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Paper:

Concept and Prototype of Soft Actuator for Liquid Nitrogen Temperature Environments

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A prototype of a soft actuator for extreme environments was fabricated, and driven in a cryogenic temperature environment. Previous soft actuators cannot be used for robots in extreme environments because resin, the main fabrication material, exhibits weak environmental characteristics. Therefore, this study proposes the application of polyimide (PI) films to soft actuators. PI is characterized by excellent environmental resistance. However, the welding of PI is difficult because of its high resistance. In this study, a welding method was developed for PI films. This method does not require pretreatment, or the use of adhesives or additives to reduce resistance. Hence, an actuator that utilizes all the characteristics of PI was realized. The actuator was characterized in a cryogenic environment, which is one of the extreme environments, and was successfully driven at a liquid nitrogen temperature of 78 K. This proposed technology is not limited to cryogenic environments and is expected to provide extreme environmental resistance to existing soft robots.

Keywords: soft robotics, low temperature, extreme environment, polyimide, Filmotics

1. Introduction

An extreme environment is one where the ambient conditions considerably deviate from the normal surviving conditions for organisms including humans. Examples include high-temperature environments, vacuum environments, and polluted environments. Extreme environments have attracted the interest of researchers, and various applications have been developed in advanced scientific fields to facilitate different operations in such environments.

Cryogenic environments are found to be useful in various fields. For example, in the field of biochemistry, rapid freezing technology is used to reduce the damage caused by long-term storage and thawing of animal and plant samples [1, 2]. The cell survival rate is high when samples are frozen at a temperature that is considerably lower than that found in general refrigerators [3].

However, cryogenic temperatures cause low-temperature brittleness in objects to be processed, such as cells, plants, and organs. Therefore, a mechanism with softness and mechanical passive compliance, such as backdrivability, is necessary for the manipulation of objects.

On the other hand, temperature reduction can cause brittleness in several materials. The materials that make up the actuators are no exception. Thus, a majority of the actuators used in cryogenic environments are made of metals such as stainless steel and titanium, which are resistant to low-temperature brittleness [4–6]. Consequently, the use of a rigid metal device may break the target object. To solve this problem, virtual passive compliance can be achieved by controlling the actuators. However, automatic operation at cryogenic temperatures, where many valuable samples are available, requires a safer and softer robotic element. Therefore, at present, the treatment of frozen biological tissue and the extraction of frozen cellular tissue must be performed manually by a human in a protective suit.

Our final goal is to create a soft actuator that has human-like softness even at low temperatures and does not damage the target object. This mechanical element can be used not only in the field of biochemistry, but also in robots operating at low temperatures or sample recovery mechanisms in a cold place, such as on the far side of the moon.

One of the actuators with a human-like softness is the pneumatic soft actuator [7–9], which is driven by applying air pressure to an air chamber made of a flexible material. The softness of the actuator is attributed to air compressibility and the softness of the material used to make the actuator. The air compressibility can be equated to the compression caused by applying force to a piston containing air. The softness of materials can be harnessed by fabricating the actuator using resin materials such as rubber. There are various types of actuators, depending on the air chamber shape, the forming method, and the actuator movement [10–12]. Owing to their softness, such actuators have been used in robots that coexist with humans, for example, in rehabilitation [13–15].

However, existing pneumatic actuators cannot be used with robots operating in extreme environments because resin, the main fabrication material, exhibits weak environmental resistance characteristics. Therefore, these actuators can achieve human-like softness only in limited environments where living things (humans, animals, and plants) can survive.

To solve this problem, the present study realized a soft actuator for extreme environments. The actuator is made of polyimide (PI) films and can be driven at a liquid nitrogen temperature of 78 K. There are no examples of pneumatic actuators at extremely low temperatures, and the lowest temperature for soft actuators is approximately 253 K with ionic polymer-metal composites (IPMCs) as the drive source [16]. Our proposed actuator lowers the operating temperature limit of the previous soft actuators by 175 K. To generate extreme environmental resistance in the soft actuator, a welding method for PI films is also developed. This study describes the fabrication technology used for the actuator, and evaluates the actuator in a liquid nitrogen temperature environment. We expect the characteristics of an actuator to change at extremely low temperatures, and therefore, the developed actuators are evaluated at room temperature and liquid nitrogen temperature.

2. Welding Method for Polyimide Films

Silicone rubber, which is the primary material used to make the previous soft actuators, has a low environmental resistance at low temperatures. The stiffness of rubber increases as the temperature decreases, and low-temperature brittleness occurs below 158 K [17, 18]. Therefore, rubber cannot be used at cryogenic temperatures.

In this study, we focus on PI, which is a super-engineering plastic. PI has excellent environmental resistance. It can be used in temperature environments from 4–600 K, with chemicals such as alkalis, acids, and organic solvents, and in radiation and cosmic ray environments [a]. However, the welding of PI is difficult because of its excellent stability. Therefore, a common technique used in many cases to join PI elements is to paste them together using adhesives such as adhesive tapes. Consequently, the previous devices cannot make full use of the high resistance of PI, and the usage environment is limited because of the limitation of the adhesives.

Two main techniques are available for directly welding PI films together. One is to activate the PI surface using plasma irradiation and then perform thermal welding. This method increases the number of required processes and reduces productivity. Additionally, it is unsuitable for joining films with complex shapes. The second technique is to develop a PI that can be welded. The PI obtained using this technique has degraded mechanical properties and low resistance to extreme environments.

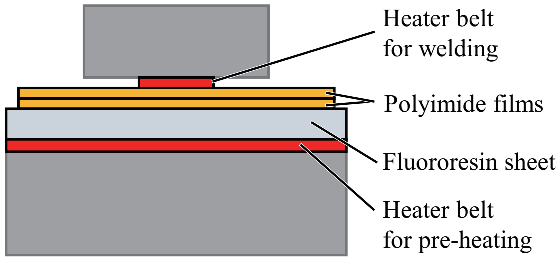


Fig. 1. Schematic view of PI welding machine.

This study succeeded in welding commonly available PI films without employing pretreatment or using adhesives or additives. A schematic view of the welding machine is shown in **Fig. 1**. A fluororesin sheet and PI films are stacked on the heater belt for preheating. The PI films are preloaded by the sheet and heater belt for welding. Welding is performed by heating the heater belt for welding. Simultaneously, the fluororesin sheet, which has a lower melting point than PI, melts temporarily but not into the PI films. Owing to this characteristic, the welding of the PI films is realized using the fluororesin sheet as a release agent and cushioning material.

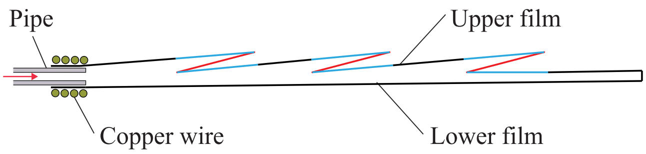
The PI soft actuator described below is realized by employing this welding method without using any adhesives, additives, or complex treatment. In the proposed actuator, the entire resistance of PI can be utilized because no adhesive is used.

3. Structure and Fabrication Process of the Soft Actuator

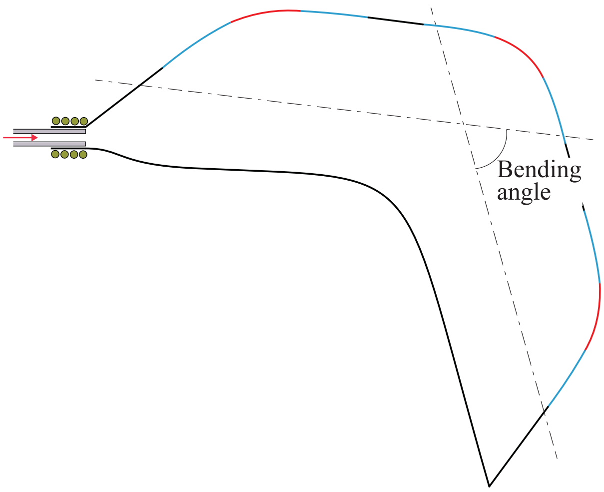
PI is generally a highly rigid material whose strength is similar to stainless steel in any temperature range [a]. Therefore, by using PI in the form of an ultrathin film and by fabricating the air chamber, a softness similar to that of a rubber actuator can be realized, primarily through air compressibility.

The structure of a soft actuator that can be used in liquid nitrogen temperature environments is illustrated in **Fig. 2**. The actuator is an inflatable air chamber made of PI films. The air chamber is fabricated by welding two 25-μm thick PI films together. One side of the film is folded into pleats. The pleated film is bent along its width and welded to the unpleated film. The pleats can be unfolded by applying gas pressure, and the actuator can bend like a finger. The actuator changes from a curved to a linear state by changing the internal pressure from positive to negative. A reciprocating motion is achieved by repeating the positive and negative pressures.

In small and low-pressure pneumatic equipment, the

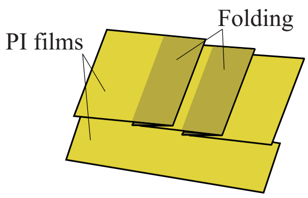


(a) Without gas applied

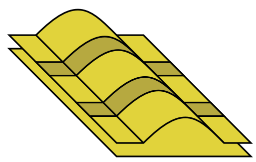


(b) With gas applied

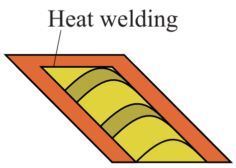
Fig. 2. Structure of soft actuator for use at liquid nitrogen temperatures.



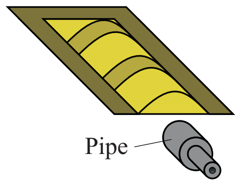
(a) Folding process



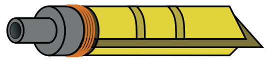
(b) Curved film



(c) Welding process



(d) Connecting pipe



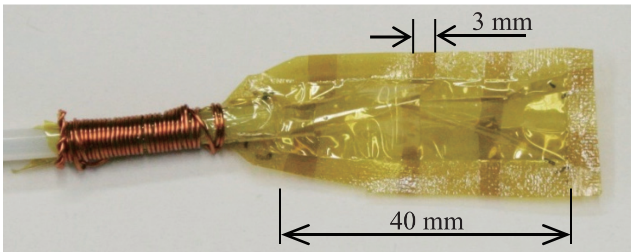
(e) Winding process

Fig. 3. Actuator fabrication procedure: (a) folding upper film, (b) curving pleated film, (c) welding three sides of two films, (d) connecting pipe to chamber, and (e) winding of chamber and pipe.

pipe and air chamber are often glued together. However, connections formed using adhesives cannot be used in a liquid nitrogen temperature environment because the adhesives deteriorate at low temperatures. Therefore, the actuator and pipe are caulked by winding a copper wire and thus, connected without an adhesive.

The actuator fabrication procedure is illustrated in **Fig. 3**. First, one film is folded to create pleats on it. Next, a chamber is formed by welding the three sides of the two films using the abovementioned method. At this time, the pleated film is welded in a curved form along its width. Finally, the chamber and pipe are caulked by winding a copper wire.

The fabricated actuator is shown in **Fig. 4**. The shape of the actuator is a prototype to investigate the feasibility of the drive in a cryogenic environment and is not designed for a specific application. The actuator is 50-μm thick with a 40-mm-long air chamber. The width of the chamber differs in individual samples because the actuator is fabricated manually. Therefore, the width is normalized by unifying the ratio of the width of the upper film to that of the lower film. The width for the bending angle evaluation is 12.5 mm, and that for the torque evaluation is 10.0 mm. The air chamber has three pleats, and the central pleat contributes to the bending movement. The pleats at both the ends form an actuator when inflated. The thickness of the actuator is 100 μm locally at the point where a pleat (3 mm wide) is provided. The inner and outer diameters of the pipe in this prototype are 2 mm and 4 mm, respectively.



(a) Before applying pneumatic pressure

(b) Curving like a finger (applying pressure)

Fig. 4. Fabricated actuator.

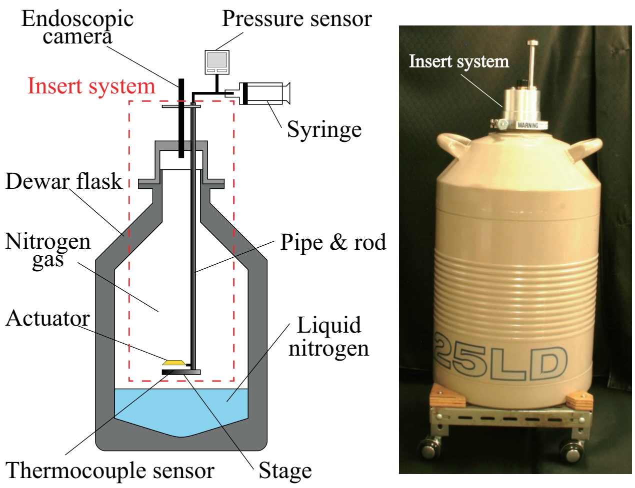


Fig. 5. Schematic view and photograph of evaluation system at liquid nitrogen temperature.

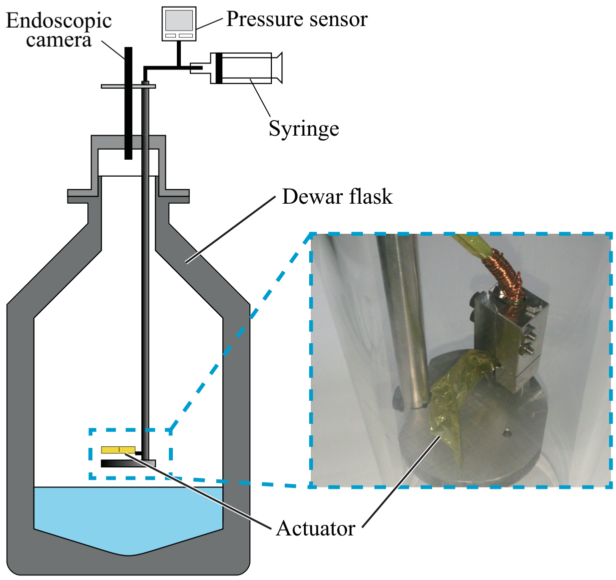


Fig. 6. Schematic view of setup for bending angle evaluation.

4. Measuring System for Soft Actuator in Liquid Nitrogen Temperature Environment

No devices were available for evaluating the soft actuator in a liquid nitrogen temperature environment. Thus, an evaluation apparatus that could evaluate the actuator was developed.

A schematic view and photograph of the apparatus are shown in **Fig. 5**. The apparatus consists of an insert system and a Dewar flask. The insert system consists of a stainless-steel rod, a stage for mounting the actuator, a T-type thermocouple sensor, a stainless-steel pipe for applying gas pressure to the actuator, and an endoscopic camera. A liquid nitrogen temperature environment is constructed by inserting the system into the flask. A stage for mounting the actuator is attached to the tip of the insert system, and a temperature sensor is fixed to the stage. The actuator is cooled by vaporized nitrogen gas. After a sufficient amount of cooling time, a temperature of 78 K is achieved.

In a temperature environment below 90 K, the oxygen in the air liquefies and the water vapor solidifies. Therefore, air cannot be used as the working fluid for cryogenic pneumatic actuators. In this study, vaporized liquid nitrogen is recovered from the evaluation apparatus and used as the working fluid for the actuator. The gas is temporarily stored in a syringe and supplied to the actuator.

Because the nitrogen gas recovered by the syringe is supplied to the actuator, the working fluid cannot be supplied continuously. Therefore, driving the actuators at a constant pressure for a long time is not possible. In addition, the applied pressure is measured at 295 K because it cannot be measured in a cryogenic environment. Thus, it is expected that there is a time shift between the measurement results of the applied pressure and the values of the bending angle and generated torque. Therefore, it is assumed that the maximum values are achieved at the maximum applied pressure, and the measurement results are synchronized.

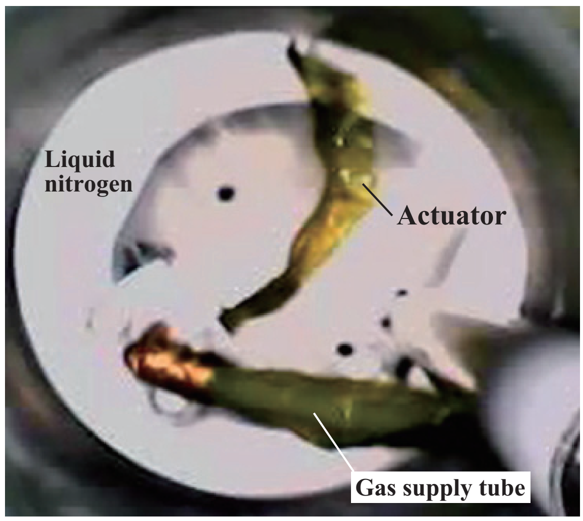


Fig. 7. Actuator bent inside Dewar flask (liquid nitrogen temperature environment).

5. Evaluation of the Bending Angle

The maximum bending angle of the fabricated actuator was evaluated under no load. The configuration of the evaluation experiment is shown in **Fig. 6**. An endoscopic camera fixed at the top of the insert system was used to record the behavior of the actuator when the gas pressure was applied. The actuator was mounted at 90° to the camera so that the bending angle could be measured from the camera. Based on the image captured by the camera, the angle of the welded line at the central pleats was measured as the bending angle.

Figure 7 shows a photograph of the actuator bending at 78 K. The actuator was placed in the air above liquid nitrogen in the Dewar flask, which was photographed with an endoscopic camera at the top of the evaluation

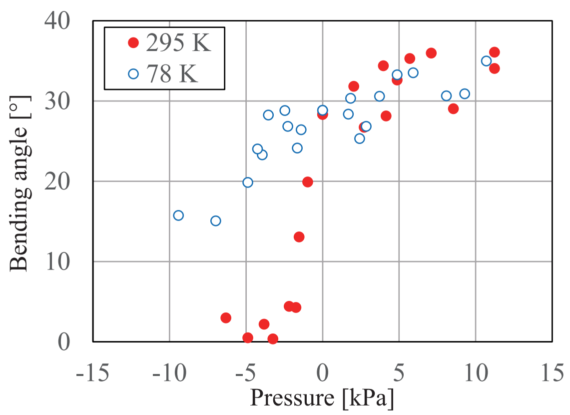


Fig. 8. Relationship between applied pressure and bending angle of actuator.

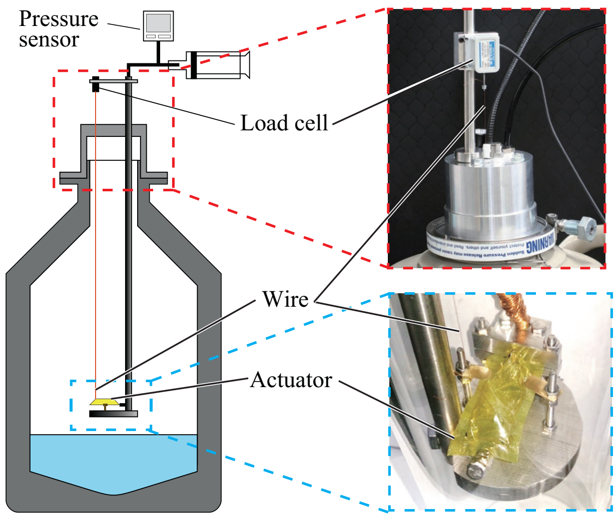


Fig. 9. Experimental setup for evaluation of generated torque.

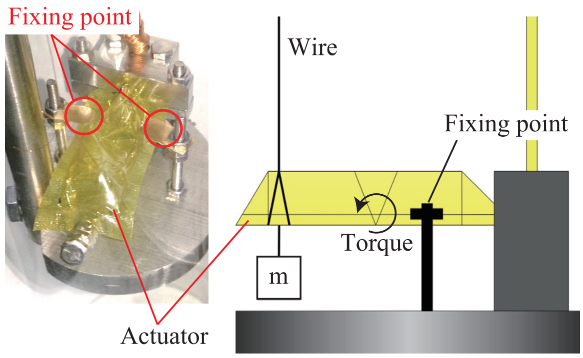


Fig. 10. Schematic view of around measuring point.

system. This result demonstrates that the actuator was successfully driven in a liquid nitrogen temperature environment.

Figure 8 shows the relationship between the applied pressure and bending angle at 78 K and 295 K. The maximum bending angle was not affected by the driving temperature. This was because if the pressure was sufficiently large, the pleats could unfold completely and the angle was determined by the geometric shape. In the transient state, the pleats unfolded rapidly with a pressure fluctuation of approximately 3 kPa at 78 K and 295 K. General rubber-based soft actuators deform by utilizing the elasticity of the rubber material; therefore, slow deformation occurs with an increasing pressure. The fact that the bending angle changed with a low-pressure fluctuation indicated that the elasticity of the films was extremely low, and the stiffness and softness of the actuator were expected to be caused mainly by gas compressibility.

In addition, because the actuator stiffness was extremely low, the actuator did not return to its initial shape when the applied pressure was released, or a negative pressure was applied. Therefore, it can be considered that there was a difference in the bending angle when negative pressure was applied depending on the temperature. This phenomenon also occurs in other actuators with similar stiffness mechanisms. Such actuators are used in robots by limiting their use to cases where only positive pressure is required.

Additionally, a difference was observed in the pressure at which the pleats started unfolding with temperature. The difference was attributed to the drive in a closed pneumatic system using a syringe and the contraction of the working fluid owing to the temperature difference between the fluid and experimental environment, which is apparent from the Boyle-Charles law. The working fluid at the low-temperature side is compressed as the temperature decreases, and the pressure inside of the closed tube becomes negative. Because the actuator is driven based on this condition, the starting pressure of the actuator at low temperature is lower than that at room temperature. In addition, the reason for the angle not returning to 0° at low temperatures under negative pressure was considered to be the difference in the deformation resulting from the thermal contraction of the upper and lower PI films. Under negative pressure, the two films overlapped and deformed like a bimetal. At this time, the contraction of the upper film side was reduced in the pleat structure, and the initial state was mainly influenced by the contraction of the lower film.

6. Evaluation of the Generated Torque

The generated torque of the actuator was evaluated at 295 K and at a liquid nitrogen temperature of 78 K. The configuration of the torque evaluation experiment is shown in **Fig. 9**. The actuator to be evaluated was fixed to the stage of the evaluation device. The force of the tip was measured by pulling a copper wire attached to a load cell. The torque was calculated by multiplying the measured force by the distance of the joint center from the measurement point.

An enlarged schematic view of the area around the measurement point is shown in **Fig. 10**. A mass was attached to the end of the wire to remove the deflection of

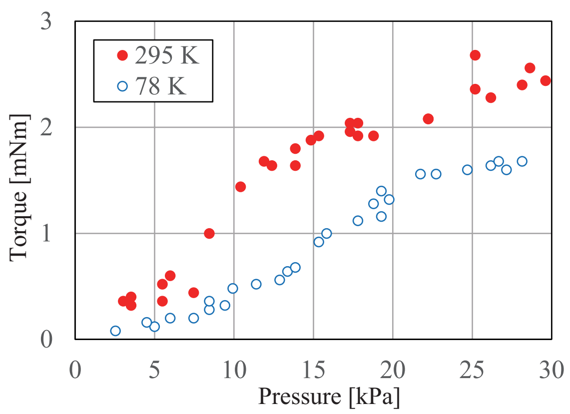


Fig. 11. Relationship between applied pressure and generated torque at different temperatures.

the wire and to reduce the nonlinearity of the output near the zero of the load cell. The actuator was connected to the wire in a straight manner. Only the torque generated at the central pleat was measured by fixing the welds on both sides of the central pleat. Because the soft actuator was too soft, the measurement was started after the pre-pressure was applied. Applying a constant pressure was difficult because the nitrogen gas recovered from the evaluation apparatus by the syringe was used as the working fluid. Thus, the generated force at the maximum applied pressure was measured.

The results of the measured torque at each temperature are shown in **Fig. 11**. The torque was 1.96 mNm when 30.1 kPa was applied at 78 K, and 2.76 mNm when 32.6 kPa was applied at 295 K. This torque difference is caused by a decrease in the drive pressure of the actuator compared to the 295 K part because of the thermal contraction of the drive gas in the low-temperature part. This is the same problem as the effect of temperature change in the bending angle experiment described above. These problems can be solved by realizing a constant pressure drive at a low temperature with a constant gas supply.

In the evaluation of responsiveness, the overall responsiveness is dependent on the feed rate of the syringe because it is slower than the response rate of the actuator. Therefore, the time difference between the measured pressure and torque is shown as the response in this experiment. The time difference was 0.11 to 0.16 s, depending on the applied pressure. In the future, it will be necessary to measure the step response (the relationship between applied pressure and torque) and determine the time constant of the actuator by realizing a high-speed switching valve that can be used in a cryogenic environment.

7. Conclusion

In this study, a soft actuator that can be driven in liquid nitrogen temperature environments was fabricated. The specifications of the prototype actuator are listed in

Table 1. Specifications of prototype actuator.

Specification	Value
Weight (without tube)	0.17 g
Length × Width	20 × 20 mm
Thickness (maximum)	100 µm
Bending angle (10.7 kPa, 78K)	35.0°
Torque (30.1 kPa, 78 K, One joint)	1.96 mNm
Delay of toruqe to pressure	0.11 − 0.16 s

Table 1. The actuator could bend at a bending angle of approximately 35° at 78 K. The generated torque of the actuator was 1.96 mNm when 30.1 kPa was applied at 78 K. The actuators cannot be driven at a constant pressure because the evaluation system uses only dried nitrogen gas recovered in a syringe. In addition, the temperature of the driving gas cannot be controlled. Therefore, an evaluation system will be developed to achieve an equilibrium state in a cryogenic environment, and the pneumatic actuator is evaluated and modeled.

In the present study, the actuator was evaluated only in a liquid nitrogen temperature environment; however, the actuator can be expected to fully utilize the high resistance of PI. In the future, the feasibility of such an actuator can be confirmed through drive tests under various extreme conditions. In addition, the shape of the actuator is a prototype and is not designed for a specific application. Therefore, we intend to study the design method of the actuator for the purpose of use and to expand the range of its application.

In addition, to realize the proposed actuator, a welding method for PI films was realized without employing pretreatment or using adhesives or additives. The welding method could be used to realize a PI gas chamber using a simple process, and this method could be applied to various other types of pneumatic actuators. Thus, the proposed method provides an epoch-making technology that can considerably improve the extreme environmental resistance of soft actuators. By applying this technology to soft actuators, a soft robot can be developed, which can be driven in an environment where human softness cannot be utilized.

A new robotics concept involving only actuators and structures made of film-like mechanical components has been conceptualized. It is called Filmotics, which is a compound of the words film and robotics. Filmotics involves extremely lightweight components that can be stored compactly when gas pressure is released. The fusion of PI welding technology and Filmotics is expected to facilitate the development of unique exploration devices, rescue robots, and spacecraft components.

Acknowledgements

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Main Works:

• T. Hanaki, D. Yamaguchi, Y. Ishino, M. Hara, M. Takasaki, and T. Mizuno, "Driving Performance of Soft Film Actuator for Liquid Nitrogen Temperature Environment," Proc. of the 19th Int. Conf. on Mechatronics Technology, C11, 2015.

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Membership in Academic Societies:

- The Japan Society of Mechanical Engineers (JSME)
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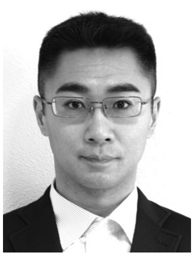

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Main Works:

- "Batch Manipulation of Submillimeter-Scale Particles in a Water-Filled Rectangular Container," IEEE/ASME Trans. on Mechatronics, Vol.22, No.1, pp. 412-421, 2017.
- "A Novel Rubber Hand Illusion Paradigm Allowing Active Self-Touch with Variable Force Feedback Controlled by a Haptic Device," IEEE Trans. on Human-Machine Systems, Vol.46, No.1, pp. 78-87, 2015.
- "Neurological and robot-controlled induction of an apparition," Current Biology, Vol.24, pp. 2681-2686, Nov. 2014.

Membership in Academic Societies:

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Main Works:

- "Active Type Surface Acoustic Wave Tactile Display," Trans. of the Society of Instrument and Control Engineering, Vol.42, No.4, pp. 327-333, 2006.

Membership in Academic Societies:

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- The Japan Society for Precision Engineering (JSPE)
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Main Works:

- "Controllability and Observability of Parallel Magnetic Suspension Systems," Asian J. of Control, Vol.18, No.5, pp. 1-15, doi: 10.1002/asjc.1263, Sep. 2016.

Membership in Academic Societies:

- The Institute of Electrical and Electronics Engineers (IEEE)
- The American Society of Mechanical Engineers (ASME)
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