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Tendon-driven Elastic Telescopic Arm
-Integration of Linear Motion and Bending Motion-

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

***Abstract*— The telescopic structure has a high extension-to-contraction ratio and is suitable for using a long manipulator that reduces the size of the structure because it is lightweight and small in diameter. There is a problem that conventional telescopic structures are only used in an open environment because it can not avoid obstacles on the axis of extension. In this paper, we propose a linear mechanism that can extend and contract one node at a time by a linear movement mechanism using a slide screw, and clarify its effectiveness by experiments. In addition, we control the tip position of the arm by the rope winding length and discuss the accuracy quantitatively. In addition, by integrating the linear mechanism and the bending mechanism, we achieved the linear motion while avoiding obstacles on the axis of extension.**

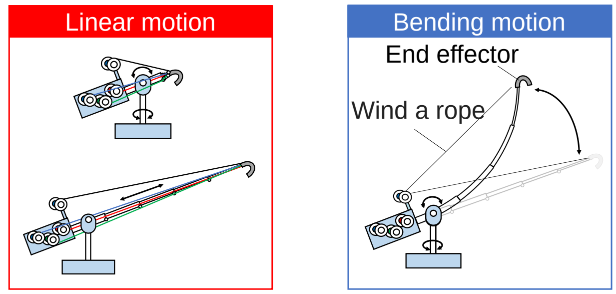

Fig. 1. Concept of tendon-driven elastic telescopic arm

I. INTRODUCTION

When using a robot for investigation or inspection in a complex environment such as a disaster site where debris is scattered or inside of a nuclear reactor with many facilities, it is desirable to use a long manipulator that can pass through a narrow route avoiding obstacles. When manufacturing a long manipulator, there is a problem that the volume and weight of the manipulator become excessive because a conventional manipulator requires a high power drive system to support a heavy arm. Therefore, in order to overcome the mass increase of the manipulator, the weight reduction of the mechanism and the weight compensation mechanism are installed.

For reducing the weight of a mechanism, there is a method of using the inflatable joint [1] which is integrated with the structure without additional mechanism or a method of transmitting power using a rope and collecting an actuator at the base [2]. As an example of the weight compensation mechanism, there is a method of supporting a gravity torque by using springs or ropes [3][4], or there is a method of supporting it by the structure itself. As an example of supporting the torque with a structure, there is the arm that supports torque with a slide screw that does not back drive [5] or the arm horizontally extending [6][7] or the arm linearly extending. By limiting the rotation axis in the vertical direction, the horizontally extending arm can receive the torque generated by the weight of the entire structure because the torque does not transmit to the rotation axis. However, the moving range in the vertical direction is limited because it is necessary to keep the arm horizontal. The linearly extending arm has the same structure as that found in fire truck ladders. Since there is no rotation axis in linear motion, the entire structure can support the gravity torque. However, it is limited to use in an open environment, as it can not avoid obstacles on the axis of extension.

A 10 m long manipulator [8] has been developed as a manipulator that enables a wide working range. It has a total of 10 degrees of freedom in the pitch and yaw axes, and a lightweight arm is achieved by installing actuators at the base and using both weight compensation mechanism and coupled tendon-driven mechanism. However, this manipulator uses many actuators for driving because of the large degree of freedom of the arm, so the base becomes large.

Miniaturization of the structure is also an important factor in expanding the applying range of the manipulator. Miniaturization of the structure increases the number of options for the installation site, which enables the manipulator to reach the target from various positions and directions. When considering a method of storing the arm so as to miniaturize the structure, there is a method of storing the arm with a jointed structure. As an arm with high storability, there is a telescopic structure in which pipes with different diameters are combined. In addition, Spiral Zipper [9] that forms a cylindrical shape by shaping a long, thin plastic band upward into a spiral, or a carbon fiber reinforced plastic (CFRP) convex tape [10] have been proposed. Both methods achieve a high extension-to-contraction ratio by winding the band, and the Spiral Zipper achieves the ratio of over 14: 1 and control the tip position. However, in both methods, Young's modulus of the arm structural material tends to be small and buckling, so there is a problem that the increase of the weight due to the elongation can not be tolerated.

From such a background, we have proposed the Tendon-driven Elastic Telescopic Arm [11] as shown in Fig. 1 as a small diameter arm that is capable of linear motion and bending motion in order to achieve a lightweight, compact,

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actuator saving, and a high extension-to-contraction ratio. In our previous work, we separately confirmed and demonstrated the mechanical feasibility of both motions.

In this paper, we integrate the linear motion and bending motion. We propose the linear mechanism that can extend and contract one node at a time by a linear movement mechanism using a slide screw, and clarify its effectiveness by experiments. In addition, we control the tip position of the arm by the rope winding length or rope tension and compare its controllability. We also control the tip position of the arm using the results and discuss the accuracy quantitatively. In addition, by integrating the linear mechanism and the bending mechanism, we achieve the linear motion while avoiding obstacles on the axis of extension.

The composition of this paper is as follows. In section II, we describe the details of the Tendon-driven Elastic Telescopic Arm. In section III, we propose a linear mechanism and demonstrate its effectiveness by experiments. In section IV, we describe the controllability and accuracy of the tip position of the arm using a bending mechanism. In section V, we describe an experiment of linear motion avoiding obstacles on the axis of extension by integrating the linear mechanism and the bending mechanism. In section VI, we present the conclusions.

II. TENDON-DRIVEN ELASTIC TELESCOPIC ARM

The proposed arm is composed of an elastic telescopic structure, a linear mechanism and a bending mechanism [11]. The elastic telescopic structure is a structure composed of an elastic body, which can be stored and bend like a fishing rod, and has the following advantages.

- Space-saving is possible due to high extension-to-conduction ratio and small diameter structure
- The lightweight and long-reaching arm can be achieved due to the cylindrical tapered shape
- Bending strength is high and can receive its weight in the structure
- Contacting with an obstacle, the structure naturally deflects

This high extension-to-contraction ratio is necessary to make a compact arm. In addition, since the elastic telescopic structure is more flexible than the conventional arm, there is an advantage that the tip position of the arm can be controlled by applying a bending moment to the structure and causing the elastic deformation by tendon drive.

This tendon-driven mechanism has the following advantages.

- The weight of the arm can be reduced by reducing the number of drive parts
- Various bending shapes can be achieved
- Accurate tip position control is possible because it pulls the tip position directly

Various bending shapes can be achieved because the distribution of bending moment can be changed due to the number of ropes, the rope tension, and the rope path.

Furthermore, since the arm is long, the range of movement at the tip position of the arm can be large by rotating the base

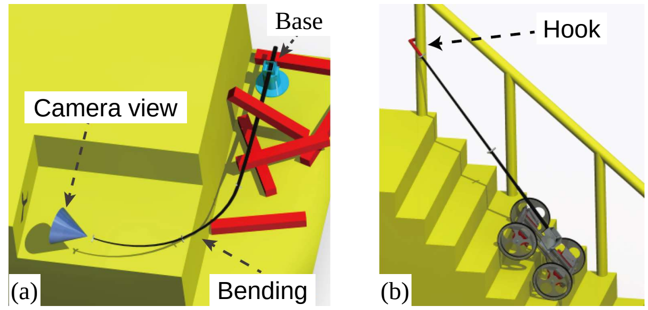

Fig. 2. Concept of using tendon-driven elastic telescopic arm: (a) Observation of remote areas, and (b) Improvement of stepping ability by mounting on a mobile robot

itself. On the other hand, since the displacement of the tip position due to bending does not depend on the arm length but the rope winding length, it is possible to control the tip position accurately with a small reel diameter.

The proposed arm can be more compact than conventional ones, so the restriction on the installation location is reduced. For the reason it is suitable for using in a disaster site as shown in Fig. 2a and for mounting on a mobile robot as shown in Fig. 2b.

On the other hand, since it is composed of a thin elastic body, a large structural vibration is easily expected. However, it may be possible to suppress vibration if it is combined with bending control by tendon drive.

III. LINEAR MOTION

In this section, we propose a mechanism to achieve the linear motion of the arm. In addition, we show the result of the linear motion experiment by using a manufactured mechanism.

A. Design

As for extending motion of the elastic telescopic structure, we proposed a method of pushing out from inside it using a stand tube [11]. However, in this method, there are some problems. When the telescopic structure becomes long, the friction between the flexible tube and the telescopic structure becomes large and it becomes impossible to push out, or when the rope is wound up for bending, the telescopic structure rotates around the longitudinal axis, and the bending direction becomes undefined.

The requirements for the linear mechanism is as follows.

- Multistage linear motion of the elastic telescopic structure
- Rope tension can be used for contraction
- Extending from the tip node, and contracting from the root node
- Extended node is constrained in the direction of contraction and rotation with respect to the base

In addition, to achieve these requirements, we will develop (1) a mechanism that selectively moves nodes linearly, and (2) a mechanism that constrains the linear motion and

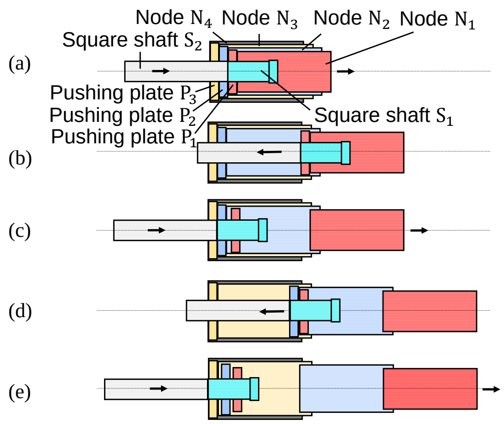

Fig. 3. Concept image of reciprocating mechanism

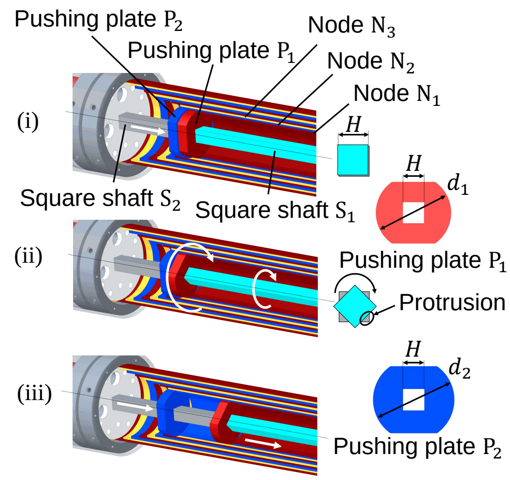

Fig. 4. Selection method. The shape of the pushing plate is chamfered for convenience of explanation.

rotation of other nodes. The requirements for them are as follows.

- Reduce the number of actuators to reduce size and weight
- Mechanism does not interfere with the pulleys and guides used for bending

We develop mechanisms that meet the above requirements.

1) Reciprocating mechanism: Fig. 3 shows the concept of linear motion by using a reciprocating mechanism that selectively moves nodes linearly. (a) to (e) show the flow in which the node N_1, N_2 extend. The mechanism achieves the extending motion of the telescopic structure by pushing out the nodes one by one with the pushing plate. The square shaft is divided into the square shaft S_1 and the square shaft S_2, which can both move linearly. The square shaft S_1 can rotate relative to the square shaft S_2, and this action allows to select the pushing plate as well as the node that extend. (a) Control the position of the square shaft so that the left edge of the square shaft S_1 is matched the left edge of the pushing plate P_1. Then rotate the square shaft S_1 with respect to the square shaft S_2 in order to select the pushing plate P_1 as well as the node N_1. To press the square shaft to the right extends the node N_1. (b) After extending node N_1 to the maximum, the square shaft moves to the left in order to extend the node N_2 so that the left edge of the square shaft S_1 matches the left edge of the pushing plate P_2. At this time, the node N_1 is kept extended. The mechanism can extend the node N_2 through the process from (c) to (e) by performing the same operation as above. By repeating this operation in the same way, the mechanism can extend multiple stages by using a linear motion mechanism which has a stroke of one node.

Fig. 4 shows the details of the mechanism to select the pushing plate as well as the node and to move them linearly in the telescopic structure. The node N_i has d_i in diameter, and the pushing plate P_i has an arc of diameter d_i. There is a square at the center of the pushing plate that is the same size as the square shaft, and it can move along the square shaft axis. (i) to (iii) represent the flow to select and extend the pushing plate P_1 as well as the node N_1. (i) Control the position of the square shaft so that the left edge of the square shaft S_1 matches the left edge of the pushing plate P_1. (ii) When the square shaft S_1 is rotated 45 deg with respect to the square shaft S_2, the pushing plate P_1 is also rotated 45 deg. At this time, a protrusion is generated at the boundary between the square shaft S_1 and the square shaft S_2. By hitting this protrusion on the left edge of the pushing plate P_1, press the pushing plate P_1 to the right. (iii) Pressing the pushing plate P_1 extends the node N_1.

The contraction motion is achieved by winding a rope for bending.

2) Constraint mechanism: When pushing out the selected nodes, there is a possibility that other nodes may move due to the friction between the nodes. Therefore, we have to constrain other nodes not to move linearly. In addition, since a longitudinal force is generated during the bending motion, the extended node must be prevented from contraction. Furthermore, if rotation occurs around the longitudinal axis during bending motion, the bending direction will not be determined, so the rotation must be constrained.

Fig. 5 shows the concept of constraint mechanism. There are two pins to constrain rotation and linear motion. The pin 1 is attached to the node N_2, and always receives the force that enters the axis center. The pin 2 is fixed inside the node N_3. The node N_2 has an L-shaped groove as shown in Fig. 5. At the left end of the node N_1, there is a hole where the pin 1 fits. By using this mechanism, extension for the selected node only is performed by the linear motion and the rotation motion according to the following procedure.

- STEP1; Extend the node N_1. At this time, both rotation and linear motion of the node N_2, N_3 are constrained by the pin 1, 2, so the node N_2, N_3 are fixed.
- STEP2; The pin 1 fits in the hole of node N_1. As a result, the rotation and linear motion of the node N_1, N_2 are constrained, so the node N_1, N_2 are fixed. Furthermore, when the pin 1 fits in the hole, the node N_2 can rotate freely with respect to the node N_3.
- STEP3; Rotate the node N_2 to the position shown in Fig. 5. When the pin 2 leaves the L-shaped groove, the

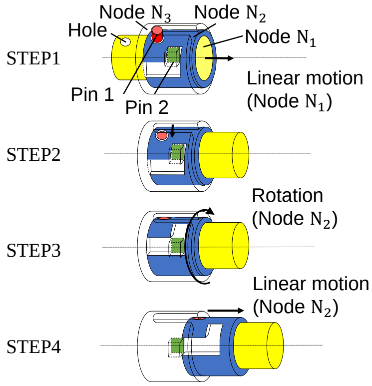

Fig. 5. Concept of constraint mechanism

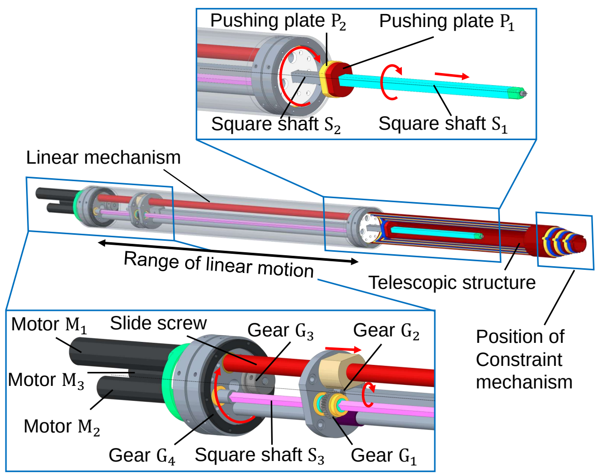

Fig. 6. Overview of linear mechanism

node N_2 can perform linear motion freely with respect to the node N_3.

- STEP4; The node N_2 can perform rotation and linear motion freely with respect to the node N_3.

We can extend it sequentially by repeating this process.

Contraction of the nodes is possible by performing in the order of STEP4 to STEP1. Note that there is a mechanism that releases pin 1 by releasing a certain amount of force in the extension direction. Please refer to the appendix for details of the mechanism.

3) Mechanical implementation: Fig. 6 shows an overview of the designed linear mechanism. The linear mechanism is driven by three motors. The motor M_1 performs a linear motion of the square shaft S_1, S_2. The motor M_2 performs a rotation of the square shaft S_1 with respect to square shaft S_2. The motor M_3 performs a rotation of the square shaft S_1, S_2 with respect to the base. This rotation is used to release the constraint of linear motion by the constraint mechanism. The motor M_1 drives the slide screw and the square shaft S_1, S_2 move linearly. The motor M_2 drives the square shaft S_3, and the rotation is transmitted to the gear G_2 through the gear G_1. The gear G_2 is attached to the shaft passing through the interior of the square shaft S_1, S_2, and the shaft is fixed to the square shaft S_1, so the rotation of the gear G_2 transmit

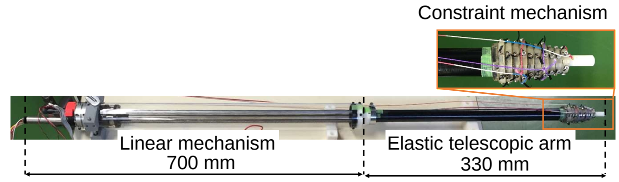

Fig. 7. Linear motion experiment device

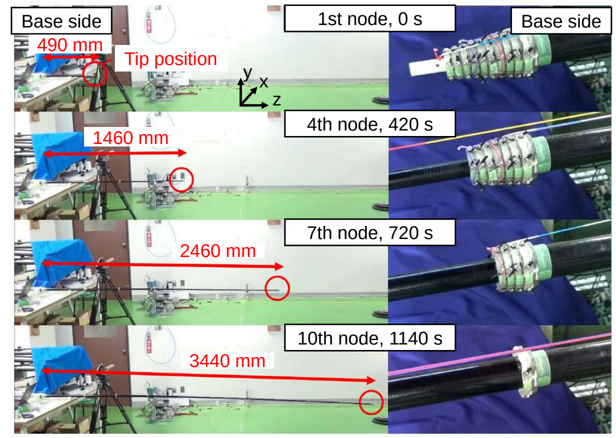

Fig. 8. Experiment result of linear mechanism

to the square shaft S_1. Then, the rotation of the square shaft S_1 with respect to the square shaft S_2 is demonstrated. The motor M_3 drives the gear G_3, and the entire internal structure rotates around the internal gear G_4. Then, rotate the square shaft S_1, S_2 with respect to the base.

B. Experiments

We performed an operation experiment of the linear mechanism. Fig. 7 shows the overview of experiment device. The elastic telescopic structure has a total length of 3440 mm for 10 nodes. In order to control, the command of the rotation angle of the motor was sent from the PC to the microcomputer by serial communication, and the microcomputer calculated the speed command value of the motor and sent the signal to the motor driver. In addition, the ropes were attached the tip of the 1st, 4th and 7th nodes and pulled by hand to generate the tensions of the ropes used for contraction.

Fig. 8 shows the experiment result. This figure shows the state of linear motion. We successfully achieved the extension of 10 nodes from the total length of 1190 mm to 4140 mm. In addition, we confirmed the contraction of 8 nodes from the total length of 3480 mm to 1190 mm. The maximum extension-to-contraction ratio was 3.5:1 during extension.

IV. BENDING MOTION

We previously performed a bending motion experiment with a predetermined rope tension and showed it is possible to bend the elastic telescopic arm [11]. However, comparison of controllability by rope tension and by the rope winding length was not examined. Also, there was no quantitative discussion about the tip position accuracy of the arm. Therefore,

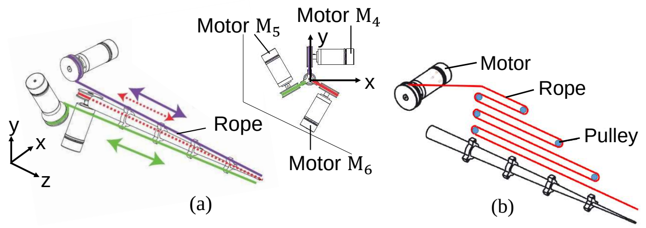

Fig. 9. Design of bending mechanism : (a) Arrangement of motors, and (b) Rope path

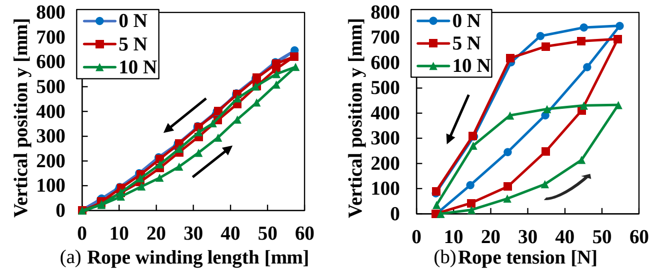

Fig. 10. Experiment result of bending: (a) Rope length control, and (b) Rope tension control

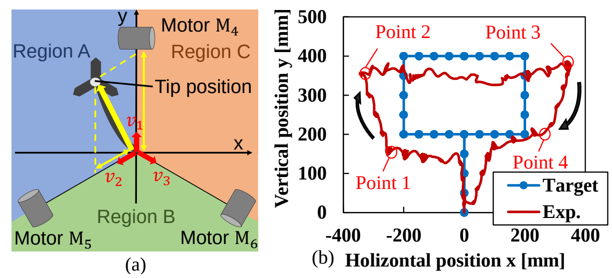

Fig. 11. Experiment result of tip control: (a) Coordinate of tip position, and (b) Trajectory of tip position

TABLE I. Rope winding length of each motor. Negative value represents the rope sending out length.

	motor M_4	motor M_5	motor M_6
Point 1	27 mm	20 mm	-16 mm
Point 2	44 mm	20 mm	-25 mm
Point 3	44 mm	-23 mm	20 mm
Point 4	27 mm	-18 mm	20 mm

the tip position of the arm is controlled by the rope winding length or rope tension, and the controllability is compared in this section. We also control the tip position of the arm using the obtained results and discuss the accuracy quantitatively.

A. Design

We developed the bending mechanism [11]. Fig. 9a shows the arrangement of motors in tendon-driven part. The coordinate system is defined as a right-handed system with the longitudinal direction of the arm as the z direction and the vertically upward direction as the y direction. In this driving method, the arm can be bent on the x-y plane by the combined force of three rope tensions. In addition, among the methods that can move on the x-y plane and always generate a force in the y direction, this method can minimize the number of driving parts.

we describe the rope path. There are studies of bending motion by using ropes [12][13]. In these studies, ropes are placed along the arm using rope guides, and the bending moment is generated by winding up the rope attached the tip position of arm. However, when using a telescopic structure in which the rigidity of the arm is high and the diameter increases by the root compared with these studies, there is a problem that only the tip is bent by winding the rope attached to the tip. So we created a rope path as shown in Fig. 9b. This is a method of reciprocating the rope by pulleys. The rope tension can be applied at multiple positions of the structure since the rope tension is applied to all passing pulleys. For this reason, it is possible to obtain a distribution of bending moment that increases continuously toward the root by changing the arrangement of the pulleys in the axial and radial directions of the structure. In addition, it is possible to wind all the ropes at the time of contraction.

B. Experiments

First, in order to compare the controllability of the tip position with the rope winding length and the rope tension, we performed the bending experiment in the y direction of the arm. We used the bending mechanism which previously developed [11]. In the experiment, we displaced the tip position in the y direction by driving the motor M_4 while applying a constant force in the -y direction by controlling the rope tension using the motor M_5, M_6. Fig. 10a shows the y direction displacement of the tip position relative to the rope winding length. Fig.10b shows the y direction displacement of the tip position relative to the rope tension. When the tension was not applied in the -y direction, the hysteresis was small at the tip position with respect to the rope winding length, but the hysteresis was large at the tip position with respect to the rope tension. The reason of this is considered that friction occurs in the sliding part between the rope and the guide, so that the tension is less transmitted from the base to the tip position. In addition, it was found that when the tension was applied in the -y direction, the tip position with respect to the rope tension was not linear. From this, it is considered that the rope length control is more suitable for the tip position control.

Second, we controlled the tip position by the rope winding length, because the relationship has small hysteresis and the tip position with respect to the rope winding length was approximately linear. Fig. 11a shows the coordinate of the tip position of the arm. The coordinate of the arm was decomposed into vectors v_1, v_2 and v_3 in the direction to which each motor contributes. Then, when the tip position was in the region A, the motor M_4 and the motor M_5 were controlled by the rope winding length, and the motor M_6 applied tension of 5 N so that the rope did not sag. The similar control was performed when the tip position was in the region B or the region C. In addition, the rope winding length was determined using the relationship of Fig. 10a by calculating the amount of displacement contributing to

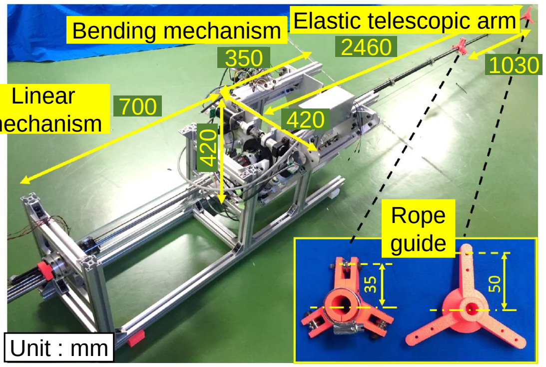

Fig. 12. Integrated experiment device

each motor from the coordinates of the tip position. Fig. 11b shows the result of experiment. The average absolute error in the x direction was 78 mm, and in the y direction was 37 mm. The average absolute error rate in the x direction normalized by the magnitude of the commanded trajectory was 20%, in the y direction was 9.2%. Also, since the arm length is 3400 mm, the average absolute error rate in the x direction normalized by the arm length was 2.3%, in the y direction was 1.1%.

In particular, the error in the x direction was large at point 2, 3. Table I shows the rope winding length of each motor. It can be seen that motor M_6 was sending out the rope at point 1, 2. At this time, point 1, 2 existed in the region A, and the motor M_6 controls the rope with 5 N tension. Therefore, when the tip position moved in a direction away from the motor M_6 and the rope of the motor M_6 was tensioned, the rope was sent out to keep the tension constant at 5 N. It is considered that the rope sending out length contributes to the tip position. It is considered that one factor of the error is the control method without using the rope sending out length.

In this experiment, the tip position was controlled with a resolution of 50 mm by bending. In order to achieve this control only by the rotation of the base, a resolution of 0.84 deg is required. In addition, if the entire arm is moved by the rotation of the base, it is difficult to stabilize the tip position because the arm vibrates. Therefore, the bending motion is more suitable for controlling the tip position.

V. MECHANICAL INTEGRATION

In this section, we integrated the linear mechanism and bending mechanism and describe the experiment on the combined motion of linear motion and bending motion.

A. Design

Fig. 12 shows an overview of the experiment device that integrates the linear mechanism and the bending mechanism. The bending mechanism and the telescopic structure are connected to the linear mechanism. The telescopic structure has 7 nodes and a total length of 2080 mm, and one rope guide with a pulley is arranged.

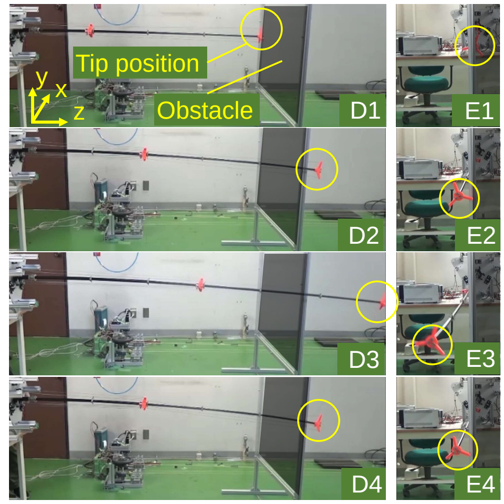

Fig. 13. Experiment result. Symbol D represents a side view and symbol E represents a front view. The same numbers represent the same time

B. Experiments

We performed an experiment to move linearly while bending as the combined motion of linear motion and bending motion. This is the operation necessary to achieve linear motion while avoiding obstacles on the axis of extension. Fig. 13 shows the experiment result.

We move the fifth and sixth nodes linearly while bending avoiding an obstacle in the z direction. We set the tension at the motor M_4, M_6 to 5 N, and the tension at the motor M_5 to higher than 5 N. In the state of D1, the arm is extended by 4 nodes, and the motor M_5 is not under tension. In this state, there is an obstacle in front of the tip position like E1. After that, in the state of D2, the fifth node was extended with a tension of 15 N applied to the motor M_5. As shown in E2, the arm was able to extend avoiding the obstacle. At this time, the distance between the obstacle and the center of the tip position is 50 mm. After that, in the state of D3, the sixth node was extended with a tension of 25 N applied to the motor M_5. Then, in the state of D4, the sixth node was contracted while applying a tension of 25 N to the motor M_5. From this result, we achieved linear motion while avoiding an obstacle on the axis of extension.

VI. CONCLUSIONS

In this paper, we proposed the linear mechanism that moves one node at a time by a linear motion. The linear mechanism extended 10 nodes from the total length of 1190 mm to 4140 mm, and successfully contracted 8 nodes from 3480 mm to 1190 mm. The maximum extension-to-contraction ratio was 3.5:1 during extension. The results showed the effectiveness of the linear mechanism. In addition, we controlled the tip position of the arm by the rope winding length or the rope tension and compared the controllability. We found that the tip position with respect to the rope tension has a large hysteresis, and when tension is applied in the -y direction, the tip position with respect to the rope tension is not linear, so we considered the rope length control is more suitable for the tip position control. We controlled the tip position by the rope winding length. As a result, the average absolute error in the x direction was 78 mm, and in the y direction was 37 mm. The average absolute error rate in the x direction normalized by the magnitude of the commanded trajectory was 20%, in the y direction was 9.2%. Also, the average absolute error rate in the x direction normalized by the arm length was 2.3%, in the y direction was 1.1%. In addition, by integrating the linear mechanism and the bending mechanism, we achieved the extension of two nodes and the contraction of one node while bending, and achieved the linear motion while avoiding the obstacle on the axis of extension.

In the future, we plan to research improvement of tip position accuracy to take into consideration the rope sending out length or consider visual feedback control of the tip position using a laser range finder.

ACKNOWLEDGMENT

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APPENDIX

Fig. A.1 shows an overview of the designed constraint mechanism. Since this mechanism is attached to the tip of each node of the telescopic structure, the total length of the telescopic structure becomes longer by the thickness of this mechanism and the number of nodes. So, we designed to be nested with the next node and achieved a thin mechanism. The pin 1 always receives a force that rotates in the direction shown in Fig. A.1, and it can passively rotate and fit in the hole of the node. When pin 1 fits into the hole of the node, it does not rotate in the direction shown in Fig. A.1 and constrains the contraction of the node. On the other hand, when the pin 1 is in the hole of the node, applying a force more than a certain amount in the extension direction causes the pin 1 to come out of the hole and the constraint is released. In addition, the pin 2 is caught in the L-shaped groove, thereby constraining the linear motion between the nodes.

Fig. A.2 shows an overview of the manufactured constraint mechanism. Since the pin housing has complicated shape and it is difficult to manufacture by cutting, we made a prototype using an optical modeling 3D printer. A belt-like rubber is used for the spring element of the pin 1 to generate rotational movement. The pin 1 has a complicated shape and it is difficult to manufacture by cutting too. In addition, since the material used for an optical modeling 3D printer is fragile, the pin 1 was made by metal 3D printing with maraging steel.

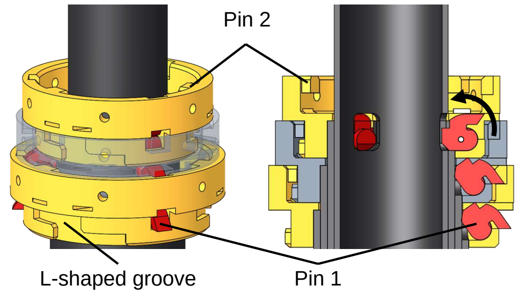

Fig. A.1. Overview of constraint mechanism

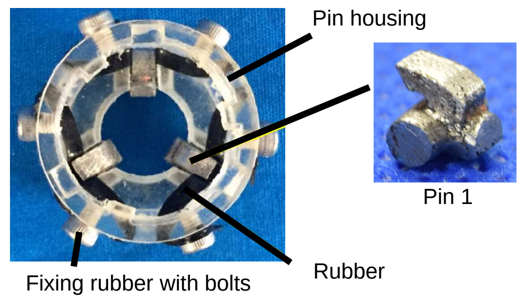

Fig. A.2. Manufactured constraint mechanism

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