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| Authors | Takashi Fujioka, Gen Endo, Koichi Suzumori, Hiroyuki Nabae |
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# Proposal of Tendon-driven Elastic Telescopic Arm and initial bending experiment

Takashi Fujioka[1], Gen Endo[1], Koichi Suzumori[1] and Hiroyuki Nabae[1]

***Abstract*— It is desirable to have an arm with a thin and long structure in order to observe a wide area through a narrow space for the survey at the disaster site. In addition, if the arm is lightweight and compact, there are fewer restrictions on the installation location, which leads to an improvement in the observation range. The telescopic structure has a high extension-to-contraction ratio and is a suitable structure to attain the aforementioned requirements. However, conventional telescopic arms can not avoid obstacles on the axis of extension because of high rigidity, so it is restricted to use in an open environment. In this paper, we propose an arm that controls the tip position by bending the structure with a wire by constructing a small diameter arm with a telescopic elastic body. We also examined the technical elements necessary to realize the proposed method and demonstrated the validity. It is difficult to bend in multiple directions or the whole structure by winding the wire only attached to the structure tip. Therefore, we devised a wire driving method in which bending moments are distributed as much as possible on the base side by arranging pulleys in multiple positions, and confirmed the desired motion through experiments.**

## I. INTRODICTION

It is effective to use a long manipulator which can avoid obstacles and move through a narrow path when using robots for observation and inspection in a complicated environment - such as a disaster site where rubble is scattered around, or inside a reactor where there is much equipment. There is a problem in that the volume and weight of the manipulator become excessive in the usual design because of requiring a strong driving system to support the heavy arm.

The weight of the mechanism was reduced and a weight compensation mechanism was installed as an attempt to overcome the constraint caused by the weight of the manipulator. As an example of weight reduction, there is the application of special rotation joints[1] and the arrangement of actuators concentrated on the base by driving force transmission using wires[2]. As an example of the weight compensation mechanism, there is a method of loading a part of gravity torque on a spring or a wire[3][4], as well as a method of supporting torque by the structure itself.

Examples of this structural supporting torque are a rotary joint mechanism without back drivability[5], the SCARA[6], and a linearly extensible arm. The SCARA is an arm that limits the rotation node to only the vertical axis. It can experience a moment due to the weight of the entire structure, because forces in the vertical direction are not received in the axis of the rotation node. The range of movement in the vertical direction becomes narrow because it is necessary to keep the arm horizontal. The linearly extendable arm is the same structure seen in a fire truck ladder. It experiences a moment from the entire structure because the linear motion does not have a rotation node. However, it is limited to use in an open environment because it is impossible to avoid obstacles immediately in front of it.

Incidentally, to expand the working range of the manipulator, reducing the size of the base is also an important factor. It becomes possible to reach the work location from various positions and directions because the number of options for the installation location increases.

In considering how to store the arm to save space, it is possible to store it by folding the node with an articulated type. In the linearly extendable arm, there is a telescopic structure that uses tubes of different sizes to extend and contract. In addition, Yuan et al. propose Spiral Zipper [7] that forms a cylindrical shape by shaping a long, thin plastic band upwards into a spiral.There are zipper-like teeth on opposited edges of the band that complement eath other, forming a tube when it is spiraled. Furuya et al. propose formation of cylindrical structure with carbon fiber reinforced plastic(CFRP) convex tape[8]. Both of them achieve a large extension-to-compression ratio by winding the band. Spiral Zipper realized a ratio of over 14:1 and controled tip position by mounting it onto a universal joint and varying the length of three tethers. However, in both cases, it is impossible to tolerate an increase in moment accompanying elongation because both of them have small Young's modulus and tend to buckle.

In this paper, we focus on linearly extendable arm con-

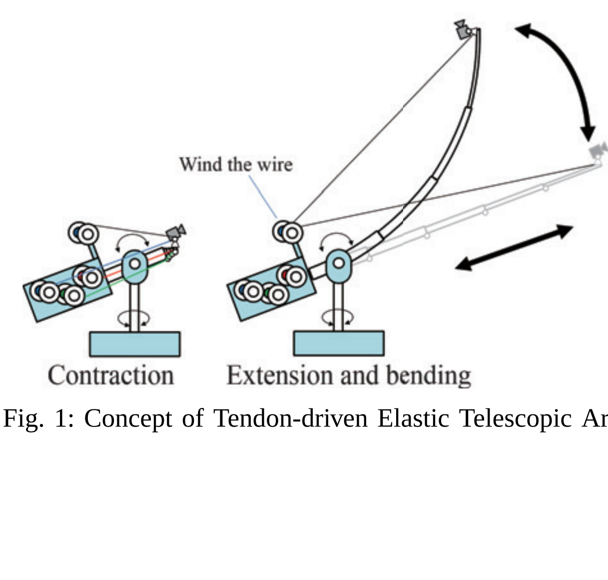



Fig. 1: Concept of Tendon-driven Elastic Telescopic Arm

[1]T.Fujioka, G.Endo, K.Suzumori and H.Nabae are with the Department of School of Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguroku, Tokyo, 152-8552, Japan fujioka.t.aa@m.titech.ac.jp

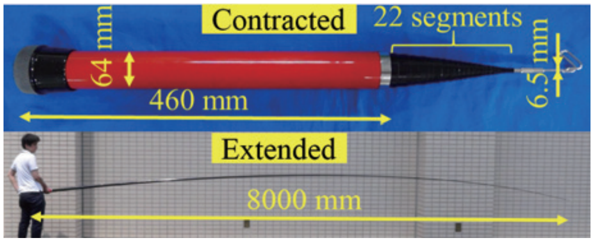
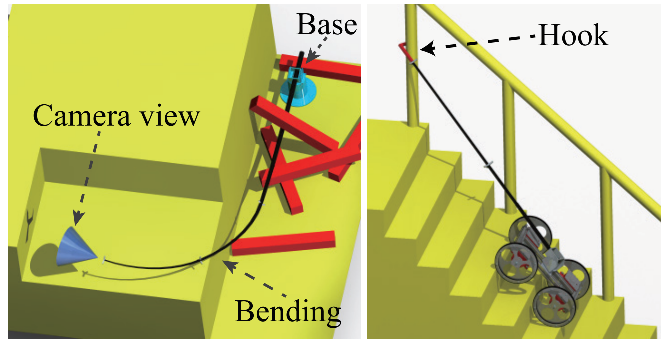



Fig. 2: A product of a long-reach and compact telescopic structure (DENSAN, DRF-8000S)




(a) Observation of remote areas by bending motion (b) Improvement of stepping ability of mobile robot

Fig. 3: Concept of using Tendon driven elastic telescopic arm

traction by a telescopic structure with light-weight, high extension ratio and high bending strength. We propose a method to solve the low obstacle avoidance shortcoming of the linearly extensible arm described above by bending the structure through wire tension as shown in Fig.1. Hereinafter we call the proposed arm Tendon-driven Elastic Telescopic Arm.

The organization of this paper is as follows. In section II, we describe the details of the Tendon-driven Elastic Telescopic Arm. In section III, we discuss the extension mechanism and the experiment. In section IV, we discuss experiments conducted on wire-driven posture determination. In section V, a summary of the results is given.

## II. Proposal of the Tendon-driven Elastic Telescopic Arm

The proposed arm consists of 1) a telescopic structure, 2) extension and contraction mechanism, 3) a tendon driven mechanism for bending the structure. The advantages of the telescopic structure are summarized below.

- Small size is possible due to high extension ratio and thin structure
- Lightweight and long-reaching arm can be realized due to the cylindrical tapered shape
- It has high bending strength and can receive its own weight by structure
- The structure naturally deflects when hitting an obstacle

Fig.2 shows an example of a telescopic structure having such characteristics. This product has extension length of 8000 mm and extension ratio is 17:1, achieving a high extention ratio and a thin structure. In addition, the weight is as light as 1.15 kg. When a weight of 100 g was applied to the tip at the maximum extension, the tip displacement was 1500 mm, and it was confirmed that this type of structure had sufficient flexural rigidity and bending strength.

This extension and contraction mechanism is necessary to realize a small arm size. In addition, there is an advantage in that it is possible to generate positioning and driving force in the cylindrical axis direction.

The advantages of the tendon-driven bending mechanism are summarized below

- Reduction of weight of the arm by compact arrangement of the driving parts
- Realization of various bending shapes
- Precise motion of tip position

Various bent shapes can be assumed becuase the distribution of bending moment changes according to the number of wires, fixed positions, and paths. Furthermore, the displacement range of the tip is broadened even though the rotation angle of the base portion is minute because of arm length. On the other hand, when the arm is bent by the wire, it does not depend on the length of the entire arm length because the bending displacement is determined by the winding amount of the wire. It is possible to achieve precise tip control by making the reel diameter small.

The proposed arm is less restricted on installation location compared with the conventional arm because it is light-weight and small in size. For this reason it is suitable for use in a disaster site as shown in Fig. 3(a) and for loading on a mobile robot as shown in Fig. 3(b). Characteristics of the environment represented by a disaster site suitable for use of this arm are as follows

- Installation location is cramped
- A narrow path exists in the observation route
- Ability to stretch further around corners

In addition, there are the following advantages by being able to move while grasping onto the surroundings with the arm loaded on a mobile robot.

- Prevention of slipping in rough terrain
- Preventing falls in rough terrain
- Using arm driving force as assisting force for movement

In the following sections, we will proceed with principle prototyping of mechanism elements for realizing the proposed Tendon-driven Elastic Telescopic arm and verify its feasibility.

## III. Extension and contraction mechanism

### A. Examination of extension method

As a method of extending and contracting the telescopic structure, 1) wire driving, 2) pneumatic and hydraulic pressure and 3) insertion of a flexible tube can be considered.

Extension and contraction by wire driving is a method found in telescopic cranes. Each segment is pulled out to the next segment by wire tension. It is necessary to provide clearance for arranging the pulley and the wire because the

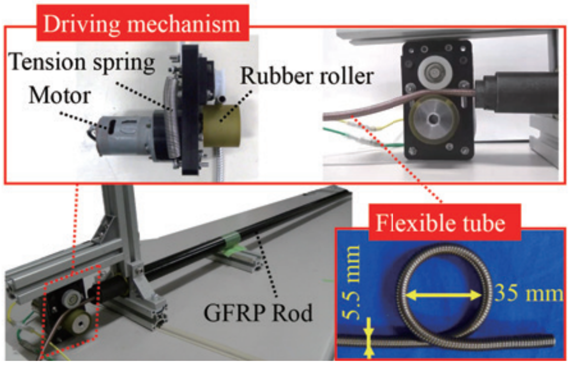



Fig. 4: The overview of extension experiment device

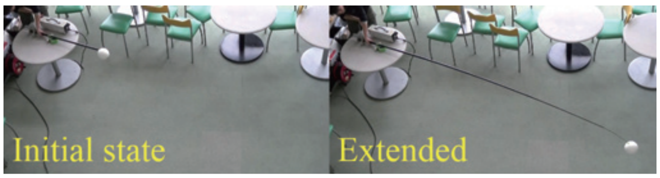



Fig. 5: The extension experiment result

wire passes between the segments of the structure. Because of this, the advantages of small diameter and light weight of the arm are lost.

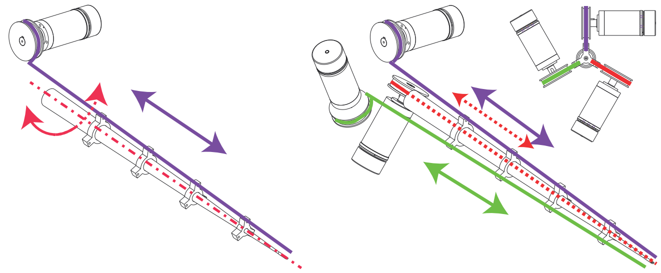
Extension by pneumatic pressure has the advantage that weight can be reduced because it does not require a complicated mechanism. However, it is necessary to increase the diameter in order to obtain the pressure corresponding to the structure's compressive force caused by the bending wire tension.

Extension by inserting a flexible tube increases the mass of the arm compared to the pneumatic pressure alternative, however it does not need to add a mechanism to the structure itself, so it can maintain the advantages of a small diameter structure. It is possible to save space on the extension mechanism part by winding up the tube with a reel. In addition, a large extrusion force can be easily obtained by using an electric motor. If the tube is a perfect rigid rod, a structure the length of the tube is required as storage space. On the other hand, when the strength in the tube's axial direction is small, it is not possible to transmit the extrusion force. It is necessary to select a tube having an appropriate strength in the axial direction so that it can both be wound up and transmit the pushing force.

An extension experiment was conducted by using a flexible tube, which is the most practical in terms of a simple mechanism, a small size, and a high strength output.

### B. *Prototyping of extension mechanism by using a flexible tube*

Fig.4 shows the overview of the extension experiment device. A flexible metal tube (stand-tube, Hagitec), excellent in repeated bending resistance and the same type used in flexible desk lamps, was used. It can wind up with diameter 35 mm so volume is $1.5 \times 10^{-4}$ $m^3$ per 1 m winding up. A glass-fiber reinforced plastic (GFRP) fishing rod of about



(a) Bending by one wire and rotation in cylindical axis

(b) Bending by wires in three directions

Fig. 6: The arrangement of driving part

3200 mm was used for the telescopic structure. The tube emerges from the structure's front end, and it contracts and extends by the frictional force of the rubber roller driven by the electoric motor. The roller and the tube are pressed by a spring in order to obtain a large frictional force.

### C. *Result of extension and contraction experiments*

A weight of 55 g was attached to the tip of the structure, and was extended and contracted horizontally. The extension experiment result is shown in Fig.5. A horizontal extension and contraction of about 2.7 m at 0.064 m/s was recorded. Also, no electrical power was needed to maintain length after extension.

## IV. Tendon-driven bending mechanism

The bending motion by the wire is determined by 1) the selection and layout of the structural material, 2) the arrangement of driving part, and 3) the wiring path.

### A. *The selection and layout of the structural material*

The structural material is desired to have a high tensile strength in order to achieve a long-reaching arm, and also to have a high specific elastic modulus in order to obtain sufficient bending motion. For this reason, GFRP was adopted. In the case that the path and thus the motion of the arm is pre-planned, it is conceivable to set GFRP at the bent portions and use CFRP at the other portions, which has a large specific elastic modulus.

### B. *The arrangement of the driving part*

Two arrangements shown in Fig. 6(a) (b) are conceivable arrangements of the driving part for bending the arm up, down, right, and left. Fig.6(a) shows a method of bending in one direction by wire as well as rotation in the cylindrical axis of the tube. This method realizes the minimum configuration with two driving parts. When the directions of the bending force and gravity are different, the influence remains in the bent shape because it can bend only in one direction.

Fig. 6(b) shows a method driven by wires in three or more directions. A bending moment in an arbitrary direction can be generated by the resultant force of a plurality of wire tensions. In this paper we adopted this mechanism for the experiment.

### C. The wiring path

Shown in Fig.7, there are two undesirable motions when winding the wire fixed to the tip of the telescopic structure at the base. The first problem is that in some cases it can not bend in the desired direction. In Fig.7 (1), the wire is bent in the direction in which the wire is pulled. If the right-hand wire is pulled (2), and then the left-hand wire is pulled, however, the tube will bend even further to the right (3).

This is because the wire on the left side is positioned on the opposite side beyond the structural central axis. This problem can be solved by attaching a guide for the wire to always be located in a specific circumferential direction with respect to the structual central axis.

The second problem is that only the region near the tip is bent. When considering an objective located passed obstacles, it is preferable that the whole structure bends because the work range can be widened. The bending of the tip is caused by being a cantilever and having a tapered shape. The bending moment $M(x)$ at the position $x$ from the tip is given by

$$M(x) = mx + \rho \pi t \int_0^x (d + \frac{D-d}{L} l)(L-l)dl \qquad (2)$$

where, $d$: Tip inner diameter [mm], $D$: Base innner diameter [mm], $L$: Structure length [mm], $m$: Tip load [kg], $\rho$: Structural density [kg/m$^3$].

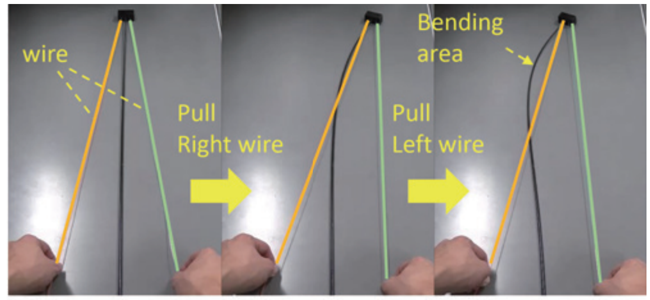
Also, the bending degree of the tapered shape depends on the second moment of area $I$ in the following equation.

$$I = \frac{\pi(D^4 - d^4)}{64} \qquad (3)$$

From the two formulas, the bending moment is due to it's own weight and the second moment of area increases at the base. The bending moment obtained by the product of the wire tension and the mounting radial position is uniformly distributed in the structure when a wire is attached via the tip. For this reason, it tends to be more bent at the tip. The section modulus also increases at the base. When the tension is increased, the tip will break if it bends too far without the entire tube bending with it.

To solve this problem, we propose a multiple pulley tendon-driven mechanism in which the bending moment increases as the base. The mechanism is shown in Fig.8. Multiple pulleys are arranged in the cylindrical axis, and the wire reciprocates. Pulleys also function as a guide because they restrain the path of the wire. A bending moment acting upon the structure is calculated as the product of twice the wire tension and the radial position of the pulley. A moment increases toward the base is obtained because the bending moment generated at each pulley is integrated. The bending moment $M_w(x)$ obtained by this mechanism is expressed by the following equation

$$M_w(x) = \sum_{i=1}^{n+1} 2Tr_i - Tr_1 \quad \text{when} \quad l_n < x < l_{n+1}$$




(1) (2) (3)

Fig. 7: Problems of bending motion

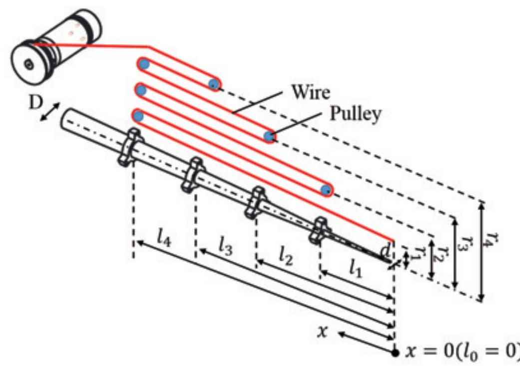



Fig. 8: Overview of a multi-pulley tendon-driven mechanism

where, $T$: wire tension [N], $r_i$: Radial position of pulley at segment $(i+1)$ [mm], $l_n$: Tip position of segment $(n+1)$ [mm].

The proposal of the multi-pulleys mechanism realizes bending entire of the arm. The tension required for bending is small because this mechanism is a force multiplier. Precise tip control is simultaneously realized because the displacement respective to the winding amount is small.

### D. Prototyping of multi-pulley tendon-driven mechanism

An overview of the experimental device is shown in Fig. 9. Telescopic structure is a GFRP fishing rod which was also used for the extension experiment. This rod has 4 segments and is 3200 mm in length, with a minimum diameter of 8 mm at the tip and a maximum diameter of 30 mm at the base. The arrangement of the motors is shown in Fig.6(b), and are arranged equally around the cylindrical axis with respect to the vertical axis. Metal wire (SINYO, SC-75, $D$=0.75 mm) is used. Bearings with resin pulleys or no-lubrication bushings are placed at the points where the wires fold back to reduce frictional resistance.

The structure, the arrangement of pulleys and wires are shown in Fig.10. Between tip and first guide and between first guide and second guide, we have arranged secondary guides that only have the functions of following the wire to the structure. The position of the pulley was determined to realize the distribution of force where the safety factor (= maximum bending moment / bending moment due to wire tension) becomes almost constant at each pulley position in consideration of the increase in the section modulus. The

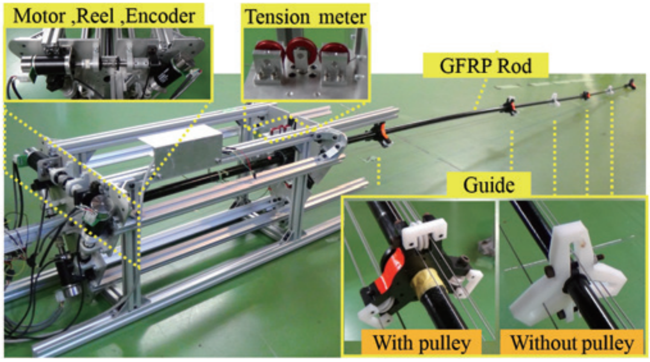



Fig. 9: Overview of bending experiment device

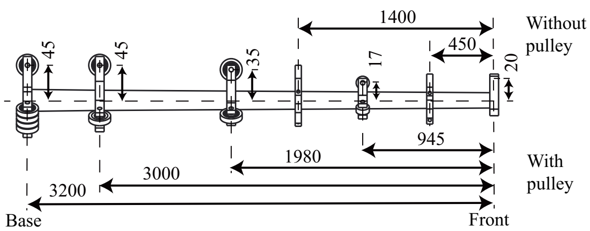



Fig. 10: Dimension of pulley position

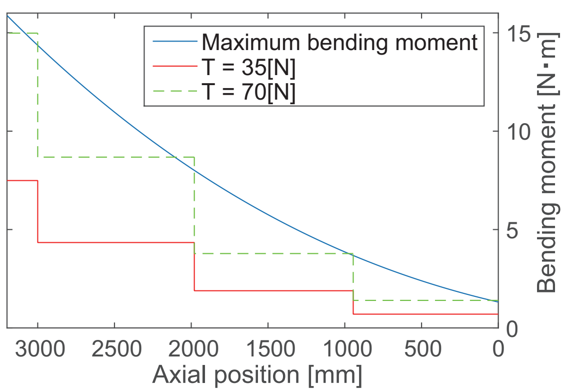



Fig. 11: Distribution of bending moment by wire tension. In order to match the graph with the direction of the tip of the experiment result, the origin is the lower right of the graph.

maximum bending moment that can be added to the structure is expressed by the following equation

$$M_{max} = \frac{\pi(D^4 - d^4)}{32D}\sigma_{fM} \tag{3}$$

where flexural strength: $\sigma_{fM} = 51.5$ [kg/mm$^2$][9].

Fig.11 shows the maximum bending moment and bending moment by wire. The safety factor at each pulley position is shown in Table I.

A load cell (MCDW-50L, Toyo Sokki) was used as a tension sensor. The force is applied to the load cell via the pulley and the shaft by the tension. The measurement error of tension was maximum 3 N. In bending experiment tension changes between 0 and 70 N, therefore the measurement error is low enough.

In Fig.12, the configuration of the control system is shown.

TABLE I: Safety factor of structure at each pulley position

| | $l_0 = 0$ | $l_1 = 945$ | $l_2 = 1980$ | $l_3 = 3000$ |
|---|---|---|---|---|
| Safety ratio(T=35 N) | 1.88 | 1.88 | 1.87 | 1.88 |
| Safety ratio(T=70 N) | 0.94 | 0.97 | 0.93 | 0.96 |

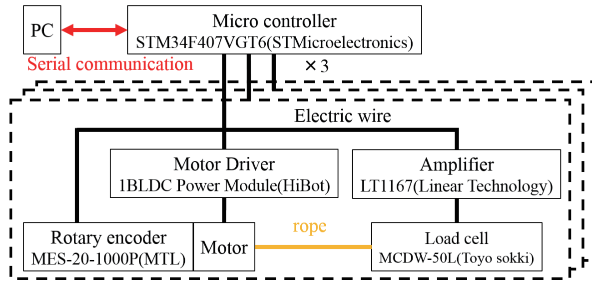



Fig. 12: Control system

The target tension of each wire is given by the PC, and the velocity command of the motor is calculated and controlled by the microcontroller.

### E. *Bending experiment*

A bending experiment was carried out in order to confirm the bending motion of the whole structure and in multiple directions. Pre-defined specific wire tension values were fed to the controller as shown in Table II so as to draw a rough hexagon. Wire directions corresponding to the direction are shown in Fig.13. Tension was applied starting at (1), and after having operated up to (9), it returned to (1) in reverse order.

In this mechanism, it is difficult to calculate the accurate bending displacement by tension because of the large deformation and the decrease in the tension of the wire. For this reason, tension distributions such as the tip drawing a hexagonal shape were determined by preliminary experiments.

Fig.13 shows the bending motion when the wire is just placed along the structure. As mentioned above, the bending of the arm is concentrated near the tip, and the displacement of the tip was 250 mm. Fig.14 shows the motion when a multiple pulley mechanism and setting tension (2). Here, the entire structure is bending and the displacement of the tip is increased to 1000 mm.

Fig.15 is the view seen from the front. Fig.16 is the tracking of this trajectory. The circles show the point where the tension distribution of the attached number converges. Starting from the blue circle (1), following the blue solid line and red dashed line, ending at red circle (1). Tip displacement was obtained within about 1400 mm in both vertical and horizontal directions. In addition, we can draw a trajectory enclosing the center in both forward and reverse directions, so that it is possible to bend in all directions. The displacement was different between the forward direction and the reverse direction because the transmission tension changes due to the friction between the wire and the guide when the winding direction is different. In this experiment, we confirmed that the arm bent in multi-direction and whole structure.

TABLE II: The order of applied tension

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| A | 5 | 5 | 40 | 40 | 30 | 5 | 5 | 5 | 5 |
| B | 5 | 70 | 60 | 20 | 5 | 20 | 60 | 70 | 5 |
| C | 5 | 5 | 5 | 5 | 30 | 40 | 40 | 5 | 5 |

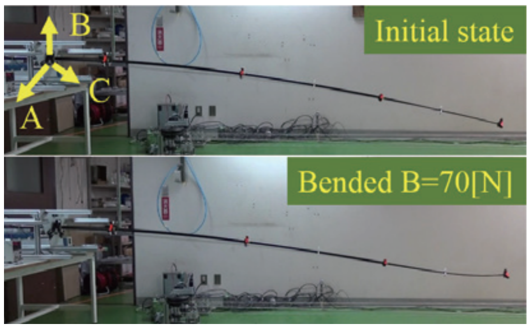



Fig. 13: Wiring attached to the tip with a straight line

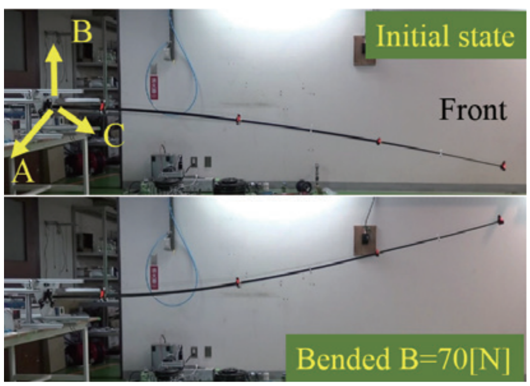



Fig. 14: Wiring by multiple pulleys

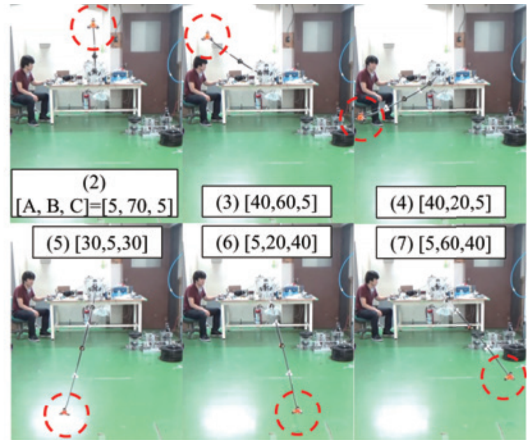



Fig. 15: Experiment result seen from the front side

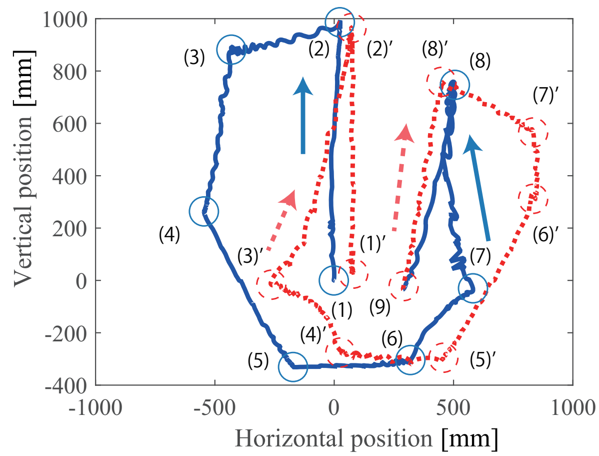



Fig. 16: Results of tip trajectory

## V. Conclusions

In this paper, we proposed the Tendon-driven Elastic Telescopic Arm that determines the tip position by bending the structure. In order to realize this proposal, the extension mechanism by flexible tube and the bending mechanism by multiple pulleys was confirmed by experiment.

In the future, we plan to examine the mechanism that reduces the frictional force of the wire and the control method that suppresses the vibration of the structure. In addition, we plan to integrate the extension machanism and the bending mechanism to confirm that the proposal of the arm is practical.

## Acknowledgment

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