**2025 IEEE World Haptics Conference (WHC)**
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

# Stiffness Control of Thermally Driven Actuator Using Phase Transition

Haruki Saito
*Dept. Applied Physics and Physico-Informatics*
*Keio University*
Yokohama, Japan
haruki.saito@keio.jp

Yukiko Osawa
*Dept. Applied Physics and Physico-Informatics*
*Keio University*
Yokohama, Japan
yukiko.osawa@keio.jp

***Abstract*—This paper proposes a method for controlling the stiffness of a thermally driven actuator by leveraging the phase transition of a low-boiling-point liquid. Using a Peltier device for cooling, the reduction in actuator stiffness can be precisely adjusted. Experiments demonstrated the actuator's effectiveness, particularly in handling fragile objects with precision, ensuring delicate interactions with contact surfaces. Since stiffness is adjusted within a safe temperature range, this approach shows promise for applications involving direct human contact, such as the outer surfaces of social robots (robot skin).**

***Index Terms*—Soft actuator, variable stiffness, thermally driven actuator, phase transition, temperature control**

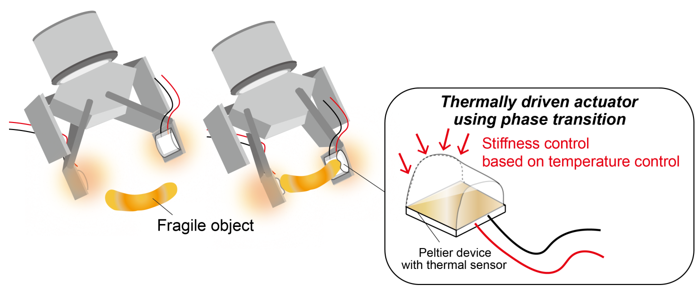


Fig. 1. Proposed thermally driven actuator using phase transition.

## I. Introduction

Human interfaces (devices that connect humans and machines and enable mutual information communication) play a significant role in human-machine coordination technology. In particular, devices that come into direct contact with humans need to meet many requirements [1], such as low rigidity and physical safety. Soft robots that meet these requirements are applied mainly to rehabilitation aids, prosthetics, human augmentation devices, and tactile interfaces [2]. The operation of these robots developed in soft robotics requires a sensor that reads information about the external environment and an actuator that converts the power into force using the received information. Actuators commonly used are broadly classified into pneumatic actuators that use compressed air for movement [3]–[5], hydraulic actuators that use compressed fluid for movement, and electric actuators that use electric current or magnets for movement [6].

Among these, a thermally driven actuator that uses the phase transition of a low-boiling-point liquid has been developed to combine the soft characteristics of a pneumatic actuator and the high torque of a hydraulic actuator. As Fig. 1 shows, the actuation mechanism is that the sample, which is initially in a liquid state, is heated by a heater to induce a phase transition from liquid to gas, thus generating pressure. The actuator is characterized by using a liquid with a relatively low boiling point as the sample and using a soft membrane. This enables actuation in a temperature range and stiffness that are safe for human contact and is being studied for application in wearable devices, mainly as rehabilitation equipment. The mechanotherapy glove proposed by Celebi et al. incorporates a thermally driven actuator that can be used to treat muscle fatigue and sensory therapy [7]. Other studies have been conducted to use this actuator as a device to assist in flexion and extension of the fingers [8].

This work was supported by JSPS KAKENHI Grant Number 25K03157.

Thus, thermally driven actuators play an important role in the field of human interface. However, there are several problems that have not yet been solved. One of them is that cooling methods for actuators have not been established. Many previous studies on thermally driven actuators have used textile heaters with metalized fibers to heat actuators. Therefore, once the actuator is activated, the on-off cycle of the actuator takes a long time because it requires air cooling to return to its initial state. In fact, in the experiment conducted by Celebi et al. [7], one cycle took 500 seconds, and in the experiment conducted by Garrad et al. [9]. It was shown that it takes at least 20 seconds for both heating and cooling. Therefore, it can be said that thermally driven actuators currently have limited applications due to their slow response. Therefore, if the actuator can be cooled immediately by some method, the response of the actuator will be improved, and the range of applications will be expanded accordingly.

Another problem is that of actuator control. Thermally driven actuators utilize the phase transition from liquid to gas, which requires high stability in controlling the actuator temperature. However, the previous studies mentioned so far have focused only on current control due to the use of textile heaters for heating, and not much attention has been paid to the aspect of temperature control, as well as to the control

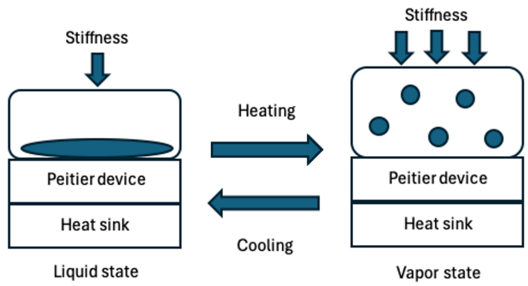


Fig. 2. Schematic model of the proposed thermal-driven soft actuator.

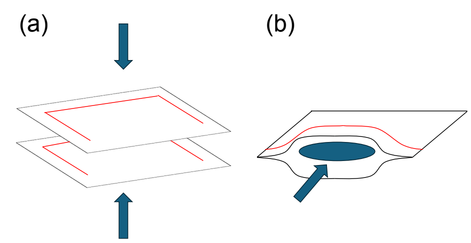


Fig. 3. Making process of the actuator: (a) seal two sheets using a heat sealer (b) the liquid is injected into the actuator.

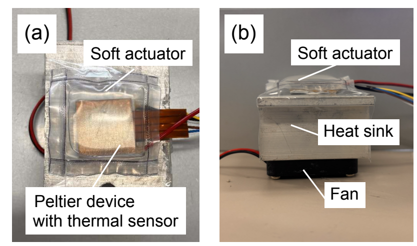


Fig. 4. Appearance of actuator: (a) upper side (b) side view.

of stiffness produced by the actuator. If precise temperature control and stiffness control of actuators can be achieved, further applications are expected to expand.

In response to these problems, this paper proposes a thermally driven actuator with a cooling function implemented by using a Peltier device and also proposes precise temperature control and stiffness control of the actuator by using a heat disturbance observer (HDOB). These proposals aim to solve conventional problems of responsiveness and control.

## II. The Operating Principle of the Thermal-Driven Actuator

Thermal-driven actuators utilize some means to heat low-boiling-point organic solvents, harnessing the pressure generated during the phase transition from liquid to gas for actuation [7]–[10]. A schematic representation of the proposed actuator is shown in Fig. 2.

As shown in Fig. 2, the proposed actuator comprises a Peltier device, a heat sink located beneath it, and a bag sealed with a low-boiling-point liquid sample on its upper side. In the initial state of the actuator, the sample inside the bag remains in a liquid state, and the actuator exhibits almost no rigidity. When heat is applied to the actuator, the sample inside the bag is heated, causing its temperature to rise. Once the temperature of the liquid sample reaches its boiling point, the heat supplied to the actuator facilitates the liquid-to-gas phase transition, gradually vaporizing the sample. This phase transition increases the pressure inside the bag, changing the actuators stiffness.

As discussed in Section I, prior studies have proposed the use of textile heaters made by weaving metalized fibers into the fabric instead of the Peltier devices [7], [9], [11]. In this method, electrical circuits are connected to the textile heater, and voltage is applied to generate an electric current. The Joule heat produced by the heater is then used to heat the actuator. While this approach enables actuator heating, it has been noted that the cooling method is limited to air cooling, which presents a significant drawback in conventional studies. Consequently, once the actuator is heated, it takes a long time to return to its initial state.

In contrast, the method proposed in this study employs a Peltier device instead of a heater, enabling both heating and cooling of the actuator. To activate the actuator, a positive current is passed through the Peltier device, whereas a negative current can be applied to return the actuator to its initial state. This dual functionality allows for a reduction in the on-off cycle time of the actuator.

In summary, the operating principle of this actuator is that heating and cooling are performed via temperature control using a Peltier device, and as a result, the stiffness of the actuator is controlled. The purpose of the paper is to improve the accuracy of stiffness control by enhancing the precision of temperature control.

## III. Device Development

### A. Material Selection for Each Component

This study used polyethylene (PE) sheets to fabricate the expansion bag of the proposed soft actuator. Polyethylene is a material with excellent heat-sealing properties, making it suitable for use in thermal-driven actuators.

Regarding the low-boiling-point liquid, we used Noah 5112, a product of Zhejiang NOAH Fluorochemical. Noah 5112 is a fluoroketone compound with excellent non-flammability and a boiling point of 49.2 C. This relatively low boiling point allows the heated vapor phase to remain at a temperature that feels warm but is safe for human contact.

### B. Fabrication Procedure of the Actuator

1) As shown on the left side of Fig. 3, two polyethylene sheets, each cut into 3 cm squares, were stacked together, and three sides (indicated by the red lines) were sealed using a heat sealer.
2) As shown on the right side of Fig. 3, 0.2 mL of the sample liquid was injected through the unsealed side using a syringe.
3) The unsealed side was then sealed to complete the fabrication of the bag portion of the actuator.
4) The bag was placed on top of the Peltier device, and heat-dissipation silicone was applied between the bag

and the heat sink for enhanced thermal conductivity. The bag and the device were then bonded together.

The appearance of the actuator fabricated through this process is shown in Fig. 4.

## IV. Robust temperature control

A Peltier device is a device that utilizes the thermoelectric effect to perform both heating and cooling and is commonly used in small cooling systems and thermal sensation transmission devices [12]. In thermal systems employing a Peltier device, it is typical to insert temperature or heat flux sensors between the target object and the Peltier device. Additionally, a heat sink or an air-cooling fan is generally attached to the surface of the Peltier device that is not in contact with the target object to dissipate heat efficiently.

When a current $I$ is applied to the device, the Peltier effect induces a cooling effect, and the amount of heat absorbed per unit of time ($q_{pe}$) is given by the following equation.

$$q_{pe} = -\alpha T_c I. \tag{1}$$

Here, $\alpha$ and $T_c$ denote the Seebeck coefficient and temperature of the Peltier device (cooling surface in this case), respectively. Additionally, the negative sign in Eq. (1) represents heat absorption; reversing the direction of the applied current reverses the cooling and heating surfaces of the device.

However, in practice, the actual heat absorption is influenced by additional factors: Joule heat $q_j$, generated by the current passing through the electrical resistance of the element, heat flow $q_{con}$, caused by thermal conduction due to the temperature difference between the cooling and heating surfaces, heat flow $q_a$, caused from the temperature difference between the cooling surface and the soft actuator surface. Consequently, the actual heat absorption of the device is expressed as:

$$\begin{aligned} q_p &= q_{pe} + \frac{1}{2}R_e I^2 + \frac{1}{R_p}(T_h - T_c) + \frac{1}{R_a}(T_a - T_c) \\ &= q_{pe} + q_j + q_{con} + q_a. \end{aligned} \tag{2}$$

Here, $R_e$, $R_p$, $R_a$, $T_h$, $T_c$, $T_a$ denote the electrical resistance, the thermal resistance of the Peltier device and the soft actuator, the temperature of the cooling and heating surfaces of the Peltier device and the soft actuator, respectively. The factor $\frac{1}{2}$ in $q_j$ accounts for the Joule heat being distributed between the cooling and heating surfaces.

Using the analogy between thermal and electrical phenomena, thermal resistance can be likened to electrical resistance, thermal capacitance to electrical capacitance, and temperature and heat flow to voltage and current, respectively. This allows thermal phenomena to be analyzed using an equivalent electrical circuit [12]–[14]. The equivalent circuit of the thermal system, created based on the analogy, is shown in Fig. 5.

From these factors, Joule heat generated within the element and heat from contact with the target object act as nonlinear disturbance heat flows, which introduce noise into the temperature control process in the temperature control of the Peltier device. To tackle this issue, various methods have been proposed for nonlinear control of Thermo-Electric Modules (TEMs), including sliding mode control based on changes mapped onto a 3D state space [10] and control methods using microreactors grouping multiple elements [8].

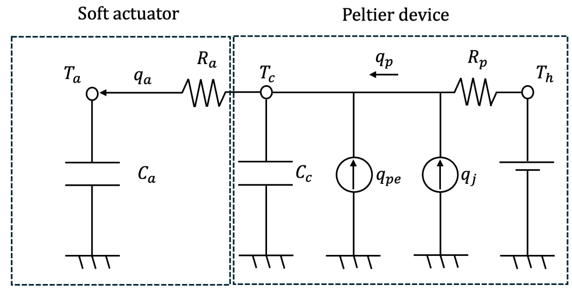


Fig. 5. Equivalent circuit of a thermal system using thermal and electrical analogies.

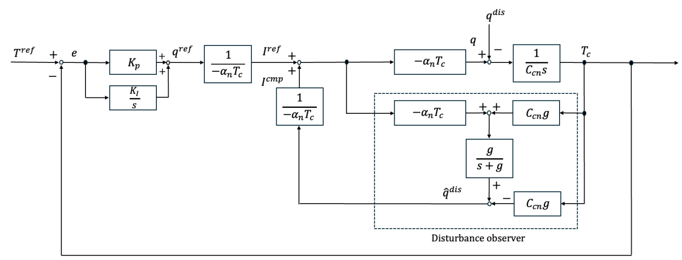


Fig. 6. Block diagram of the temperature control system using HDOB.

This study employs a heat disturbance observer (HDOB), which applies the concept of a disturbance observer to thermal systems [12], [15], [16] to linearize the Peltier device simply. The disturbance observer estimates disturbances by comparing the nominal input to the system with the response processed through the inverse system.

In the proposed system, the nonlinear heat flows are assumed to disturbance $q^{dis}$ as

$$\begin{aligned} q_p &= q_{pe} + q_j + q_{con} + q_a \\ &= q_{pe} + q^{dis}. \end{aligned} \tag{3}$$

The current compensation value calculated from the HDOB is given as:

$$I^{cmp} = \frac{1}{-\alpha_n T_c}\hat{q}^{dis}. \tag{4}$$

Here, $I^{cmp}$ represents current compensation, the subscript $n$ indicates nominal values, and $\hat{q}^{dis}$ represents the estimated disturbance heat flow. The temperature control system of the Peltier device using the HDOB is represented as shown in Fig. 6. Here, $g$, $s$ denotes the cut-off frequency of the low-pass filter and the Laplace operator. The low-pass filter is included to prevent amplification of high-frequency components. From the current compensation, the robust temperature control for stiffness regulation of the proposed actuator can be realized. The effectiveness of the control system is assessed in the following experiments.

TABLE I
PARAMETERS USED IN THE EXPERIMENTS.

| Parameter | Value |
|---|---|
| $K_p$ | 1.0 |
| $K_I$ | 0.02 |
| $g_{sen}$ | $2.0 \times 3.14 \times 5.0$ |
| $g_{dis}$ | $2.0 \times 3.14 \times 0.01$ |
| $\alpha_n$ | 0.023 |
| $C_n$ | 2.0 |

## V. EXPERIMENT

### A. Experiment 1: Cooling effect for the actuation

The proposed actuator leverages a Peltier device, enabling both heating and subsequent cooling. This design is expected to improve the responsiveness of restoring the actuator to its initial state compared to conventional methods. To validate this, an experiment was conducted to compare the time response of the actuators output under two conditions: (1) heating only (conventional heater system) and (2) heating followed by cooling. The experimental procedure is as follows:

1) A setpoint of $+30$ °C relative to room temperature was applied from 5 to 60 seconds after the start of the experiment.
2) In the first trial, the Peltier device was controlled to prevent current flow during the subsequent 60 seconds. In the second trial, a setpoint of $-10$°C relative to room temperature was applied for 60 seconds.
3) From 120 seconds onward, the actuator temperature was controlled to match the room temperature in both trials.
4) The force generated by the actuator was recorded using a force gauge, and the time response of the force was plotted and compared.

The parameters of the control system used in the experiments are summarized in Table I.

The time response of the force generated by the actuator, with and without cooling, is plotted in Fig. 7, and the states of the actuator in the case of heating up (ON) and turning heat off (OFF) are shown in Fig. 8.

From Fig. 7, in the two trials without cooling, the actuator generated a force of approximately 6.2 N and required about 15 seconds to return to its initial state after heating. In contrast, in the two trials with cooling, the actuator generated a force of approximately 6.8 N and required only about 9 seconds to return to its initial state after heating. Thus, the cooling functionality reduced the time for the actuator to cool down and reset by approximately 6 seconds, corresponding to a reduction of 40 %.

These results indicate that the proposed actuator achieves improved responsiveness by implementing the cooling function using a Peltier device compared to conventional actuators.

However, even when the temperature response of the actuator was similar, the force response did not necessarily align. Regarding this, we will address it through a thermal control approach moving forward.

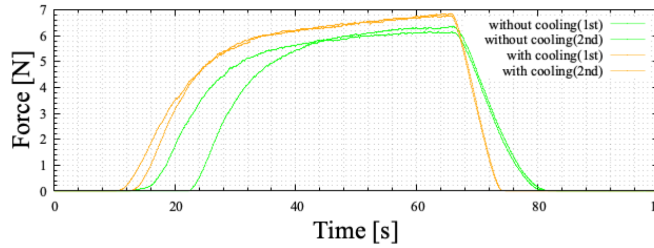


Fig. 7. Comparison of actuator performance with and without cooling.

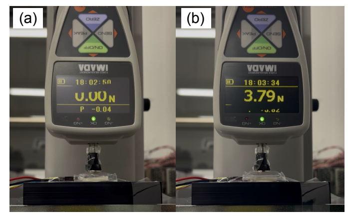


Fig. 8. State of the actuator: (a) turning heat off (OFF) (b) heating up (ON).

### B. Experiment 2: Effect of the Heat Disturbance Observer

The temperature setpoints were applied to the actuator as described below, and the time response of the force exhibited by the actuator was recorded using a force gauge.

1) The current command to the element was set to 0 for the first 5 seconds of the experiment, and no control was applied.
2) From 5 seconds to 305 seconds (300 seconds in total), the temperature of the Peltier device was controlled to maintain a relative temperature of $+40$C compared to room temperature.
3) From 305 seconds onward, the temperature setpoint was decreased by 2 C every 60 seconds until the final setpoint reached $+30$ C relative to room temperature.
4) The first experiment was conducted with the compensation of the HDOB, while the second was conducted without the HDOB compensation.

Note that the graphs are displayed with the time axis set to zero at 305 seconds after the start of the experiment. The force exhibited by the actuator, as shown in Fig. 9, indicates a decrease in stiffness after the temperature setpoint begins to decrease, with the rate of change remaining nearly constant. Here, Fig. 9 focuses on the decline from the peak force while ignoring the differences in peak force between trials.

From Fig. 9, examining the force reduction from the peak in relation to the presence or absence of the HDOB compensation reveals that in the trials with the HDOB, the force decreased by approximately 5.7 N, whereas in the trials without HDOB, the reduction was limited to approximately 7.2 N. Moreover, the variability in force change per 2 C temperature reduction was larger in the trials without HDOB.

The changes in force ($\Delta F$) at each stage of temperature reduction, as derived from Fig. 9, are summarized in Table II.

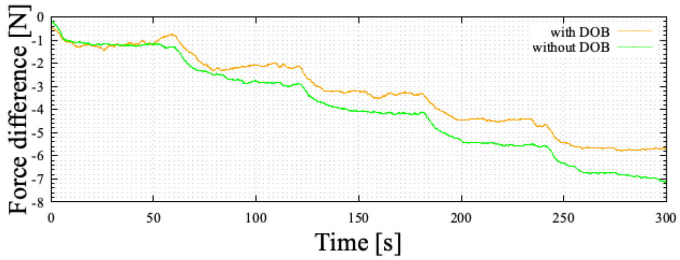


Fig. 9. Time response of force.

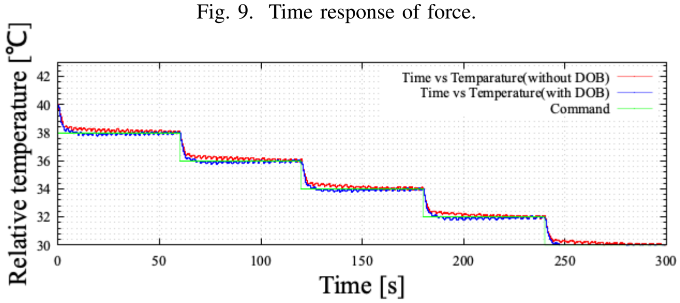


Fig. 10. Time response of temperature.

TABLE II
COMPARISON OF FORCE CHANGES $\Delta F$ WITH AND WITHOUT HDOB DURING TEMPERATURE REDUCTION.

| Temperature Change () | $\Delta F$(N, w/ HDOB) | $\Delta F$(N, w/o HDOB) |
|---|---|---|
| 4038 | -1.0 | -1.2 |
| 3836 | -1.3 | -1.6 |
| 3634 | -1.0 | -1.3 |
| 3432 | -1.2 | -1.3 |
| 3230 | -1.1 | -1.4 |
| Mean Value | -1.12 | -1.34 |
| Variance | 0.0113 | 0.0220 |

This phenomenon can be attributed to differences in the accuracy of temperature control for the Peltier device depending on the presence or absence of HDOB compensation. In the absence of the HDOB, the temperatures ability to follow the command is poorer, resulting in greater variability in the force reduction rate. To illustrate this, Fig. 10 presents the time response of temperature for each trial. From Fig. 10, it can be observed that the temperature closely follows the command in the presence of the compensation of the DOB. In contrast, the temperature fails to track the command adequately without HDOB compensation.

### *C. Experiment 3: Grasping objects with a robot gripper equipped with the soft actuator*

As an application of the proposed actuator, this study focuses on delicate object grasping using a robot gripper. To securely grasp fragile objects with the gripper, it is essential to precisely control the grip angle, the opening/closing speed, force, etc. When transitioning from handling robust objects to fragile ones, these parameters must be adjusted accordingly, making the process highly complex and labor-intensive.

By integrating the proposed actuator into the robot gripper and controlling its stiffness, it becomes possible to smoothly

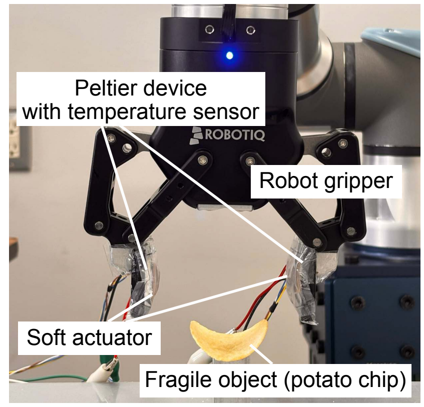


Fig. 11. The state of the actuator attached to a robot gripper.

transition from a state suitable for grasping robust objects to one optimized for delicate objects without a rich robotic controller. This simplifies the operation significantly while enhancing adaptability.

The grasping experiment was conducted according to the following procedure:

1) The proposed soft actuators were attached to both fingers of the robot gripper (Fig. 11). Due to the size of the gripper, it was challenging to attach a heat sink, so this experiment was conducted without using heat sinks.
2) A temperature command of +40 C relative to room temperature was applied to the actuators for 300 seconds. At the 270-second mark, a potato chip (fragile object) was grasped by the gripper(grasping with a high-stiffness soft actuator).
3) A command of +25 C relative to room temperature was applied to the actuators for the subsequent 300 seconds. At the 270-second mark, a potato chip was grasped again by the gripper(grasping with a low-stiffness soft actuator).

In this experiment, a heat sink was not attached to the gripper, as it was physically difficult to do so.

The time response of the actuators temperature and temperature command value are shown in Fig. 12. Additionally, the images capturing the gripper grasping a potato chip under the two temperature conditions40 C and 25 C setpointsare presented in Fig. 13.

From Fig. 12, it was confirmed that the temperature control of the actuator was generally accurate. Furthermore, from Fig. 13, it was observed that the gripper failed to grasp the potato chip when the actuators temperature was high, resulting in high stiffness. In contrast, successful grasping occurred when the actuators temperature was low, resulting in reduced stiffness to envelop objects. In other words, the proposed actuator can adjust its stiffness to match the grasped object, enabling delicate movements without the need for precise position/force control or force sensors. These experimental results demonstrate that the proposed actuator facilitates delicate object handling with a robot gripper, making it easier to grasp fragile objects effectively. The primary aim of the

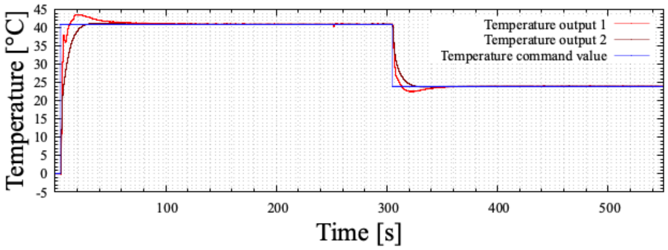


Fig. 12. Temperature responses of the Peltier devices.

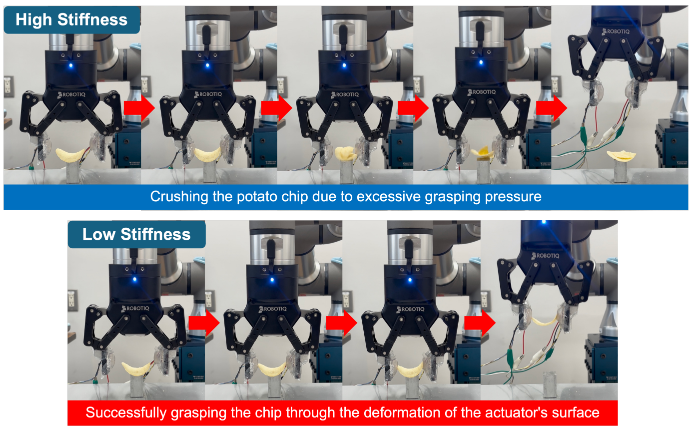


Fig. 13. Grasping a fragile object with the proposed actuator.

present paper is to introduce the design of a new actuator and demonstrate its application. Detailed evaluations of stiffness control accuracy and gripping performance are planned for future work.

## VI. Conclusion

In this study, we proposed a thermal-driven soft actuator using low-boiling-point liquids to improve responsiveness and enable stiffness control through temperature regulation. Experimental results revealed that introducing a Peltier device as the heating and cooling mechanism significantly reduced the time required for the actuators on-off cycle compared to previous studies. Additionally, the use of a disturbance observer for thermal control improved the accuracy of temperature regulation.

Furthermore, we successfully demonstrated that changing the actuators temperature command allowed for stiffness modulation, thereby simplifying the process of object grasping with a robot gripper. These findings highlight the advantages of the proposed actuator over existing solutions in various aspects.

However, precise stiffness control remained challenging. This limitation is likely due to the complexity of the physical model involving phase transitions and the simplicity of the control strategy. In this study, stiffness control was based on the assumption of a simple linear relationship between temperature and force. The actual phase transition model is more complex, suggesting that more accurate system identification is necessary to achieve precise control.
As demonstrated in Experiment 1, the temperature response of the actuator does not always correspond to the force response, with heat flux dynamics identified as a contributing factor. This finding suggests that incorporating a correction term based on heat flux into the temperature control system could improve the accuracy of stiffness control.

Future research will focus on developing more precise stiffness control methods, aiming to enhance the utility of the proposed actuator in soft robotics applications. This will contribute to making the actuator a more effective tool in advanced robotic systems.

## References

[1] Y. Osawa, I. Ogura, and A. Kheddar, "Robot soft thermal display using self-heating and cooling system," *Case Studies in Thermal Engineering*, vol. 63, p. 105328, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214157X24013595

[2] M. Zhu, S. Biswas, S. I. Dinulescu, N. Kastor, E. W. Hawkes, and Y. Visell, "Soft, wearable robotics and haptics: Technologies, trends, and emerging applications," 2022.

[3] E. M. Young, A. H. Memar, P. Agarwal, and N. Colonnese, "Bellowband: A pneumatic wristband for delivering local pressure and vibration," in *IEEE World Haptics Conference*. IEEE, 2019, pp. 55–60.

[4] K. T. Yoshida, C. M. Nunez, S. R. Williams, A. M. Okamura, and M. Luo, "3-dof wearable, pneumatic haptic device to deliver normal, shear, vibration, and torsion feedback," in *IEEE World Haptics Conference*, 2019, pp. 97–102.

[5] F. E. v. Beek, Q. P. I. Bisschop, and I. A. Kuling, "Validation of a soft pneumatic unit cell (puc) in a vr experience: A comparison between vibrotactile and soft pneumatic haptic feedback," *IEEE Transactions on Haptics*, vol. 17, no. 2, pp. 191–201, 2024.

[6] U. E. Ogenyi, J. Liu, C. Yang, Z. Ju, and H. Liu, "Physical human-robot collaboration: Robotic systems, learning methods, collaborative strategies, sensors, and actuators," *IEEE Transactions on Cybernetics*, vol. 51, 2021.

[7] M. F. Celebi, Z. Beler, E. Dede, E. D. Kocak, O. Atalay, A. T. Atalay, and V. Gazi, "Textile-based thermally driven actuators for soft robotic mechanotherapy applications," in *International Conference on Control, Decision and Information Technologies*, 2022.

[8] S. Kawahata, M. Deng, and K. Takahashi, "Nonlinear water temperature control experiment for microreactor group actuated by peltier devices," in *International Conference on Advanced Mechatronic Systems*, 2014.

[9] M. Garrad, G. Soter, A. T. Conn, H. Hauser, and J. Rossiter, "Driving soft robots with low-boiling point fluids," in *IEEE International Conference on Soft Robotics*, 2019.

[10] T. Hatano, M. Deng, and S. Wakitani, "Operator and sliding mode based nonlinear control for cooling and heat-retention system actuated by peltier devices," in *International Conference on Advanced Mechatronic Systems*, vol. 2015-October, 2015.

[11] V. Sanchez, C. J. Payne, D. J. Preston, J. T. Alvarez, J. C. Weaver, A. T. Atalay, M. Boyvat, D. M. Vogt, R. J. Wood, G. M. Whitesides, and C. J. Walsh, "Smart thermally actuating textiles," *Advanced Materials Technologies*, vol. 5, 2020.

[12] H. Morimitsu and S. Katsura, "A method to control a peltier device based on heat disturbance observer," in *IECON Proceedings (Industrial Electronics Conference)*, 2010.

[13] S. Lineykin and S. Ben-Yaakov, "Modeling and analysis of thermoelectric modules," *IEEE Transactions on Industry Applications*, vol. 43, 2007.

[14] Y. Osawa, H. Morimitsu, and S. Katsura, "Control of thermal conductance with detection of single contacting part for rendering thermal sensation," *IEEJ Journal of Industry Applications*, vol. 5, no. 2, pp. 101–107, 2016.

[15] H. Morimitsu and S. Katsura, "Two-degree-of-freedom robust temperature control of peltier device based on heat disturbance observer," *IEEJ Transactions on Industry Applications*, vol. 131, 2011.

[16] Y. Osawa and S. Katsura, "Variable heat disturbance observer for control of peltier device," *IEEJ Journal of Industry Applications*, vol. 8, no. 2, pp. 185–191, 2019.