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Flexible Sliding Actuator Using A Flat Tube And Its Application To The Rescue Operation

Yotaro Mori, Hideyuki Tsukagoshi, and Ato Kitagawa

***Abstract*— This paper proposes a novel flexible sliding actuator driven by fluid power. The actuator called Λ-drive is basically composed of a flat tube and a slider. In the slider the tube is bent, then the buckling point occurs, which helps to cut off the fluid passage in order to provide the driving force to the slider when pressurizing one side of the tube. The proposed actuator is applicable to not only the straight path but the spiral and the curved one as well. Moreover, the design method to drive stably and the analysis of the output force are discussed in this paper. Finally, "Fluid Ropeway" is also proposed as the application of Λ-drive aiming to search and rescue survivors in the half collapsed houses, and its feasibility is verified through the experiment.**

I. Introduction

FLEXIBLE fluid actuators are generally composed of such deformable chambers as flexible tubes and soft bags, which can generate the force to the desired direction when their insides are pressurized by fluid power. Unlikely to cylinders and electric motors composed of the rigid structure, the big advantage of them is that they possess human-friendly characteristics and outstanding shape adaptability to the outer environment.

From the aspect of how to pressurize the chamber, the flexible fluid actuators proposed previously can be classified into two categories. One of them is the method of pressurizing the whole area inside of the chamber at one time and deforming the entire chamber simultaneously, which is supposed to be called "simultaneous entire chamber drive." Without the complex mechanism, this method allows to generate the various types of performance directly to the chamber, such as the expansion and contraction, the curving, the twisting, and etc. Mckibben Artifical Muscle[1], Flexible Micro Actuator[2], Wound Tube Actuator[3], and Zigzag Tube Actuator[4] are the examples taking advantage of this method.

The other pressurizing method has been also considered in which a part of the fluid passage in the chamber is cut off in some way and its cutoff point is slid from the upstream to the downstream as pressurized. The output in this method is generated as the relative motion of the cutoff point against the chamber. This method is supposed to be called "cutoff sliding drive," which makes most of its characteristics when the long tube is used as the chamber. Moreover, it has three advantages as follows. 1) It allows its output to generate approximately as long stroke as the original length of the installed tube. 2) It can perform the reciprocating motion even along the curved passage. And 3) it forms the differential mechanism to keep the mechanical balance among three input and output ports. Although a couple of examples were previously proposed, it remains some problems in this method for practical use.

In this paper, after reviewing the previous examples based on "cutoff sliding drive," the buckling phenomenon is focused as the improved method to cut off the fluid passage. Next, introducing the new actuator named "Λ-drive" shown in Fig.1, the structure to realize its stable drive is examined and its performance is analyzed. Moreover, we show experimental results of its basic operation and the validity of the analysis is verified. Finally, the application to the rescue operation is proposed and its performance is discussed.

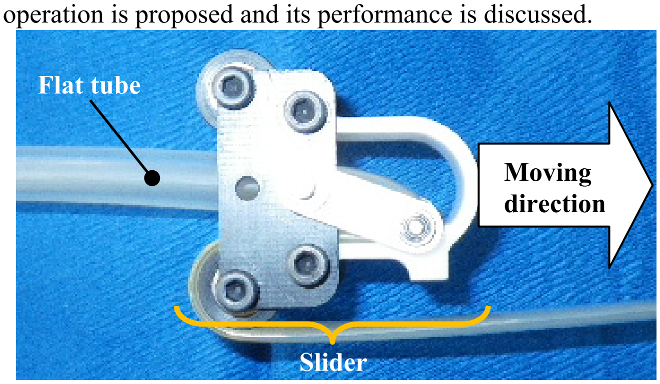


Fig.1 Developed Λ-drive composed of a flat tube and a slider.

II. Conventional Method of the Cutoff Point Sliding

Two types of "cutoff sliding drive" were proposed up to now, as shown in Fig.2. One of them is called pinch-roller drive[5,6,7], in which the fluid passage is cut off with two passive rollers pinching the flexible tube. Since this drive is easy to miniaturize the whole structure, it has been adopted to not only the linear motion but the infinite rotational one as well. However, adjustments of the force pinching the tubes tend to be complicated. An overly-strong force increases viscous resistance accompanying deformation of the tube, and a too-weak force causes losses by internal leaking. Additionally, the optimum strength of the pinching force that minimizes these losses changes during operation with variations in internal pressure, tube slack, and tube curving. Therefore, continuous stable drive of the pinch roller was difficult.

Manuscript received February 7, 2010. Yotaro Mori is with Tokyo Institute of Technology, Ohokayama 2-12-1-S5-19, Tokyo, 152-8552, JAPAN (corresponding e-mail: yo-ta@cm.titech.ac.jp).

Meanwhile, “Flexible Rodless Cylinder[8]” proposed by Akagi et al. can cut off the fluid passage by a ball sliding along the inside of the tube, which allows to generate relatively large output force by combining with Mckibben Artifical Muscle. However, as the ball slides along the inner walls of the tube, methods to reduce friction and wear of the tube are needed and have been investigated.

The above driving mechanisms require a structure that presses against the tube with sufficient force to make a seal at the cutoff point, and at the same time is able to smoothly slide the cutoff against the tube, which are two conflicting design requirements. Therefore, in this study we investigate methods to cut off the flow passage without pressing against the tube.

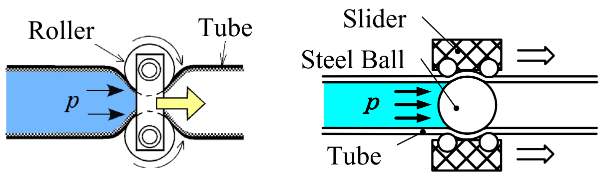


Fig.2 Conventional method of the cutoff sliding drive. The left is the pinch-roller drive and the right is Flexible Rodless Cylinder.

I. Proposal of “Λ-drive”

A. Basic driving principle

A newly proposed actuator is based on an extremely simple structure composed of a flat tube and a slider. The flat tube is the one whose cross section forms the flat shape in non-pressurized condition, while it approaches the circle shape in pressurized condition keeping its peripheral length approximately constant. The slider forms the ring shaped structure whose middle hole lets the flat tube pass through. We made a part of the flat tube set to pass through the slider with it doubled as shown in Fig.3. When the flat tube in this state is pressurized by air or water from one side, the buckling point is induced at the bent part of the tube, which results in cutting off the fluid passage, while the fluid flows until it reaches the point. Pressurizing the tube still more makes the slider push to the downstream with the buckling point moving. This driving method is named “Λ-drive” after the resemblance of the bent shape to the Greek alphabet of Λ. The Λ-drive possesses a couple of advantages different from the previous cutoff sliding drive, which are listed as follows.

1) The Coulomb friction force and the viscous drag can be reduced drastically when the passively rotating element is added to the slider, since the fluid passage is cut off without generating the excessive force on the axial and radial direction of the tube.

2) It can drive without rubbing against the outer environment, since no moving elements exist on the opposite side of the slider through the tube.

Note that use of pipe-shaped tubes in place of the flat tube in the Λ-drive is not appropriate. Although pipe-shaped tubes buckle when bent, the force crushing the tube downstream of the buckling point resists smooth motion of the buckling point. Therefore, the word “tube” in this paper always refers to a flat tube from this point onwards.

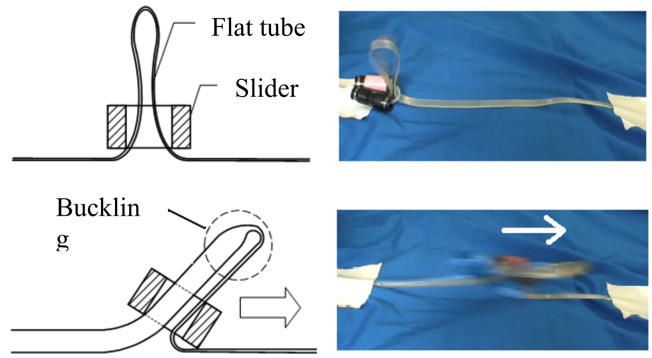


Fig.3 Basic driving principle of Λ-drive comparing the initial condition in the above and the pressurized condition in the bottom.

B. Mechanism for stable driving

We investigate the structure of a slider that stably drives the Λ-drive with increases or decreases in the load on the slider or changes in position with respect to the direction of gravity. Here, “stable” drive means continued buckling of the flat tube to maintain cutoff of the flow passage while smoothly moving the slider.

The first criterion is that the slider must be kept in an appropriate range to maintain the cutoff of the flow passage. If the length of the bent section is too short, the tube slips out of the slider, and self-excited oscillation [10] occurs if the bent section becomes too long. Therefore, as shown in Fig. 4 we place a holder in the center of the slider. A stopper to prevent the tube from slipping out and a cover to stop the tube from shooting out is attached to the holder.

The second criterion is that the Coulomb friction and viscous resistance acting on the slider must be reduced for the slider to move smoothly. The Coulomb resistance can be reduced by adding a rotating element at the point of contact of the tube and slider; therefore rollers that can passively rotate are used as the entrance and exit to the slider and the stopper at the center of the slider. The viscous resistance may be decreased by reducing the deformation of the tube. The tube and stopper are in contact in the relatively limited space inside the cover, substantially contributing to the increase or decrease of viscous resistance. Thus we choose a structure that limits deformation of the tube by the stopper caused by bulging of the tube; an arm is attached that can passively swing around a pivot, and the tip of the arm is used as the stopper. This allows the stopper to automatically tilt from the

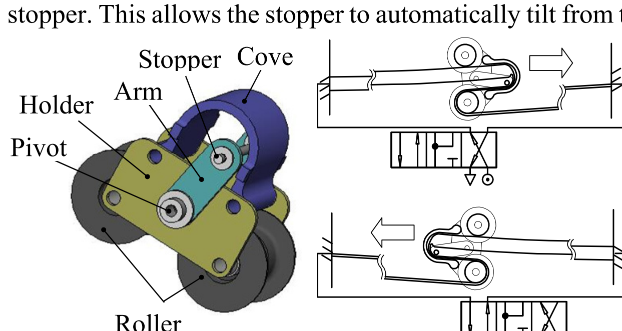


Fig.4 Structure of the slider to keep driving stably.

upstream side to the downstream side regardless of which side of the tube is the upstream side as seen from the buckling point. Such a structure is especially effective when the slider is driven in both directions.

C. Noteworthy designing point and characteristics

The key point of designing Λ-drive can be illustrated as follows. First, the distance between two rollers should be kept short enough for the tube to form the narrow angle at the bent part, in order to preserve the buckling phenomenon stably. The gap between two rollers requires at least the total of the radius of the pressurized tube and the thickness of the non-pressurized tube, while it should avoid touching into contact of each other. In this work, the roller span is narrow enough to consider the upstream tube and the down stream tube are parallel.

Furthermore, the radius of the rollers is necessary to be designed keeping large enough not to induce the buckling and not to prevent bending. Actually it depends on the material and the thickness of the flat tube, the minimum radius of the roller such that the tube does not buckle has to be investigated. Considering the design of the cover, its width should be kept equivalent to that of the roller. Besides, the stopper and rollers are supported by the ball bearing to rotate passively. The above designing points let Λ-drive move smoothly.

II. ANALYSIS OF THE DRIVING FORCE

A. Basic principle of force generation at the buckling point

The driving force at the buckling point is derived as follows. Let us assume that the flow rate ΔQ with the pressure p flows into the tube, while the displacement Δl_b with the force F_b is produced at the buckling point as the output. Assuming a perfect state with no energy loss from input to output, the following equation

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

holds from the conservation law of energy.

At the same time, the next equation can be also obtained, assuming that the most expanded part in the tube, whose cross sectional area is expressed as A, becomes long for Δl_b with the buckling shape kept constant, shown in Fig.5.

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

Considering the above two equations, the following relationship can be derived.

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

While the buckling point moves a distance Δl_b, the downstream tube is pulled by $2\Delta l_b$. Therefore, equation (4) holds, where F_t is the traction. As a result, the relationship in equation (5) can be deduced.

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

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

This equation shows the pulling force F_t is not affected by the angle between the upstream and the downstream tube.

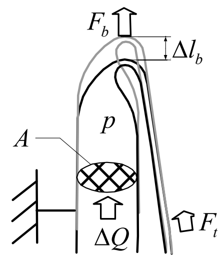


Fig.5. Model of the flat tube.

To be exact, the energy is consumed to deform the cross-section of the tube, therefore and may be smaller than the values in equations (3) and (5). However, in this work we use equations (3) and (5) as approximations valid when flat tubes that are soft enough are used.

B. Classification of driving modes

On the basis of the above principle, the driving force of the slider in Λ-drive will be analyzed in the following steps. First, we assume that the both edges of the flat tube are fixed to the ground. From the aspect of how to contact of the buckling point to the slider, how to generate the driving force will be classified into three categories shown in Table 1, such as the buckling mode, the cover mode, and the stopper mode.

They are determined by the relationship between the distance of the fixed points and the tube length. Let us suppose that the tube with its length of l is strung without the slack between two points with its distance L, as shown in Fig.6 Assuming that one side of the tube is pressurized and the slider starts moving, the length of the turned tube with the shape of 'S' is set as follows respectively, such as U_s when the buckling point touches to the stopper and U_c when it touches to the cover.

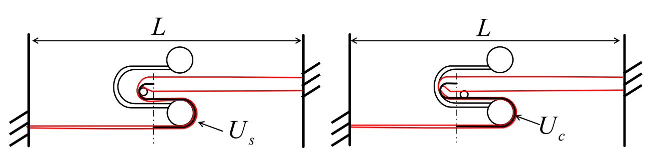


Fig.6 Critical condition determined by the tube length and the fixed distance.

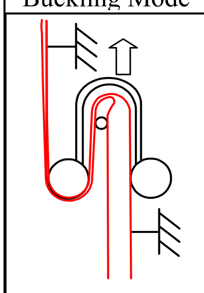
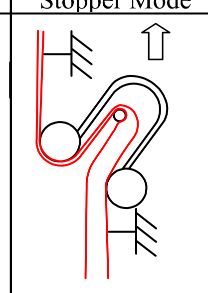
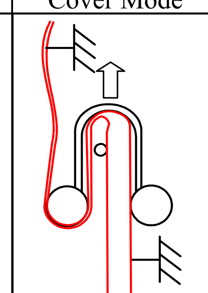
$L+U_s < l < L+U_c$	$l < L+U_s$	$l > L+U_c$
Buckling Mode	Stopper Mode	Cover Mode
		

Table 1 Classification of driving modes on the slider.

C. Buckling mode

In the buckling mode, the buckling point B does not directly touch the slider, therefore the slider drives according to the following principle, illustrated in Fig.7. Point B is pushed downstream with regard to the upstream tube fixed to the external environment, creating tension in the downstream tube. As a result, the slider is pulled by forces on the downstream side roller (roller D). Here, the force pulling roller D in the direction of propulsion F_{out} is the sum of traction F_t, therefore can be expressed using the relationship in equation (5) as

$$F_{out} = 2F_t = p \cdot A \quad (6)$$

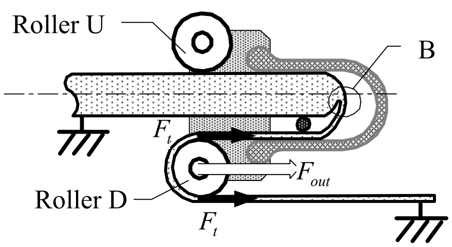


Fig.7 Driving principle of the slider in the buckling mode.

D. Stopper mode

In the stopper mode, the tube is not long enough and the buckling point touches the stopper, then the stopper itself becomes a pulley element at the buckling point (Fig.8). The shorter the tube length becomes, the more the slider inclines.So the following two phenomena not observed in the buckling mode occur because. 1) The upstream side of the tube bends, causing the upstream side roller (roller U) to be pushed from the tube by force F_u that depends on the tube stiffness. 2) The tension between the stopper and roller D F_t cancels out in the slider, and therefore does not contribute to the driving force of the slider. These phenomena add up to a loss of $F_u \sin\theta_u + F_t$ compared to the buckling mode. The driving force of the slider in the stopper mode is given in equation (7).

$$F_{out} = F_t - F_u \sin\theta_u \quad (7)$$

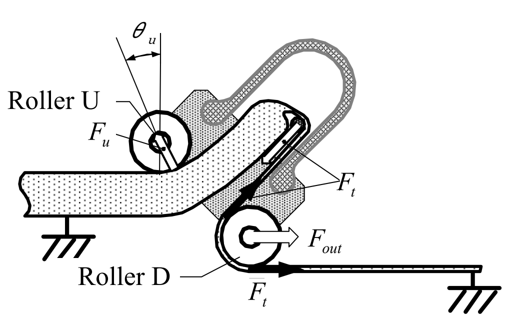


Fig.8 Driving principle of the slider in the stopper mode.

E. Cover mode

In the cover mode, the tension of the tube touching roller D is zero, therefore there is no traction on roller D. Instead, the buckling point pushes the inside of the cover to drive the slider (Fig.9). The driving force of the slider is decreased compared to the thrust at the buckling point F_b due to losses such as 1) slack in the tube upstream from the buckling point, and 2) friction R caused by the buckling point sliding inside the cover, and can be expressed as in equation (8).

$$F_{out} = F_b \cos\theta_c - R\sin\theta_c \quad (8)$$

$$R = \mu F_b$$

(9)

Here, θ_C is the bending angle of the buckling point measured from the center line of the upstream tube toward the direction of propulsion and μ is the coefficient of friction between the cover and tube.

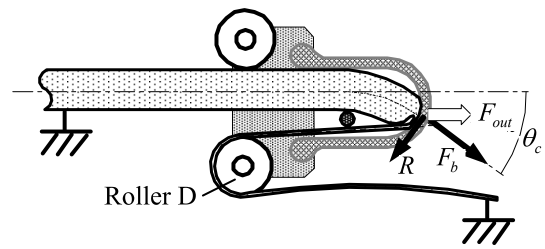


Fig.9 Driving principle of the slider in the cover mode.

III. Basic experiments

A. Variation of the cross sectional area of the flat tube

The thrust F_b and tension F_t are determined by the internal pressure p and cross-sectional area A of the flat tube as shown in equations (3) and (5). The cross-sectional area changes with internal pressure, and the trend of change depends upon parameters such as the size, thickness, and restoring force to return to the flat shape of the tube. We will discuss a model to predict the trend of change in tube cross-sectional area based on these parameters in a different paper, and for the tube in this work we obtain the cross-sectional area by actual measurement.

The tube specification and the results are shown in Fig. 10. When pressure was less than 0.1MPa, the increase in the minor axis was dominant, therefore the cross-section increased at high rate. On the other hand, when pressure rose above 0.1MPa, the increase in the minor axis and the decrease in the major axis balanced out, and as a result the cross-section increased at a slow rate.

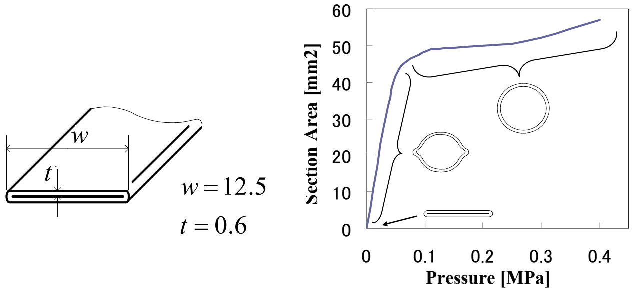


Fig.10 Variation of the cross sectional area of the flat tube.

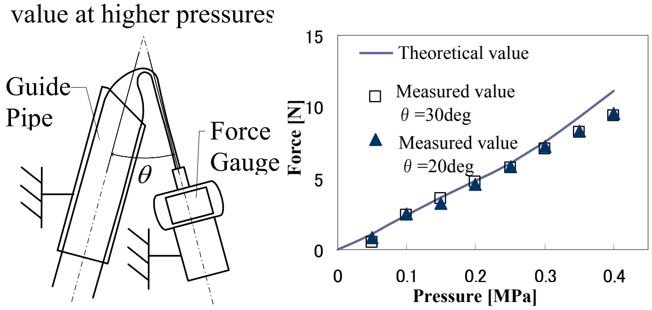
B. Driving force

First, the traction force generated at the buckling point was investigated by using the flat tube shown in the above section. In order to prevent the upstream tube from curving, the rigid guide pipe was covered with it, while the digital force gauge was attached to the downstream tube to measure the traction force as shown Fig.11 (a).

Regardless of the angle between the upstream and the downstream tube, the experimental results shown in Fig.11 (b) correspond to the theoretical value calculated by the equation (5), which indicates the consideration in IV.A is valid.

Next, the driving force of the slider in three modes was measured. A prototype slider is shown in Fig.12. We conducted experiments using this slider in the buckling mode when both ends were fixed, the stopper mode when $\theta_u = 0$, and the cover mode. The measured and theoretical driving forces as functions of pressure are given in Fig. 13.

The results show that the measured and theoretical values in the buckling and stopper mode match well. Here, the theoretical values of the cover mode are those for bending angle $\theta_c = 30°$ and coefficient of friction $\mu = 0.8$ .In the cover mode we believe an increase in the bending angle caused the measured value to deviate from the theoretical value at higher pressures



(a) Experimental setup. (b) Tension of flat tube.

Fig.11 Experimental setup to measure the tension on the tube and the tension of flat tube.

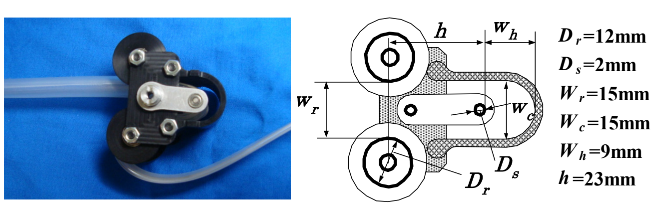


Fig.12.A developed slider and the installed flat tube.

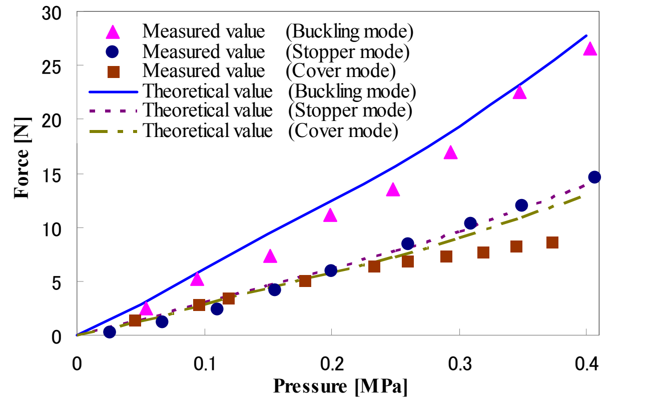


Fig.13 Input pressure and output force of the slider shown in Fig12. The buckling driving mode is most efficiency and nearly equal to theoretical maximum value that given as a product of its section area and pressure.

C. Experiment to test operation

We tested the prototype Λ-drive using motion along a straight line and a spiral line. Initially, the flat tube was placed along a straight line, and operated in buckling mode with both ends fixed. We observed smooth reciprocating motion as in Fig. 16 when pressure was alternately added from both tube ends. The pressure added was 0.25MPa, and the maximum velocity of the slider was about 1.4m/s.

Next, we coiled the flat tube around a cylinder with diameter φ130mm. We again observed smooth reciprocating motion on the spiral, as shown in Fig. 15, by pressurizing both tube ends alternately. Here, the slider moved without touching the cylinder because there were no moving elements touching the cylinder surface.

Third, we created an actively-driven zipper as one of the Λ–drive applications in certain specific fields .The tube was set in parallel to the chuck to pull the zipper in both directions, shown in Fig.16. The zipper was experimentally proven to be able to open and close actively and the characteristic of Λ-drive allows operation of the zipper without using moving elements that touch the body.

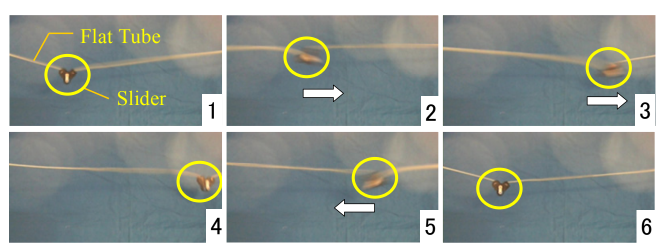


Fig.14 Straight line motion of the slider

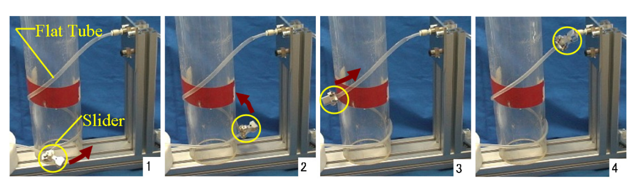
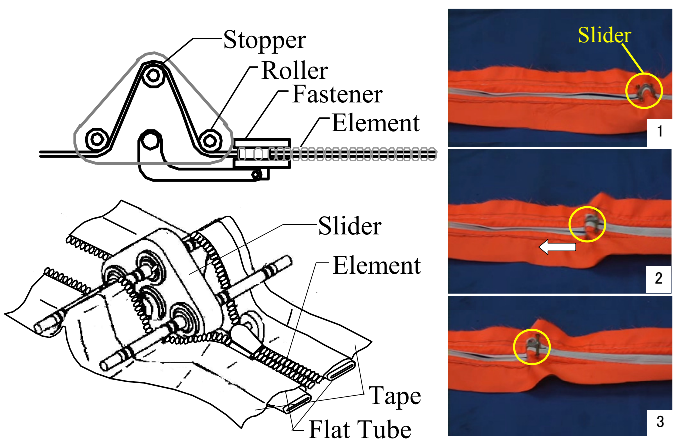


Fig.15 Slider movement on a spiral line



(a) Mechanism. (b) Developed device.
Fig.16 Active operation of a zipper by the Λ -drive.

IV. Application to the Rescue Operation

A. Proposal of Fluid Ropeway

Every time the big earthquake occurs, efficient search of survivors inside the collapsed houses becomes the big issue. As one of the tools to search safely under the condition of the strong aftershock, a camera with long pole has been used by rescue parties staying outside of the houses, while its search area is limited within the reachable distance of the pole. Besides, it must have approached only through the linear path. Although mobile rescue robots using wheels or crawlers might be capable of searching much wider region in 3D, they are still hard to cross over irregular terrain with the obstacles higher than their own size.

To cope with the above circumstance, throwing a sensor ball with a rope into the deep area of houses can be one of the options, which is expected to search survivors in process of pulling the rope to pick up the sensor ball. Although this method might be feasible even on irregular terrain where mobile robots are hard to traverse, there remain three problems in the actual case such as the impact on the sensor in the ball when thrown, the stuck condition of the ball, and the friction of the rope against the ground when pulling.

To solve these problems, a new device named "Fluid Ropeway" shown in Fig. 17 is proposed, which consists of a gondola probe unit carrying sensors to search survivors, a flat tube instead of the rope, and a dummy ball as a weight. This device is operated as follows. 1) First, the dummy ball with the flat tube is thrown into the house by the operator. 2) Taking advantage of Λ -drive, the gondola probe unit goes and returns along the pressurized flat tube between the operator and the dummy ball, while sensors gather information on survivors. 3) Finally, the gondola probe unit and the flat tube are collected, while the dummy ball is left at the dropped spot. The big advantage of this device is no large impulse on sensors and no large friction of the flat tube occur, since sensors are not carried in the thrown dummy ball and the tube is not necessary to be pulled with the tension working.

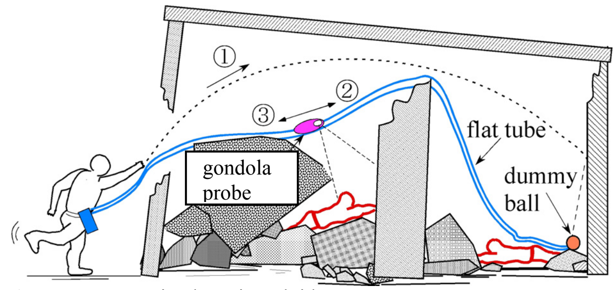


Fig.17 Rescue operation by using Fluid Ropeway.

B. Demonstration

For practical use of Fluid Ropeway, the gondola probe unit itself is also requested to move smoothly even on the debris filled environment, keeping the friction against obstacles as small as possible. Accordingly, the tube leading mechanism is mounted on the gondola probe unit as shown in Fig.18, which is composed of pulleys, two links, a slider and a lever. When the flat tube is pressurized from the left side, for example, a slider of Λ -drive rotates round the center O. At the same time, Link-A is rotated around Pulley-A to counterclockwise due to the expansion of the left tube, then Lever is pulled which makes Link-B rotate to the same direction as the downstream of the flat tube is pushed forward. This part of the tube plays a role as the buffer on both the front and the bottom to avoid the direct contact between the gondola probe unit and the ground. Even if the tube is pressurized from the opposite side, the tube leading mechanism works reversely and then the inversed front side can be protected as well.

The prototype of the gondola probe unit was designed with the size of L155 H44 W40(with camera:80)mm, whose weight was 120g. As the search function, two wireless cameras with a microphone were attached to each edge of the central shaft of the slider. Synchronized with the swing of the slider of Λ -drive, the cameras could also swing to shoot the different scene while the gondola probe unit went and returned.

In the experimental environment, the operator stayed away from the outer wall of the building, keeping 7m apart by the wide ditch. The doll was laid down in the building. That is, the doll was invisible for the operator. After a dummy ball with a flat tube was thrown in, the gondola probe unit could be driven with the compressed air of 0.4MPa supplied by the portable compressor. Simultaneously, the picture from the wireless camera was monitored by the display in the operator, which could successfully find out the doll, as shown in Fig.19.

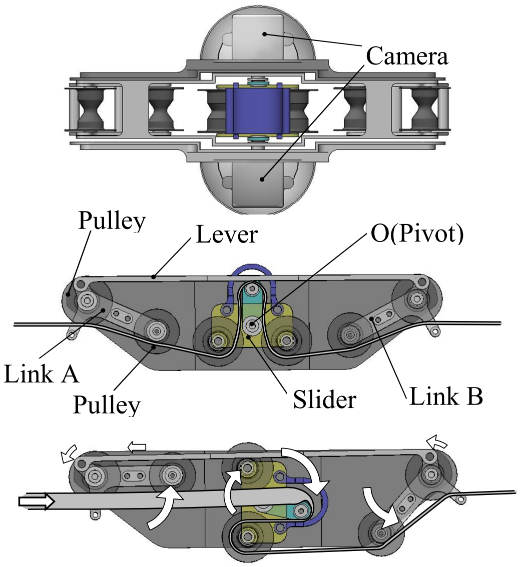


Fig.18 Mechanism of the gondola probe composed of the slider and cameras.

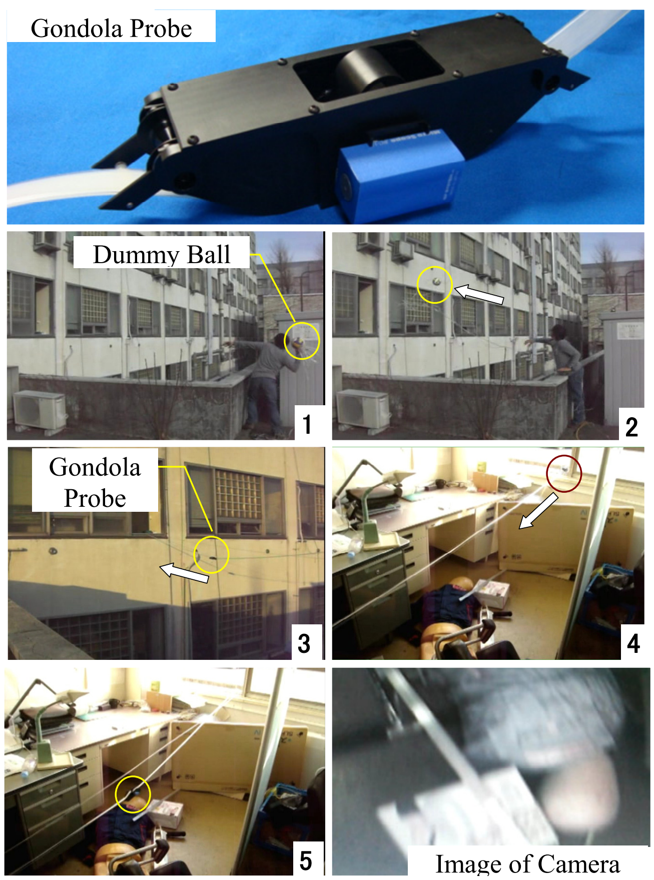


Fig.19 Pictures of operating Fluid Ropeway to find out the doll lying down inside the building.

V. CONCLUSIONS AND FUTURE WORK

A novel flexible sliding actuator driven by fluid power, named Λ -drive, was proposed in this study. Its driving principle is based on the peculiar phenomenon of the flat tube, in which the buckling point to cut off the fluid passage can be smoothly propelled by the fluid force. Compared to the previous sliding actuators, it has three advantages as follows. 1) No excessive force working on the tube to cut off the fluid passage, 2) the decrease of wear of the tube, and 3) the possibility of moving without rubbing against the outer environment. Moreover, this paper also shows the suitable structure of the slider to keep the buckling point stable, the analysis of the driving force of the slider, and the experimental for verifying their validity. Finally, "Fluid Ropeway" was proposed as the application of Λ -drive to the rescue operation aiming to search survivors in the half collapsed houses, and its feasibility was inspected through the prototype. As the future work, we are planning to study the velocity control method and how to prevent from the stuck condition assuming the actual rescue application.

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