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Paper:

Tip Growing Actuator with the Hose-Like Structure Aiming for Inspection on Narrow Terrain

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This paper proposes a flexible hose-like fluid actuator to inspect narrow curved or bumpy terrain. The tip alone moves forward and the rest remains stationary, enabling the actuator to move smoothly without interfering with the outer environment – a concept based on the plant growth process. The actuator consists of multiple flexible flat tubes bent in the skin, whose bending point is involved in preventing fluid from passing through. The actuator can also steer the direction in which the tip lengthens, while the shape of the rest remains unchanged. Our Grow-hose-I prototype is 62 mm in diameter and grows at a maximum speed of 500 mm/s while producing a 45 N drive. The way of carrying a head unit equipped with a camera is discussed and feasibility of the actuator's inspection on narrow terrain is demonstrated.

Keywords: pneumatic actuator, plant mimetic actuator, search and rescue robot

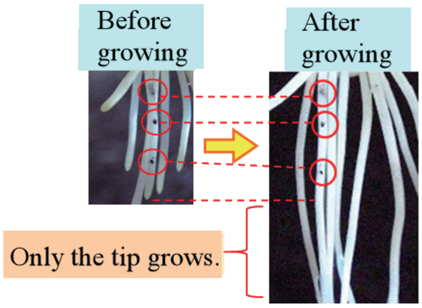


Fig. 1. Plant root growth process.

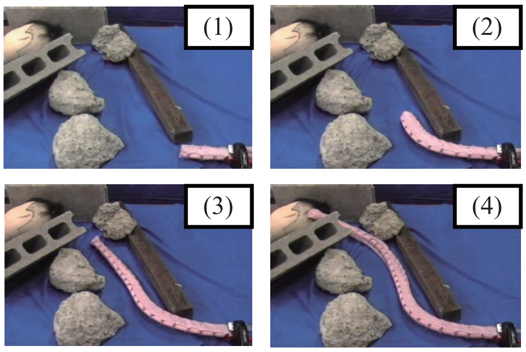


Fig. 2. Tip growth in the initial prototype steering along a curved path.

1. Introduction

A rod with a camera and a fiberscope have been used in most cases to look for victims buried, for example, in collapsed houses caused by big earthquakes. These are useful for straight paths or nearby sites but less so for complex paths or deeply buried locations. Given that victims may require water, oxygen, or medication, a hose-like link may be needed to connect victims and rescuers.

In the sections that follow, we discuss flexible, mobile hose-like structures able to pass through narrow curved or bumpy terrain while carrying sensing devices and fluids.

The mobile methods studied thus far are roughly divided into (i) moving the entire device forward at the same speed, and (ii) moving different parts of the device at different rates. Examples of (i) include a robot with actively driven wheels or crawlers [1, 2] or a vibrating hair-like surface [3]. Some of them were also used in endoscopes to reduce friction in the colon [4–6]. Although these are helpful in a narrow pipe-like environment, the direction of movement tends to be unstable due to the uneven terrain.

Examples of (ii) involve fixed and moving modes, based on earthworm or inchworm movement [7–12]. The problem is how to enable parts fixed on an uneven path to remain stable in fixed mode and how to reduce friction in moving mode.

Our approach is based on the growth process of a plant root (**Fig. 1**). The fluid actuator we propose consists of multiple flat tubes. Controlling the direction of lengthening and carrying the head unit with sensing devices are clarified, Grow-hose-I is introduced, and results of experiments confirming its feasibility are discussed (**Fig. 2**).

2. Basic Design Concept

Roots of the plant grow as their growing points on the tip extend, while the base and the middle part remain stationary. The tip growing movement like this enables the root to extend in the deep area in the earth, as it reduces

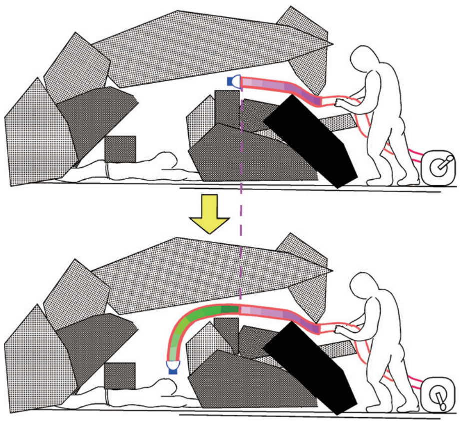


Fig. 3. Search using actuator extension with a camera at a disaster site.

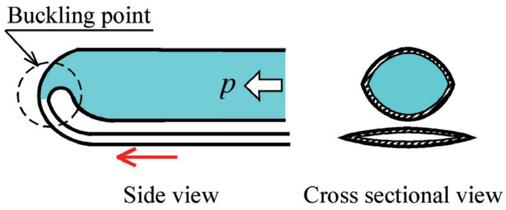


Fig. 4. Driving principle using the buckling phenomenon on a flat tube.

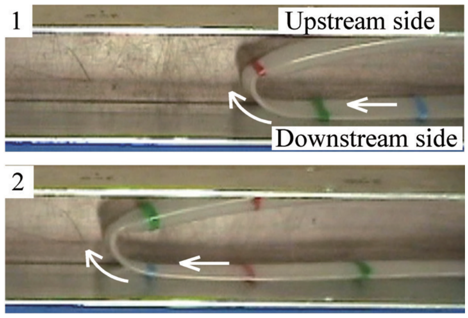


Fig. 5. Downward side of the flat tube drawn out.

the friction against the soil. This mobile method would be helpful for a long actuator to advance on narrow terrain with the friction against the outer environment reduced.

We aim to design a hose-like actuator whose speed of lengthening is fast enough to be practical for the inspection. One of the effective ways to realize is to draw out the skin of the actuator from the inside, as discussed in Section 3. Steering the direction of tip growth is required to enable it to pass along a narrow curved path while the outer shape of the rest remains unchanged.

We use pneumatic power to make the tip grow, because unlikely to the electricity it has no fear of explosion even in the atmosphere of the flammable gas and still it is applicable in various types of environment at disastrous site.

Cases similar to our concept previously reported include a flexible cylindrical hose whose tip was folded inward and extended by pneumatically pressurizing the inside. This has been used for temporary gas pipeline connection in crack and for extendable probes carrying cameras, as proposed by Hirose [13]. These approaches had no function of actively steering at the diverting point. Another example is a flexible stick-like crawler robot proposed by McKenna [14] whose skin was rotated axially by electric motors. Although this is suitable for wireless operation, it is not suitable for conveying long hoses in order to link victims and rescuers directly.

In contrast to the above previous driving methods, we present a driving structure composed of the plural tubes, which allow the tip to steer the direction actively by being extended independently. Since these tubes do not need to be infinitely rotated, it can be also applicable for the path with the long distance with it reducing the friction against the outer environment.

3. Driving Principles

3.1. Introduction of a Flat Tube

As the basic element to realize the tip growing actuator driven by pneumatics, a flat tube is introduced. The feature of the flat tube is that its cross section forms the flat shape in non-pressurized condition, while it approaches the circle shape in pressurized condition with the circumference of the cross section kept approximately constant. It is easily fabricated by pressing thermoplastic resin piping at 120 degrees Celsius.

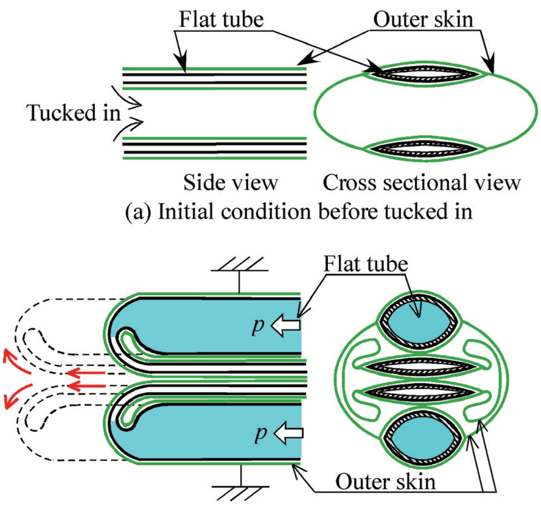
The flat tube is first bent to 180 degrees so that when one side is pneumatically pressurized, buckling is induced at the tube bend, blocking the passage of fluid that has flowed up to that point. Under continued pressure, the buckling point slides from upstream to downstream, while the flat tube in the downstream side is drawn out (**Figs. 4**, **5**). This phenomenon can be also seen when the flat tube is pressurized by other types of fluid power, such as water hydraulics.

Note that using a pipe-like tube instead of a flat one is not appropriate for moving the buckling point. Although the pipe-like tube blocks the passage of fluid at the buckling point, crushing the tube below the buckling point prevents smooth motion, so "tube" as used in this paper refers specifically to the flat tube from this point on.

3.2. Structure for Tip Growth

Based on the bent tube discussed above, two bent tubes are placed parallel to the central axis to fit the two buckling points together. When outside tubes are pressurized, non-pressurized inside tubes are drawn out at the same speed while both buckling points move forward (**Fig. 5**). This structure's advantage is enabling the actuator to move forward without interfering with the ground.

Preventing two tubes from separating requires an additional element – a skin of slippery cloth, for example, that forms a cylinder. After tubes are surrounded by slippery cloth, two tubes are arranged outside the skin to parallel to the central axis. Individual tubes slide passively slide against the skin (**Fig. 6 (a)**). Next, one end of the cylin-



(a) Initial condition before tucked in

(b) Pressurized condition after tucked in

Fig. 6. Tip growth with two flat tubes facing.

drical skin is tucked inside another (**Fig. 6 (b)**), so when outer tubes are pressurized, inner tubes are drawn out with the tucked skin.

No friction occurs between the skin and the outer environment nor between the two tubes because they move at the same speed. The non-pressurized tube inside the actuator moves against the pressurized tube outside it, so friction must be minimized – hence, use of the slippery cloth as the skin.

3.3. Driving Force

As a basic operating principle, tube buckling-point thrust is calculated. When the upper end of the tube is fixed in the outer environment and fluid volume ΔQ with pressure p is inserted into the tube, the buckling point is assumed to move distance Δl_b exerting thrust F_b. Assuming an ideal condition with no energy loss from input to output, the following equation holds based on the principle of virtual work:

$$p \cdot \Delta Q = F_b \cdot \Delta l_b \quad (1)$$

Assuming that the part of the tube with cross-section area A moves length Δl_b:

$$\Delta Q = A \cdot \Delta l_b \quad (2)$$

From equations (1) and (2), F_b is obtained as follows:

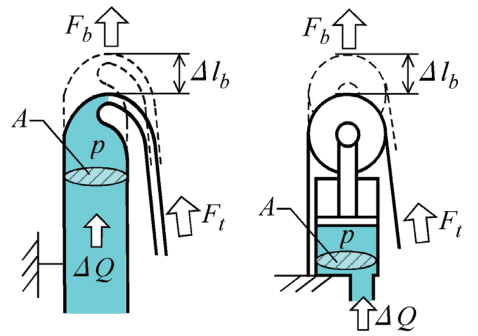
$$F_b = p \cdot A \quad (3)$$

As the buckling point moves Δl_b, the tube downstream is pulled $2\Delta l_b$, so Eq. (4) holds where F_t is traction, yielding the following relationship:

$$F_b \cdot \Delta l_b = F_t \cdot (2\Delta l_b) \quad (4)$$

$$F_t = F_b/2 = (p \cdot A)/2 \quad (5)$$

This is confirmed by an equivalent model consisting of a moving pulley with its center pushed by a cylinder and a wire wound around the pulley as shown in **Fig. 7**.



(a) Model of a flat tube. (b) Equivalent model using a pulley and a wire.

Fig. 7. Tube model (left) and its equivalent (right).

Buckling-point thrust corresponds to the output force of the cylinder and traction on the tube downstream is replaced by tension on the wire. Eq. (5) is also derived based on the principle of mechanics in this equivalent model. The energy of pressure applied to the tube is consumed, swelling the tube and thrusting buckling point, F_b so F_t may be smaller than values in Eqs. (3) and (5). In this study, however, Eqs. (3) and (5) are used as an approximated valid, assuming that tubes are soft enough to neglect deformation energy.

4. Controlling the Growth Direction

Having the actuator to steer along a curved path or to select the desired direction at the diverting point requires two additional functions – curving the tip in the desired direction and keeping the rest unchanged. This is discussed below assuming that the operator judges the desired direction using cameras or sensors on the actuator tip to measure the distance to obstacles.

4.1. Curving the Tip

To have the tip become curved, the difference in the distance grown between two tubes must be generated. This means that the outside tube in the curve must grow faster than the inside one.

To do so, the inner pressure of the outside tube is set at p_H and while that of the inside tube is set at p_L satisfying $p_H > p_S > p_L \geq p_M$. p_S represents the pressure value in the two tubes when the tip is to grow straight. p_M stands for the minimum pressure requested to keep the shape unchanged, as discussed below.

Since the drive of the tube with p_H exceeds that of the tube with p_L, the tube with p_H is expected to be drawn out longer than the tube with p_L. Due to friction between the two downward tubes, however, the tube with p_L is considered dragged out, hindering tube curving with a small curvature diameter. Thus, the tube to be inside is pulled by the operator at the base to stop moving. This enables the tip to grow curved, as the skin on the inside of the curve makes wrinkles, as shown in **Fig. 8**.

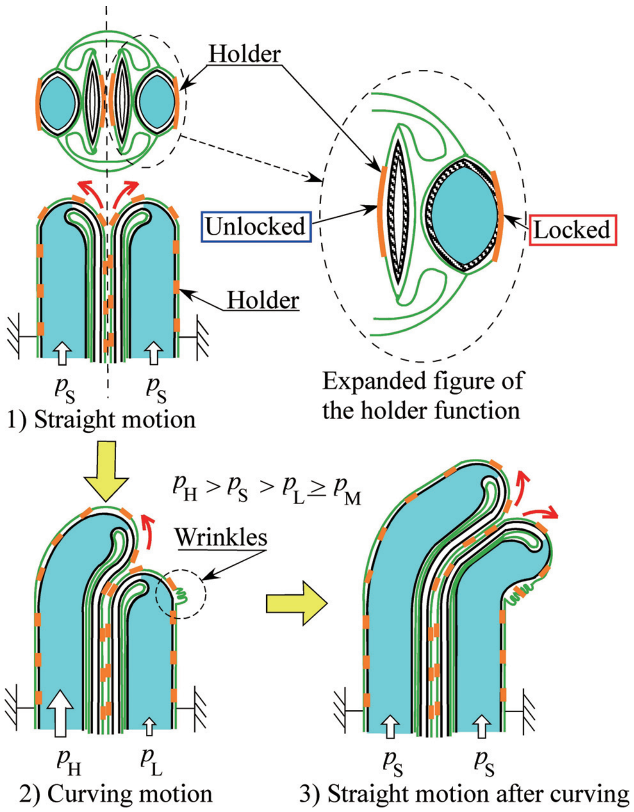


Fig. 8. Steering the direction of tip.

4.2. Keeping the Actuator Shape Unchanged

If the whole shape of the actuator changes on narrow terrain with the tip growing in different directions, stress on the actuator from the outer environment would increase, making it difficult for tubes downstream to be drawn out. To enable the downstream tube to be drawn out smoothly, the rest shape except for the tip must be kept unchanged.

As stated in Section 4.1, wrinkles occur on the skin inside of the curved actuator, suggesting that it would be effective to fix wrinkles to keep the actuator shape unchanged. In other words, the pressurized tube outside the actuator should be locked in the skin and the non-pressurized tube inside the actuator should slide freely along the skin.

To do so, the following structure is installed as one of the candidates, which consists of holders on the skin as shown in **Fig. 8**. Holders are very thin, hard, flat plates arranged separately in a "ladder" with a constant interval. When the tube is not pressurized, holders do not affect tube movement. Once the tube is pressurized higher than p_M and the cross-section of the tube approaches the circle, the holders cut in the pressurized tube, locking the tube in the skin as below in **Fig. 8**.

Based on the above principle, the direction can be steered as follows: Assuming that the actuator is changed from linear to curved, pressure in the tube inside of the curve is set at p_L from p_S. The tube to be outside is set at p_H from p_S while the inside tube is pulled from the base. Only the tube to be outside is drawn out, while the inside tube stays still with the wrinkles generated on the skin. Wrinkles are maintained by holders, so the curve is retained even if two tubes are pressurized by p_S and made linear that. In the experiments that follow, p_H, p_S, p_L and p_M were set at 0.5 MPa, 0.4 MPa, 0.2 MPa and 0.2 MPa respectively.

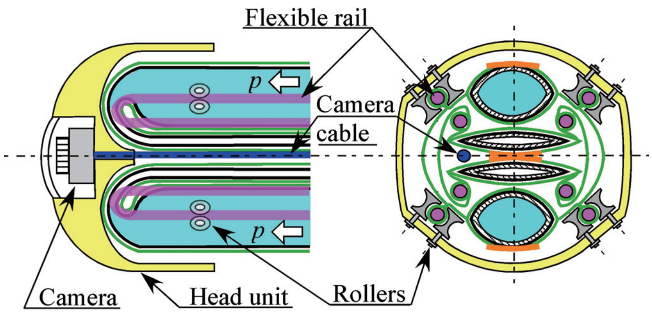


Fig. 9. Head unit with a camera.

5. Experiments

5.1. Carrying Sensing Devices

To collect information with the proposed actuator, a head unit with sensing devices should be carried with the actuator growing. However, the head cannot be fixed directly on the actuator due to the way the skin is drawn out, so flexible rails are set along the skin. The head has two pairs of rollers enabling the head to slide along the rails with it pinched by the rollers (**Fig. 9**).

5.2. Developed Prototype: "Grow-hose-I"

The developed prototype named "Grow-hose-I" was with 50 mm in outer diameter and 3 m in length (**Fig. 10**). The tube was made of urethane which allows to be pressurized by 0.5 MPa, while the outer skin was made of the mixture of polyester and nylon with slippery characteristics. As the holders, paper clips were introduced, which were attached on the outer skin in every interval of 25 mm. The head unit with 62.5 mm in diameter was equipped with a wireless camera. More detail specification is shown in **Tables 1** and **2**.

When one of the tubes was pressurized at $p_H = 0.5$ MPa and the other at $p_L = 0.2$ MPa with the inner tube kept still, Grow-hose-I could curve actively at a radius of 120 mm, the minimum radius of curvature. This could be maintained even with both tubes pressurized at $p_S = 0.4$ MPa to make it go straight. This indicates that the holders in **Fig. 8** work effectively.

5.3. Experimental Results of the Driving Force

The driving force F of Grow-hose-I was measured, while pressure p inside two tubes and gap d between two tubes were changed using the experimental setup shown in **Fig. 11**. The theoretical value of the drive indicates the

Fig. 10. Overall view of Grow-hose-I with a head unit on its tip.

Table 1. Specification of Grow-hose-I.

Size	Length: 3.0 m, Diameter ϕ50 mm
Tube	Flat tube made of urethane inner diameter ϕ10 mm outer diameter ϕ12 mm
Air pressure	0.5 MPa
Holder	Paper clip with thin flat shape (22 mm × 6 mm × 0.5 mm) Stainless Installed Interval: 25 mm–35 mm
Flexible rail	Nylon string Outer diameter ϕ2 mm

Table 2. Specification of the head unit.

Unit size	Acrylic plastic case Diameter ϕ62.5 mm Length 40 mm
Camera size	21 mm × 21 mm × 16 mm
Roller	Stainless steel ϕ4 mm × 8 mm

ideal condition assuming that the pressurized tube cross-section forms a perfect circle.

Results of experiments, shown in **Fig. 12**, demonstrate an optimal gap of 50 mm to maximize drive. If the gap is too narrow, the non-pressurized tube inside the actuator is difficult to move against the pressurized tube outside due to their mutual friction. On the other hand, if the gap is too wide, the flow leaks at the tube's bending point, which results in losing the drive. Thus, the gap of Grow-hose-I was set at 50 mm.

5.4. Drive Experiments

In the drive experiments below, the hose operated as (a) a crank drive (**Fig. 2**), (b) a drive inside a pipe (**Fig. 13**) and (c) a drive with a head unit with a camera module (**Fig. 14**). In crank driving, the hose was controlled by inputting air pressure of 0.5 MPa to the tube outside of the curve and 0.2 MPa to that inside. A bigger curve curvature is generated by pulling the wire inside of the curve.

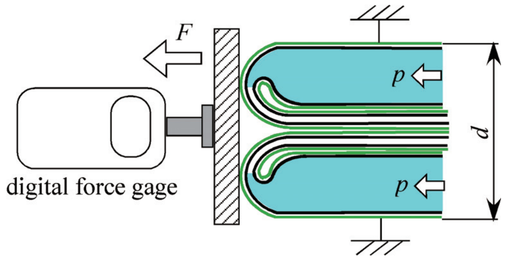


Fig. 11. Experimental setup to measure the driving force.

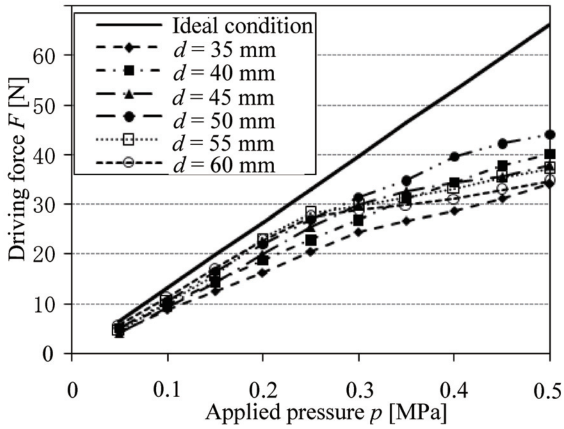


Fig. 12. Experimental results of driving force.

Results of experiments showed that on a crank drive, the direction of the hose is controlled toward the destination and the curve is maintained by the effect of the holders. When the camera module was set at the head of the hose, the module moved during synchronization with the tip moving forward. The tip growth was done smoothly in a narrow conduit, so this hose is applicable to both rescue operations and piping inspection.

6. Conclusions and Future Works

6.1. Conclusions

The new flexible hose-like fluid actuator we propose advances smoothly on a narrow curved path using mobile tip growth in which the tip alone moves forward by drawing the skin out from inside of the actuator, based on the growth process of plants. The skin of the actuator was expected to creep without generating much friction toward the outer environment. The actuator consisted of two flexible flat tubes, whose tips were bent to block fluid passage to draw out the downstream tube by pneumatics. Designing and operating the direction actively were shown by curving the tip while the outer shape remained constant. Assuming application to search and rescue operations, how to carry sensing devices was also proposed. The Grow-hose-I prototype successfully crept in the curved path and pipe with movement steered and the head carrying the camera.

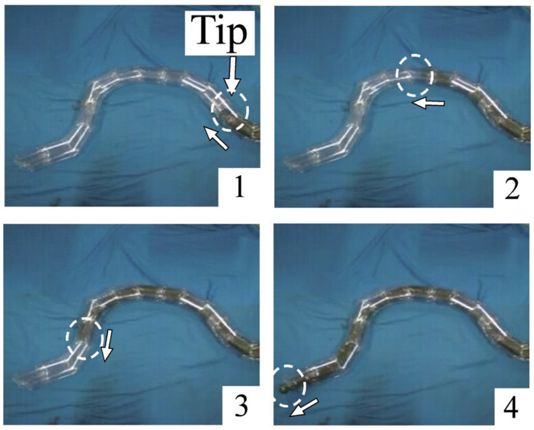


Fig. 13. Experimental Grow-hose-I results in a pipe with an inner diameter of 70 mm.

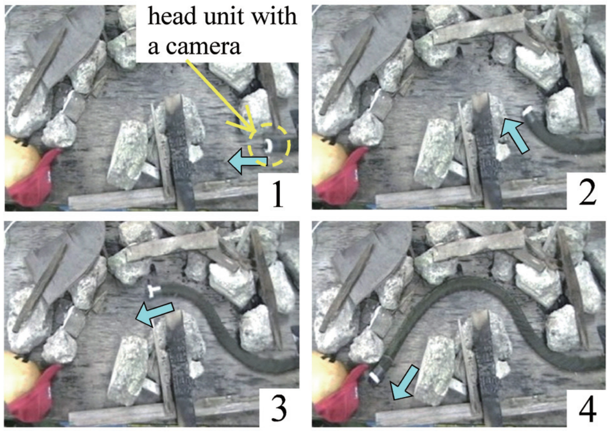


Fig. 14. Experimental results of Grow-hose-I steering in the narrow path.

6.2. Future Works

1. For the actuator to grow on more sharply curved, much longer path, two problems must be solved.

   One is the brake function on the inner tube in curving. Since this function in the prototype was operated by traction pulled at the remote area from the tip, it was difficult to transmit in the sharply curved path. The brake function must thus be installed on the head, which pinches the skin and the tube located on the inner side of the curve.

   Another is friction between the inside of the skin and the skin covering the downstream tube. Since both types of skin are made of slippery cloth, friction between the two is quite small when the actuator becomes linear. Once the actuator forms a curve, friction increases due to wrinkles generated in the inner side of the curve. To solve this problem, the inside of the skin must be coated with some resin with lubrication.

2. Practical use in complex disaster terrain requires 3D steering. To realize it, at least one more tube must be installed on the actuator. In this case, the three-tube section should be located to form each triangular side.

Acknowledgements

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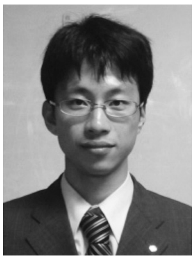

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