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Laser HaPouch: Modeling and Implementation of Laser-driven Liquid-to-gas Phase Change Actuator Arrays for Haptic Displays

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***Abstract*— Liquid-to-gas phase change actuators are pneumatic actuators that utilize liquid-to-gas phase transitions for actuation and have attracted attention as high-output, wirelessly driven actuators whose actuation is directly induced by heating. In this study, we propose a shape-changing haptic display that can be fabricated through computer-controlled processes, utilizing actuator arrays of liquid-to-gas phase change actuators arranged on a two-dimensional plane. The developed automated fabrication system enables high-precision fabrication of actuator arrays with diverse geometric patterns, such as grid and honeycomb types, from design patterns. Furthermore, we constructed a system capable of independent control of each pouch-type actuator through selective wireless driving using CO_2 lasers and galvanometer scanners. This allows users to safely perceive shape deformation through direct touch. We also constructed a theoretical model of polygonal actuators and established a method for calculating the minimum liquid volume for arbitrary shapes. Through pressure distribution measurement experiments, we demonstrated that the system can generate approximately 7.4 N of force per actuator and achieve selective driving without affecting neighboring actuators. This research provides a new approach to shape-changing haptic displays that require fewer components and offer excellent scalability.**

I. INTRODUCTION

In virtual reality, augmented reality, and robotics systems, providing haptic feedback in addition to visual or auditory information is crucial for achieving more effective human-machine interaction and immersive experiences. Grounded haptic displays [1], [2], [3], [4], which provide tactile experiences through physical shape changes of objects, are devices capable of delivering haptic feedback through object deformation. Unlike wearable haptic devices [5], [6], these displays do not require users to wear any equipment. This removes the need for physical attachment and reduces the sensation when worn, enabling more natural sensory experiences. Therefore, such devices have attracted attention for providing user-friendly haptic experiences. However, conventional pin-array type shape-changing haptic displays [7], [8], [9] face challenges such as high manufacturing costs due to numerous components, difficulty in scaling to large areas, and low safety when users experience impacts due to their high rigidity.

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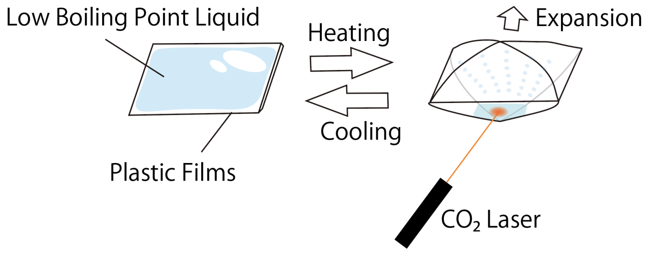

Fig. 1: Principle of the liquid-to-gas phase change actuator used in our method. The pouch expands by heating the liquid inside the pouch with laser light.

In response to these issues, shape-changing haptic displays using soft actuators [10], [11], [12] have been studied in recent years. Soft actuators integrate actuation and mechanism, resulting in relatively fewer components and simpler mechanisms. Additionally, their low rigidity and structural safety against impacts enable them to potentially provide more user-friendly haptic experiences. However, soft actuators having small energy density have difficulty achieving sufficient output pressure. Furthermore, conventional electrical or pneumatic actuation methods require wiring or tubing, thereby limiting wireless operation and presenting scalability challenges similar to those encountered in traditional pin-array haptic displays. To overcome these limitations, it is essential to develop soft actuators capable of wireless driving that also deliver high output performance.

Liquid-to-gas phase change actuators [13], [14], [15] meet such requirements. Liquid-to-gas phase change actuators generate force by vaporizing an enclosed liquid through heating and are characterized by high power density. In particular, pouch-type liquid-to-gas phase change actuators [16] have easy fabrication methods, making it possible to create relatively free-form shapes, and they are expected to be applied to computer-controlled automated manufacturing. Uramune et al. proposed a very lightweight wearable haptic device by driving these actuators using Peltier elements [17]. However, the device requires electrical power for operation, making wireless actuation difficult, and it lacks extensibility such as arranging multiple units for large-area implementation. On the other hand, Hiraki et al. proposed a method for remotely heating liquid-to-gas phase change actuators using CO_2 lasers; however, this technique has not been applied to haptic displays [18].

In this study, we propose a shape-changing haptic display that can be manufactured through computer-controlled automated processes, combining actuator arrays of liquid-to-gas phase change actuators arranged on a two-dimensional plane with selective driving using CO_2 lasers (Fig. 1). By adopting a CO_2 laser as the driving method, the wireless operation of actuators becomes possible, and eliminating wiring to each cell enables highly scalable actuator arrays. Furthermore, by controlling the laser irradiation position, individual actuators can be selectively driven, enabling the generation of complex haptic patterns. Additionally, by developing an automated fabrication system using XYZ tables and soldering iron-based heat sealing, liquid-to-gas phase change actuator arrays in various shapes can be manufactured under computer control. Since the power source and driving mechanism are physically separated, arrays with different arrangements or shapes can be actuated without changing the driving system. We proposed the basic concept of laser-driven liquid-to-gas phase change actuator arrays in our previous work [19], however it remained at the conceptual level without detailed design methods or quantitative performance evaluation. In this work, we advance this concept and address technical challenges toward practical implementation.

This paper presents the design and fabrication methods of liquid-to-gas phase change actuator arrays and a wireless actuation method. Actuation speed and output force are evaluated by measuring pressure distribution during operation. In addition, polygonal actuators are modeled based on existing pouch-type actuator models, and the minimum liquid volume is calculated. We apply these analytical results to the design of actuator arrays that are manufacturable through computer-controlled automated processes. In summary, the main contributions of this research are as follows:

- Proposal of a shape-changing haptic display using liquid-to-gas phase change actuator arrays
- Development of an automated fabrication system for liquid-to-gas phase change actuator arrays using heat sealing-based patterning
- Modeling of polygonal liquid-to-gas phase change actuators and calculation of their minimum liquid volume
- Evaluation of actuation speed, driving force, and achievable spatial resolution of actuator arrays through pressure distribution measurements

II. METHOD

In this study, we developed a novel haptic display system that combines liquid-to-gas phase change actuator arrays with selective driving using CO_2 lasers. The system consists of two key components: (1) a selective wireless driving system using CO_2 laser and galvanometer scanner, and (2) an automated fabrication method for liquid-to-gas phase change actuator arrays through computer control.

A. Laser Driving System

The basic concept of the proposed system is shown in Fig. 2. The system achieves wireless driving through selective thermal projection using CO_2 laser light on liquid-to-gas phase change actuators that are driven by heating and phase change of low-boiling-point liquid sealed in plastic films.

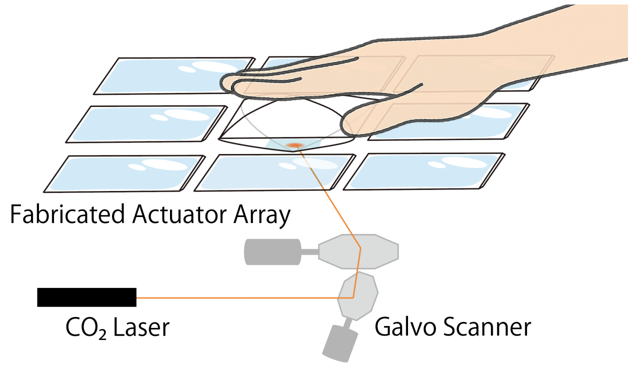

Fig. 2: Conceptual diagram of the proposed system. CO_2 laser light is controlled by a galvanometer scanner to selectively drive liquid-to-gas phase change actuator arrays for haptic rendering.

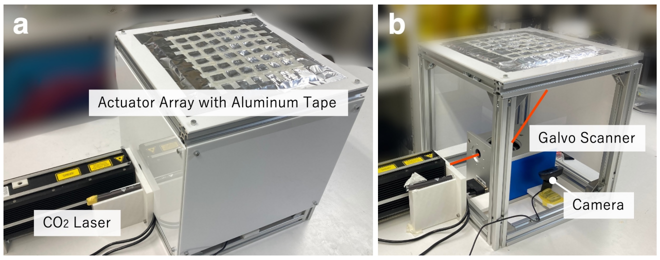

Fig. 3: Structure of the proposed haptic display system. (a) External view: 3D-printed frame and liquid-to-gas phase change actuator array mounted on top of aluminum frame. White acrylic panels form the enclosure for safety. (b) Internal structure: Galvanometer scanner and web camera enable precise control of laser irradiation position for selective wireless driving.

As the working fluid, we used low-boiling-point liquid Novec 7000 (3M Company) with a boiling point of 34 °C. This liquid has been used in previous studies [18] and is chemically stable with confirmed safety for human contact. Additionally, it has high absorption efficiency for the CO_2 laser at 10.6 μm wavelength, enabling efficient conversion of laser energy to thermal energy. The low boiling point minimizes the energy required for driving and prevents overheating, ensuring safety even when users directly touch the system.

The specific configuration of the system is shown in Fig. 3. The system uses a rectangular structure based on an aluminum frame (Misumi) with various devices mounted on it. A CO_2 laser (48-1, SYNRAD, 30W output) is fixed to the outside of the frame, while a web camera (C310n, Logicool) and galvanometer scanner (JD2808, Sino-Galvo Technology) are fixed inside the frame. A 3D-printed support frame is placed on top, on which liquid-to-gas phase change actuator arrays fabricated using the method described below are installed.

Although the laser light is controlled to irradiate only

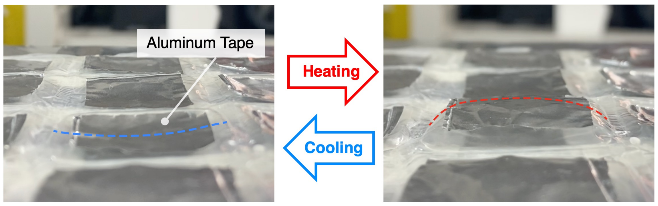

Fig. 4: Liquid-to-gas phase change actuator during operation. The plastic film deforms due to vaporization and expansion of the sealed liquid by laser heating. Aluminum tape prevents direct contact with laser light.

the liquid-to-gas phase change actuator arrays, for safety considerations, aluminum tape (3M Company) is attached to the support frame and the upper surface of the actuator arrays that users contact to block the laser light. Furthermore, the entire system is enclosed with white acrylic panels to enclose the system to prevent beam leakage. Control of the laser irradiation position is achieved through coordination between a pre-calibrated web camera and galvanometer scanner. This enables selective driving of individual actuators as shown in Fig. 4.

B. Automated Fabrication System for Liquid-to-Gas Phase Change Actuator Arrays

The liquid-to-gas phase change actuator arrays consist of low-boiling-point liquid (Novec 7000, 3M Company) sealed in plastic films (Nylon-Poly B-type standard bags, Fukusuke Kogyo, thickness: 70 μm). While previous studies employed manual fabrication using heat sealers [16], this study developed a new computer-controlled automated fabrication system to arrange actuators of various geometric shapes with high precision and consistency.

The system consists of a modified 3D printer (Ender3, Creality) with a soldering iron attached to the nozzle section for XYZ table control (Fig. 5). The soldering iron tip was polished to optimize contact area, and PTFE-coated glass

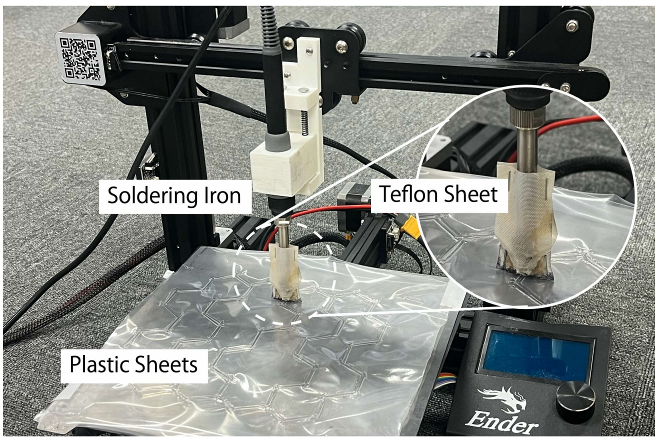

Fig. 5: Configuration of the automated fabrication system. A soldering iron is attached to the head of a modified 3D printer to precisely execute heat-sealing patterns through XYZ table control.

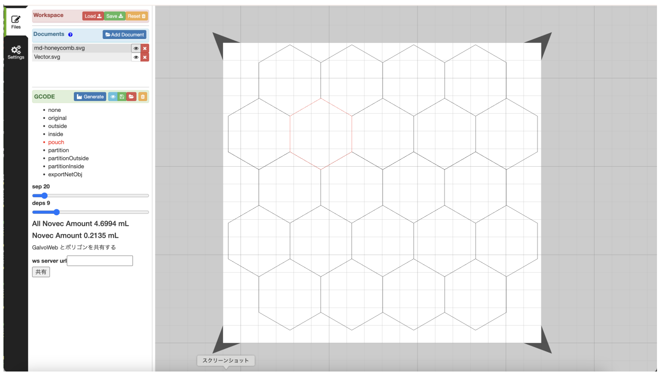

Fig. 6: Automated fabrication control software. Analyzes heat-sealing patterns from SVG files and automatically calculates XYZ table control programs and liquid encapsulation volumes.

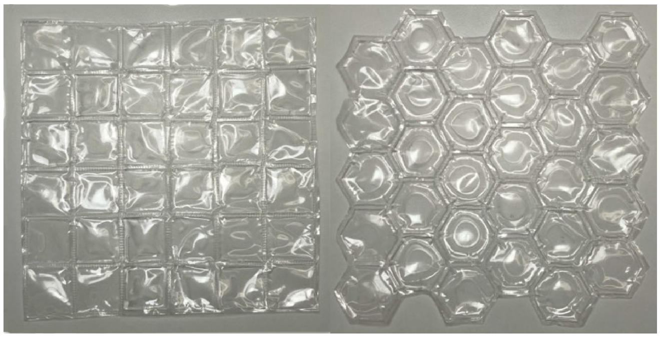

Fig. 7: Examples of fabricated liquid-to-gas phase change actuator arrays. Various geometric patterns such as grid and honeycomb types can be realized as defined by SVG files.

cloth for heat sealing was attached to prevent plastic film adhesion. The fabrication conditions were set to a soldering iron temperature of 200 °C and movement speed of 2 mm/s.

The control software was newly developed based on laser processing software LaserWeb (Fig. 6). This software analyzes polygonal patterns from user-created SVG files and provides the following functions:

- Generation of heat-sealing programs for bag formation before liquid injection
- Generation of heat-sealing programs for sealing after injection
- Automatic generation of 3D objects for support frames
- Calculation of minimum liquid encapsulation volume through geometric analysis

The fabrication procedure for liquid-to-gas phase change actuator arrays is as follows:

1) Pattern design using SVG files
2) XYZ table operation program generation by control software
3) Execution of heat-sealing for bag formation
4) Precise injection of low-boiling-point liquid using syringes
5) Execution of heat-sealing for sealing

Fig. 7 shows various liquid-to-gas phase change actuator arrays fabricated with this system. The system can accommodate diverse geometric patterns such as grid and honeycomb.

III. MODELING OF POLYGONAL SHAPES

In this study, we derive equations to calculate the minimum amount of low-boiling-point liquid to be encapsulated from the pattern information of designed liquid-to-gas phase change actuator arrays, and theoretically calculate the minimum amount by solving these equations. From previous studies [16], [20], the minimum amount of low-boiling-point liquid $V_{l,min}$ used in rectangular pouch-type liquid-to-gas phase change actuators (Fig. 8a) is expressed by the following equation based on the ideal gas law:

$$V_{l,min} = \frac{M}{\rho}\frac{P}{RT}V_{max} \tag{1}$$

where R is the universal gas constant, M is the molar mass of the low-boiling-point liquid, and ρ is the density of the low-boiling-point liquid, all of which are constants. T is the temperature inside the pouch, P is the gas pressure, and V_{max} is the volume when the pouch-type liquid-to-gas phase change actuator is maximally inflated. For temperature T, we set the boiling point of Novec 7000, which is 34 °C, and for gas pressure P, we set the desired pressure value to be achieved. Here, from previous studies [20], the continuous volume $V(\theta)$ of pouch-type actuators can be expressed using cross-sectional area A as follows:

$$V(\theta) = AD = \frac{L^2 D}{2}\left(\frac{\theta - \cos\theta\sin\theta}{\theta^2}\right) \tag{2}$$

where D is the long side of the rectangle and L is the short side.

However, to realize liquid-to-gas phase change actuator arrays with diverse geometric patterns, it is necessary to support polygonal shapes other than rectangles. In this study, we extend this equation for polygonal shapes, calculate the volume for each pouch and sum them to obtain the maximum volume of the pouch array, and use this to calculate the minimum encapsulation amount of low-boiling-point liquid.

First, we find the minimum bounding rectangle that can cover the target polygon and consider the form where this rectangle covers the target polygon. Let the length of the long side of the minimum bounding rectangle be D_r, place this on the x-axis, and place the short side on the y-axis. Fig. 8b shows an example of this operation performed on a hexagonal pouch-type actuator. Through this operation, by defining the length of the polygon in the y-axis direction at any x-coordinate as $l(x)$, the cross-sectional area $A'(x,\theta)$ of the pouch-type actuator becomes as follows from Eq. (2):

$$A'(x,\theta) = \frac{l(x)^2}{2}\frac{\theta - \cos\theta\sin\theta}{\theta^2} \tag{3}$$

Since the volume $V'(\theta)$ of the pouch-type actuator is the value obtained by integrating $A'(x,\theta)$ with respect to x, it becomes as follows:

$$V'(\theta) = \frac{\theta - \cos\theta\sin\theta}{2\theta^2}\int_0^{D_r} l(x)^2 dx \tag{4}$$

Also, since $V'(\theta)$ is maximized when $\theta = \frac{\pi}{2}$, the maximum volume $V'_{\max}$ of the pouch-type actuator is expressed by the following equation:

$$V'_{\max} = \frac{1}{\pi}\int_0^{D_r} l(x)^2 dx \tag{5}$$

The length $l(x)$ in the y-axis direction at x for an n-sided polygon on the coordinate plane can be divided into $n-1$ regions $t_k \le x \le t_{k+1}$ on the x-axis, and becomes a linear function in each region as follows:

$$\begin{gathered} 1 \le k \le n-1 \quad (k \in \mathbb{N}) \\ 0 = t_1 \le t_2 \le \cdots \le t_k \le \cdots \le t_{n-1} \le t_n = D_r \\ \text{where} \\ l(x) = a_k(x - t_k) + l_k \quad \{x \mid t_k \le x \le t_{k+1}\} \end{gathered} \tag{6}$$

Here, if $l(t_k) = l_k$, then a_k is always as follows:

$$a_k = \frac{l_{k+1} - l_k}{t_{k+1} - t_k} \tag{7}$$

From Eqs. (5), (6), and (7), the following equation is derived through calculation:

$$\begin{aligned} V'_{\max} = &\frac{1}{\pi}\sum_{k=1}^{n-1}(t_{k+1} - t_k) \\ &\times \left\{\frac{1}{3}(l_{k+1} - l_k)^2 + l_k(l_{k+1} - l_k) + l_k^2\right\} \end{aligned} \tag{8}$$

Since the parameters t_k and l_k of this equation can be calculated geometrically by a program, the maximum value of the volume of pouch-type actuators can be computed. By calculating the total value for liquid-to-gas phase change actuator arrays, the minimum encapsulation amount of low-boiling-point liquid can be obtained from Eq. (1). We incorporated a program that automatically calculates the minimum amount of low-boiling-point liquid obtained in this way into the aforementioned software. Note that, similar to previous studies [17], in practical use, approximately twice the calculated minimum encapsulation amount of liquid is encapsulated to consider driving stabilization and leakage during encapsulation.

To verify the validity of the theory constructed in this study, we examine the case of rectangles. The calculated Eqs. (3), (4), and (5) become $t_1 = t_2 = 0$, $t_3 = t_4 = D_r$

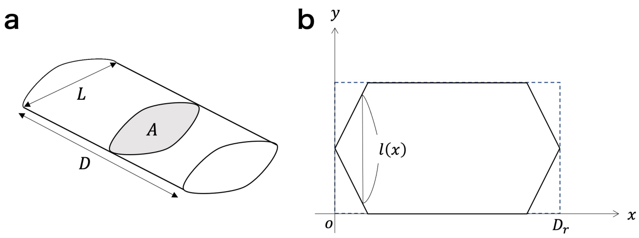

Fig. 8: (a) Schematic diagram of rectangular pouch-type actuator, (b) Hexagonal pouch-type actuator on coordinate plane and its minimum bounding rectangle (dashed line)

when the target is rectangular, and thus can be confirmed to be the same as Eq. (2).

Similar to previous studies, since we calculate by geometrically modeling pouch-type actuators as shown in Fig. 8a, there are edges that are not closed in the z-axis direction when expanded to form a three-dimensional structure. However, since actual pouch-type actuators have all edges closed by heat sealing, an error occurs between the actual volume and the calculated volume in the model. However, since this error is considered small compared to the overall volume, its impact is thought to be negligible for practical purposes.

In the calculation process, it is necessary to find the minimum bounding rectangle of the target pouch shape, but this can be calculated efficiently. For convex polygons, the minimum bounding rectangle always shares an edge with some edge of the target figure, so it can be found by examining all edges, and the required computational complexity is $O(n)$ where n is the number of points in the target polygon. For concave polygons, since it always shares an edge with a line connecting some vertex to vertex, the computational complexity becomes $O(n^2)$ by examining all vertex pairs. Also, when the target figure is rectangular, the minimum bounding rectangle is congruent to the target figure, and $V'_{\max} = V_{\max}$ holds.

IV. EVALUATION

To evaluate the selective driving performance of our method, we conducted pressure distribution measurement experiments. We selectively drove the liquid-to-gas phase change actuator arrays by selectively irradiating CO_2 laser light and measured the pressure using a high-sensitivity touchpad. The experimental setup is shown in Fig. 9.

A touchpad (Sensel Morph, Sensel) capable of acquiring pressure distribution was fixed above the haptic display with its pressure-sensitive surface facing toward the display to measure the pressure generated by the expansion of the liquid-to-gas phase change actuators. For the actuator array pattern, we used a grid arrangement of square liquid-to-gas phase change actuators with 25 mm sides. The ambient temperature of the experimental environment was 30 °C. The distance between the pressure-sensitive surface and the liquid-to-gas phase change actuator array was set to 4 mm. We raster-scanned the CO_2 laser over two actuators at different positions.

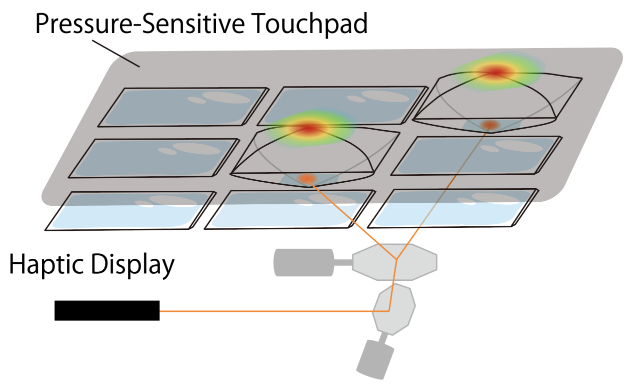

Fig. 9: Conceptual diagram of the pressure distribution measurement experiment setup. Liquid-to-gas phase change actuators expanded by heating exert pressure, which is measured by a high-sensitivity touchpad installed directly above.

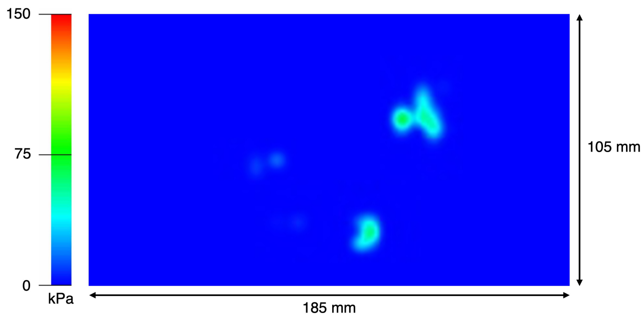

Fig. 10: Results of pressure distribution measurement. The pressure distribution covers 105 mm vertically and 185 mm horizontally, with each pixel corresponding to an actual 1 mm^2. Pressure information from 0 Pa to 150 kPa is converted to colors for display.

As a result of the measurements, we obtained the pressure distribution shown in Fig. 10. The pressure distribution covers 105 mm vertically and 185 mm horizontally, with each pixel corresponding to an actual 1 mm^2. The upper limit of displayable pressure was set to 150 kPa, and the pressure applied to each pixel is represented by converting it to corresponding colors. The maximum pressure value in these results was 70.6 kPa, and the average pressure on the touchpad was 0.8 kPa; the area in contact with the touchpad that recorded pressures of 15 kPa or more was 310 mm^2 in total, corresponding to 155 mm^2 per pouch. When we calculated the total output force by integrating this data, it was 14.8 N, resulting in an output of approximately 7.4 N per actuator. From the measured pressure distribution, we can observe that pressure appears as small hill-like shapes corresponding to the number of liquid-to-gas phase change actuators that received thermal irradiation. Although liquid-to-gas phase change actuators exist in all eight directions around the target actuators (up, down, left, right, upper-right, upper-left, lower-right, and lower-left), as can be seen from the pressure distribution diagram, no cases were observed where neighboring actuators were unintentionally driven due to the thermal effects required for driving.

The output measured in this study is significantly larger compared to many existing wearable haptic devices and can be evaluated as capable of presenting forces that humans can clearly perceive. According to previous studies [21], [22], the typical output of grounded pneumatic haptic devices ranges from 10 N to several dozen kPa, and the 70.6 kPa measured in this study is positioned in the range of this spectrum, demonstrating sufficient performance. Therefore, we confirmed that the proposed haptic display can provide sufficient haptic feedback for human perception while enabling selective driving of individual liquid-to-gas phase change actuators for haptic rendering.

V. DISCUSSION

A. Design Flexibility and Wireless Actuation

A key characteristic of our method is that the automated fabrication system for liquid-to-gas phase change actuator arrays enables the arrangement of actuators with relatively flexible shapes across a two-dimensional plane. Additionally, the selective wireless actuation using laser light creates a physical separation between the power source and actuation mechanism, eliminating the need to modify hardware for different actuator geometries. This capability opens up possibilities for easily designing and implementing various actuator array configurations beyond the grid and honeycomb patterns shown in Fig. 7, tailored to specific applications.

For instance, honeycomb patterns can generate larger forces and displacements compared to grid patterns while maintaining the same area and resolution. Triangular tessellation patterns (three-scale type) may offer advantages in terms of continuity between adjacent actuators and stress distribution. By combining such geometric configurations, it becomes possible to develop tactile displays specialized for specific use cases and enable the development and mass production of soft robots, thereby expanding the application range of liquid-to-gas phase change actuators.

The critical achievement is that our method accelerates the prototyping process for complex-shaped liquid-to-gas phase change actuator arrays. Moving forward, establishing design principles for actuator arrays suitable for flexible, large-area tactile displays represents an important challenge.

B. Actuator Displacement Limitations

The displacement capability of tactile displays constitutes a crucial factor for both visual and tactile effects on users. While pouch-type liquid-to-gas phase change actuators can generate substantial forces, their displacement output faces structural constraints as demonstrated by theoretical models [20]. The vertical displacement (height direction), which is particularly important for tactile displays, is limited by the planar structure of pouch-type actuators [17], creating different constraints compared to planar expansion.

Simply enlarging individual actuators to achieve larger displacements would degrade the spatial resolution of the tactile display. As discussed above, establishing design principles for actuator arrays represents a critical element toward solving this problem, though alternative approaches focusing purely on displacement enhancement are also conceivable.

Potential strategies include using stretchable plastic films to increase actuator displacement or fabricating bellows-type liquid-to-gas phase change actuators instead of conventional pouch-type structure. Furthermore, hybrid tactile displays combining multiple geometric patterns could achieve regions with high displacement alongside areas of high resolution.

For computer-controlled, automatically fabricated actuator arrays, determining how to generate high displacements while utilizing various geometric patterns and how to control such systems remains an open challenge. Leveraging the design flexibility of our method, developing actuator array patterns with optimal displacement-resolution balance according to specific applications will be a crucial element for future advancement.

C. Safety

The optical safety of our system is ensured through a multi-layered approach. First, laser irradiation is restricted to the central portion of each liquid-to-gas phase change actuator through software control, preventing unintended exposure to other areas. In addition, even if laser light were to reach unintended locations, physical shielding using aluminum frames and aluminum tape effectively prevents direct leakage. For scattered light, the energy is sufficiently attenuated to pose no safety concerns. The low-boiling-point liquid (Novec 7000) used in our system has also been employed in numerous previous studies [15], [18], [16] with confirmed safety, and its low boiling point of 34 °C minimizes overheating risks.

However, the overheating risk of the aluminum tape itself cannot be neglected. The tape is the portion that users can directly touch and may be exposed to the laser beam. For instance, if the laser continuously targets a single point, the liquid inside the actuator can completely evaporate, leading to potential overheating at the contact surface. Implementing real-time temperature monitoring of the haptic interface and establishing a corresponding feedback control mechanism will further enhance safety and practical usability.

D. Toward Closed-Loop System Integration

The current prototype functions as an open-loop actuation platform that demonstrates fabrication scalability and selective laser-driven inflation. The next step could be to evolve this system into a closed-loop haptic interface while maintaining a fully non-contact sensing and control scheme. A possible layered architecture may consist of (i) non-contact sensing of temperature and deformation, (ii) state estimation based on coupled thermal–mechanical modeling, and (iii) actuation control through laser modulation and targeting. Such a hierarchy could enable more precise deformation control, improved thermal safety management, and robust operation under user interaction and environmental variations.

For sensing, optical and magnetic field–based methods could be explored to infer actuator inflation and surface deformation states without direct physical contact. Infrared thermography may provide spatially resolved thermal feedback, while monitoring magnetic field perturbations caused by embedded or external magnetic markers could be utilized to estimate local displacement and contact-like events. Previous research has demonstrated contact detection with users and actuator shape control based on such information using magnetic sensors [10] and silver nano-ink [23]. These non-contact approaches could eliminate the need for physical wiring or embedded sensors, thereby preserving the mechanical simplicity and scalability of the platform. Building on these findings, our approach could implement mechanisms that detect user behavior and provide feedback to laser control through coordination with surface sensing technologies. Based on such feedback, adaptive optimization of laser irradiation points and intensities may become feasible, potentially enabling coordinated thermal actuation among multiple laser sources and scalable tactile rendering across large arrays.

Future evaluation could include dynamic response characterization (rise time, repeatability, and actuation bandwidth) and user studies to quantify perceptual thresholds and validate this non-contact haptic rendering performance. Through this progression, the system is expected to evolve from a component-level demonstration toward a fully integrated, contact-free tactile display platform with closed-loop control and scalability.

VI. CONCLUSION

In this study, we proposed a printable shape-changing haptic display that combines liquid-to-gas phase change actuator arrays with selective wireless driving using CO_2 lasers. We developed an automated fabrication system using soldering iron-based heat sealing, which enables the fabrication of actuator arrays with diverse geometric patterns such as grid and honeycomb types from SVG files, replacing conventional manual fabrication methods. The system achieves selective wireless driving of individual actuators without wiring through CO_2 laser control using a galvanometer scanner.

We established mathematical modeling of polygonal liquid-to-gas phase change actuators and developed a geometric calculation method for determining the minimum liquid encapsulation volume for arbitrary polygonal shapes. This enables automated liquid volume calculation and array design during the design phase. Through pressure distribution measurement experiments, we demonstrated that the system can generate approximately 7.4 N of force per actuator while achieving selective driving without unintended activation of neighboring actuators caused by thermal effects. This output falls within the range of conventional haptic devices and can provide sufficient haptic feedback that humans can clearly perceive. Compared to conventional pin-array haptic displays, our method requires fewer components and achieves excellent scalability through the physical separation of power source and actuation mechanism enabled by wireless driving.

Future work will focus on increasing displacement capability and safety, and on integrating real-time sensing for temperature and displacement monitoring. We plan to validate the practical utility of the system in real applications through user studies.

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