximum extension/contraction in experiments conducted without and with support three times each. The horizontal axis indicates horizontal distance and the vertical axis indicates vertical distance, and the numbers in the figure indicate arm lengths. The arm tip position and the degree of arm bending are approximate estimates obtained from measurements with a tape measure and video recorded in the experiments. Fig. 9 indicates the maximum extension with support, and the upper left number in the figure indicates the extension time. The result of the upward extension was obtained using a 10 m conduit since the conduit was not long enough for the upward extension in the driving experiment. The arm tip touched the ground during horizontal extension, as shown in Fig. 9 (a).



(a) 0.5 kg (b) 1.0 kg (c) 1.5 kg (d) 2.0 kg

Fig. 10. Results of payload experiments.

As shown in Fig. 8, extension ”with support” is better than extension ”without support”, which achieved approx. 7 m in three directions. The reason for this is thought to be that the friction between the pipes increases when multiple pipes are extended ”without support”, whereas the friction between the pipes is smaller ”with support” because the pipes are pushed out one at a time. As shown in Fig. 9, the extension time is 420 sec at 0 deg, 500 sec at 45 deg, and 360 sec at 90 deg, with the extension time increasing in the order of 90 deg, 0 deg, and 45 deg. The effect of the mass of the conduit is dominant at 90 deg, and the effect of friction between arm pipes is dominant at 0 deg. The load on the motor was increased by the mass of the arm/conduit and the friction between the pipes at 45 deg, and it is thought that it took longer for the arm to extend. In addition, the outer diameter of the conduit is subject to dimensional tolerance, and the outer diameter changes slightly when loaded due to the flexibility of the conduit. If the outer diameter is slightly thickened, the conduit cannot be inserted into the extension/contraction mechanism properly, requiring hand adjustment by twisting the conduit to correct the thickened portion, which takes time.

On the other hand, it was confirmed that the arm can be contracted to the base of the arm, as shown in Fig. 8, although it cannot be contracted to the end at 0 deg and 45 deg because a pipe is stuck by other pipes.

B. Payload experiments

In decommissioning work, a certain amount of payload is required to mount cameras and sensors on the arm tip to investigate the inside of the RPV.

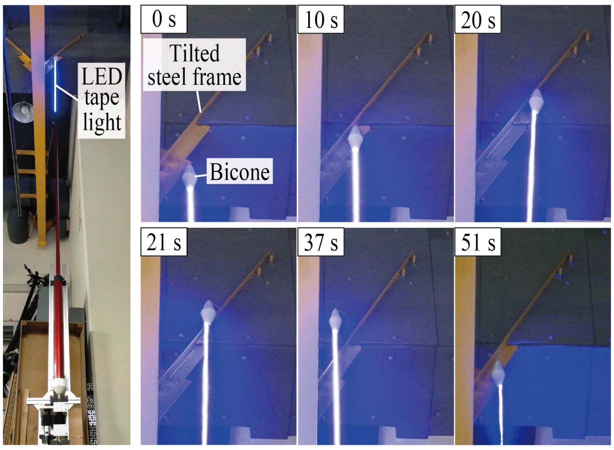
We therefore conducted extension/contraction experiments in which weight was attached to the arm tip in 0.5 kg each, and a maximum weight of 2.0 kg was loaded. The weights are plastic bottles filled with sand. Fig. 10 indicates the results of the payload experiments. Although the arm can be extended beyond the experiment results, it was limited to a height at which it can be extended stably, because overextension causes it to bend too much and break or the tip

TABLE I

COMPARISON BETWEEN THE ETA AND SIMILAR EXTENSIBLE ARMS.

Arm name	Outer diameter [mm]	Weight [kg]	Max extension length [m] (*)	Max payload [kg]	Tilted extension
ETA (conduit: Ø 14 mm)	53	4.9	8.6 (13.2)	2.0	○
14-stage telescopic pipe [5]	97	-	7.3 (7.2)	2.0	△
Spiral Zipper [10]	114	1.7	2.2 (-)	54 (Load capacity)	△
ZipperMast ZM-4 [11]	240	7.0	2.5 (11.4)	3.5	△
ZipperMast ZM-10 [11]	430	48	6.0 (17.1)	15	△
RoboPole 5ESJ-200/800 [12]	-	50	8.0 (4.0)	15	○
RoboPole 6ESJ-2510/1200 [12]	-	240	12 (4.8)	50	○
NK-9 [13]	102.5	26	9.0 (3.9)	22	-

* Extension-to-contraction ratio



(a) Overview (b) Change of arm tip position with time

Fig. 11. Result of external environment interference experiment.

position to become unstable.

The maximum extension length decreased as the weight increased, and the arm could be extended approx. 6.0 m at 1.0 kg and 4.5 m at 2.0 kg. Therefore, it was confirmed that the arm can be extended/contracted while a camera or other investigation equipment is mounted on the arm tip. Nevertheless, the arm used in this study tends to bend easily and is difficult to extend linearly. To achieve linear extension and higher payload, a thicker or a different type of conduit will be used and the pipe diameters should be increased. It is considered that there is a trade-off between ease of bending and high payload.

C. *External environment interference experiment*

The arm must either actively avoid obstacles or passively bend and extend even when obstacles interfere with it because the situation inside the RPV is not guaranteed to enable a linear extension of the arm.

We therefore conducted an experiment in which the arm was extended/contracted while interfering with the external environment. Fig. 11 indicates the results of the external environment interference experiment. As shown in Fig. 11, a blue LED tape light is attached to the arm for visibility, and a bicone object fabricated by a 3D printer is attached to the arm tip so that the arm can extend and contract along the external environment.

It was confirmed that the arm extended while bending passively along the tilted steel frame from Fig. 11. It was also confirmed that the bicone object attached to the arm tip could make the arm overcome the steel frame and extend/contract.

VI. COMPARISON BETWEEN THE ETA AND SIMILAR EXTENSIBLE ARMS

TABLE I indicates the comparison between the ETA and similar extensible arms. The ETA which we proposed in this paper is smaller in diameter and lighter in weight than other arms but achieves a high extension-to-contraction ratio. The arms utilizing zippers [10] [11] are robust against axial compression, but when they are extended at a tilted angle, they cannot withstand the bending moment and are considered to be unable to be extended properly because of the disengagement of the zippers. On the other hand, the ETA can bear its own weight and is capable of tilted extension and extension while passively bending along the external environment. Furthermore, the ETA has a short length of one pipe section compared to RoboPole [12] and NH-9 [13].

Based on the above, the ETA with the conduit has a simple structure and is lightweight, making the ETA effective in investigating the inside of RPV from the viewpoint of integration with a long-reach arm. However, the payload capacity of the ETA is insufficient compared to other arms, and improvement is needed.

VII. CONCLUSION

In this paper, we proposed extension/contraction mechanisms of the ETA using a helically grooved flexible conduit for the decommissioning of the Fukushima Daiichi Nuclear Power Plant. The performance and characteristics of the ETA with the proposed extension/contraction mechanism obtained through experiments are summarized below.

- The arm can be extended approx. 7 m in three directions (0 deg, 45 deg, 90 deg) by supporting the arm pipe so that it is pushed out one by one.
- When using a conduit of approx. 14.0 mm, an equipment of 2.0 kg can be lifted up to about 4.5 m.
- The arm can extend while bending along the tilted external environment.
- Extension/contraction is extremely fast compared to pneumatic-driven arms.
- The arm pipes and extension/contraction mechanism are mostly made of plastic, making it lightweight.

In our future works, we will attempt to improve the arm so that its pipes can be pushed out one by one without hand support and increase the payload capacity by using a conduit thicker than the one used in this study and increasing the pipe diameters at the arm tip. In addition, we will further demonstrate the effectiveness of the ETA by integrating it with a long-reach arm and conducting extension/contraction experiments with either an energy supply or a camera mounted on the arm tip.

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