A Multimodal Haptic Interface for Simultaneous Softness and Thermal Modulation

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Abstract. Haptic interactions, such as touching an object in virtual reality, involve detecting a plethora of sensations through the skin. Whilst tactile displays exist to simulate and manipulate all of these cues individually, little progress has been made constructing devices that can control multiple cues simultaneously. This paper presents a tactile display technology that offers both softness and temperature change.
A prototype display, based on particle jamming and the thermal transfer of heated and cooled water is evaluated in terms of its ability to change both stiffness and temperature. Mechanical evaluations demonstrate controllable stiffness increase of 300%, whilst thermal characterisation demonstrated strong surface uniformity and heat output of up to 39 °. This work advances the design of multimodal tactile displays with applications to perceptual research, medical simulation, and affective haptics.

Keywords: Soft haptics · Thermal haptics · Tactile displays

1 Introduction

Variable stiffness surfaces are becoming increasingly important for creating realistic haptic interactions in VR and medical simulation. Rapid technical advances have been enabled by advances in soft robotics techniques. Softness changing haptics have wide-ranging applications, from wearable haptic suits devices for enhancing entertainment experiences [13, 2] to simulation-based training for medical procedures and examinations with realistic soft tissues [24, 4]. Softness may be approximated via impedance control of haptic robots, emulating force-deformation properties of compliant materials [**?**], by directly altering the properties of a surface or device to change its compliance [23], or a combination of the two [17].

Particle jamming is becoming an increasingly popular technology for creating tactile displays that can alter their softness. In a jamming system, granular media which are normally highly malleable, may be stiffened by compressing their volume, causing the individual particles to brace against each other, or 'jam', thereby creating the appearance of a solid mass [10]. Jamming has been applied to haptic surfaces that can change their softness to influence user interaction [8], retain their shape after being moulded by a user [18], or simulate palpation in medical training [15]. It has also been applied to gloves [19] and exosuits [2], to restrict movement by stiffening the joints in these wearable devices. Particle jamming has also been proposed as a mechanism for creating 'remote touch' - perceiving solid objects buried in granular media [7], as well as a basis for multimodal cutaneous interfaces that can leverage the adaptability of jamming technology as a medium for generating other cutaneous sensations [5]. This has become possible with the advent of fully mechanical jamming technologies that do not rely on airtight containers or pneumatic systems [4].

Whilst softness has many important applications in haptics, it is just one of many cutaneous sensations that enable humans to perceive the world via touch [12]. Thermal sensations resulting from changes in skin temperature also play an important and varied role, from warning of danger due to the skin burning or freezing, to playing a more nuanced role in multisensory cutaneous experiences such as perceiving wetness [3], or discriminating between physical materials based on the rate with which skin temperature changes [11]. Such cues can even influence the 'pleasantness' of different tactile experiences [1]. Thermal sensations have also been shown to influence the other senses via crossmodal correspondences, such as the associations between colour and temperature (red-hot, blue-cold) [22]. Thermal cues can be generated in a number of ways, including directly using thermoelectric Peltier modules [20], via convection using heated and cooled air [21] or water [16], or through radiation via infrared light [14].

With these applications in mind, there is a strong motivation for creating tactile display technology capable of producing both softness and thermal sensations simultaneously. Such a device could be used to simulate thermal properties of vascular disease in medical schools, or the varying stiffness and thermal emissivity of different materials in a VR simulation. This paper presents a novel multimodal surface that integrates constrictive particle jamming with a fluidic thermal skin. Key contributions are: a demonstration of how pump-free jamming can mediate otherwise incompatible technologies; a mechanical design that optimizes thermal transfer without compromising jamming compliance; and an experimental characterisation of the device's performance.

2 Hardware design

2.1 Softness

Softness change is achieved using particle jamming, and specifically the constrictive approach described in [4], whereby particles are held in a fabric container which is twisted from one end, exerting radial forces on the fluid in all directions and causing it to jam. The implementation used for the prototype described here departed from the earlier design in that it used a circular shape to improve the uniformity of the jamming effect (which was previously reported as being harder in the centre than the corners) as well as being larger, with a 150 mm diameter and 60 mm depth. It is constructed in a 3D printed plastic frame produced in PLA plastic using the '0.2 mm strength' profile on a Bambu Lab P1S 3D printer. To account for the larger volume of particles, a more powerful Maxon EC90 brushless DC motor with a nominal torque output of 1.26 Nm and stall torque of 9.95 Nm was selected as an actuator. A Maxon EPOS4 70/15 controller was used to provide closed-loop torque control, enabling faster and more accurate control of the display's stiffness.

2.2 Temperature

Thermal feedback is provided by a thin silicone skin attached to the top surface of the jamming container. This is made from silicone and cast in two sections. Channels to route the fluid through the skin are cast in a sheet from SmoothOn Dragon Skin 10 FAST, and attached to a touch surface, made from a composite of Dragon Skin 10 FAST and copper powder (mesh size 325 μm) at a 60:40 ratio by mass. The copper composite layer provides a more thermally conductive interface between the temperature controlled liquid and a user's finger, and the pure silicone insulates the relatively larger thermal mass of the particle fluid.

The liquid temperature is controlled by a custom control unit based on a 100 W Peltier module (Model ET-161-12-08-E, European Thermal Dynamics, UK) with two 40 mm × 40 mm copper water blocks used to transfer heat into and out of the water in a closed-loop design. A switch valve directs either hot or cold water to the thermal skin to adjust its temperature. The system is controlled by an Arduino Giga R1 Wifi microcontroller running a PID control-loop based on feedback from Amphenol 10 kΩ thermistors placed on the bottom of the thermal skin. The system is shown in Figure 1.

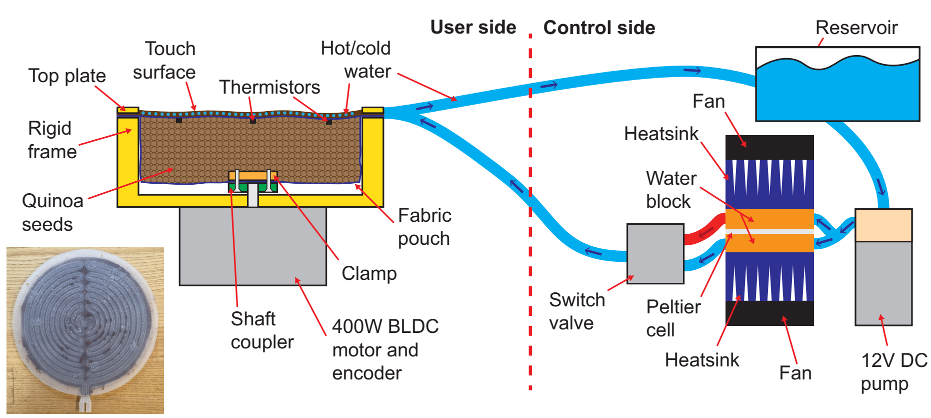

Fig. 1. Schematic view of the mechanical and hydraulic components of the combined softness and temperature changing tactile display. Insert: The cast silicone skin with fluid channels visible.

3 Performance and characterisation

The performance of the device was characterised in terms of both the range of its achievable softness change, and the range and consistency of its achievable surface temperature.

3.1 Softness

The softness of the device was assessed as the initial contact stiffness, since particle jamming systems are known to be actuated by the large contact force that would be incurred by measuring bulk stiffness [6]. To generate and measure small contact forces, a digital force gauge (Shimpo FGV-1Z, capacity 5 N, sampling rate 20 Hz) with an 8 mm flat circular indenter was suspended above the tactile display from a linear motion stage. This was then driven into the surface by the motion stage, up to a contact force of 4 N. This setup is shown in Figure 2 (left). Stiffness was calculated as the average force-displacement gradient over the 0.5-1 N range, simulating initial contact with a finger.

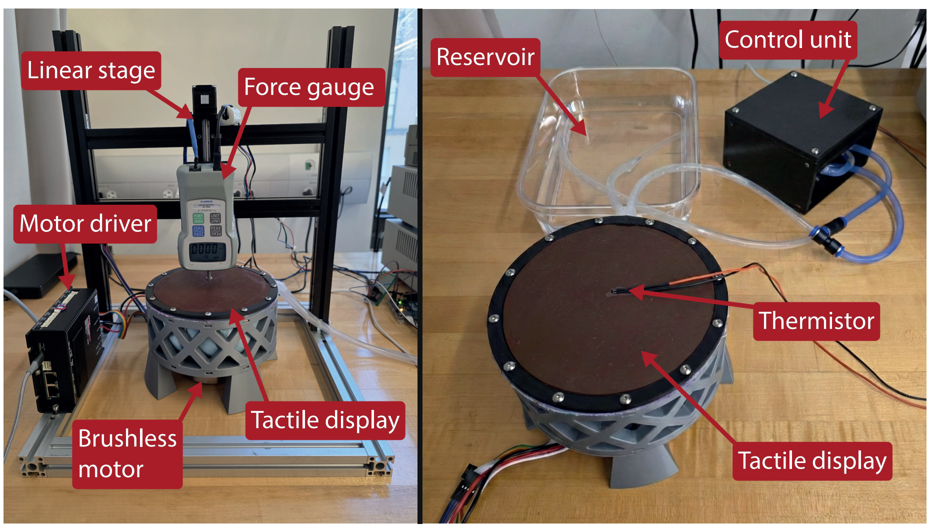

Fig. 2. Apparatus and setup used for initial contact stiffness (left) and temperature (right) measurement

Stiffness of the display was measured as a function of motor torque (via closed-loop current control) from 0-2 Nm in increments of 0.2 Nm.

3.2 Temperature

The tactile display's achievable temperature range was assessed by passing water through the cold-side of the temperature controller at maximum power (no temperature control). Temperature change over time was recorded with an Amphenol 10 kΩ thermistor attached to the top surface. Measurements were taken every 0.25 seconds and the lowest stable temperature recorded as a minimum temperature. The maximum temperature was then tested by taking water from the hot-side of the controller and again recording temperature over time. The setup is shown in Figure 2 (right).

Finally, surface uniformity was measured with a thermal camera (Fluke Ti125, IR resolution 120 $\times$ 160), throughout each test and at the minimum and maximum temperatures.

4 Results

The results of the characterisation experiments are described below.

4.1 Softness response

The display exhibited an average minimum stiffness of 0.63 N/mm in its unjammed state. Average hysteresis in this state was 84%. Stiffness then increased very linearly at an average *stiffness sensitivity* of 0.00164 mm^{-2} [3] up to 1 Nm (2.27 Nm, hysteresis 10.4%). Stiffness then remained broadly level with increasing torque, increasing to only 2.38 Nm at the maximum 2 Nm torque. Hysteresis however continued to decrease broadly exponentially, reaching 2.1% at the maximum torque. Stiffness was broadly consistent across repeated measurements, though with particularly low variance at high torque (0.00016). Hysteresis deviation was consistently low except in very soft states. The full stiffness results are shown in Figure 3.

4.2 Thermal response

When heated at full power, the display warmed to a moderate temperature of approximately 25 °in 58 seconds before the rate of warming decreased. A maximum temperature of 39.0 °was achieved in 35 minutes. There was a very small drop in temperature at the beginning of the test due to water circulating the display before being heated. When chilled, the display temperature dropped rapidly to 20.2 °in 59 seconds, before rising slowly to 23.2 °. All thermal measurements were taken at an ambient temperature of 21.6 °. These results are shown graphically in Figure 4.

The display temperature was generally uniform during heating, with a central line of lower temperature (up to 2 °below the rest of the display) due to the arrangement of channels in the silicone skin. There was very little observable temperature difference between water channels ($<$0.5 °). The display was slightly warmer ($<$2 °) near the inlet, but then remained consistent. Due to the limited overall temperature change, uniformity was not assessed in the cold condition. Thermal images of the display during heating are shown in Figure 5.

[3] Stiffness sensitivity is defined as the change of stiffness with respect to torque. Although unintuitive, mm^{-2} is the simplified form of $\frac{\text{N/mm}}{\text{Nmm}}$.

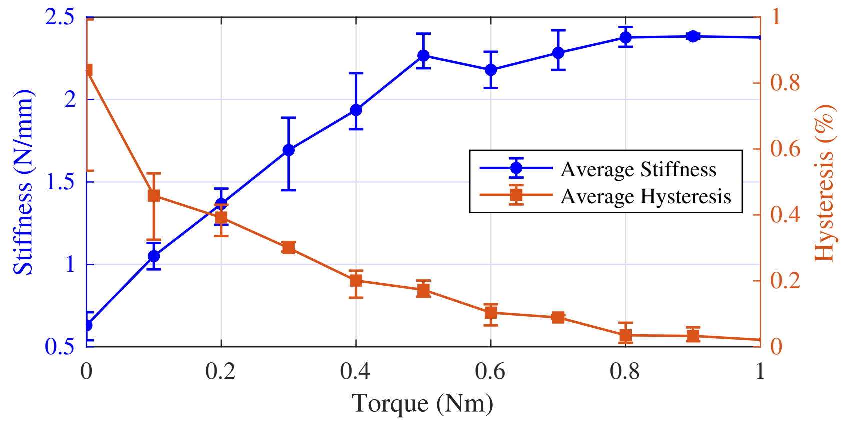

Fig. 3. Stiffness and hysteresis of the display under different motor torques. Error bars represent the highest and lowest values observed across repeated measurements.

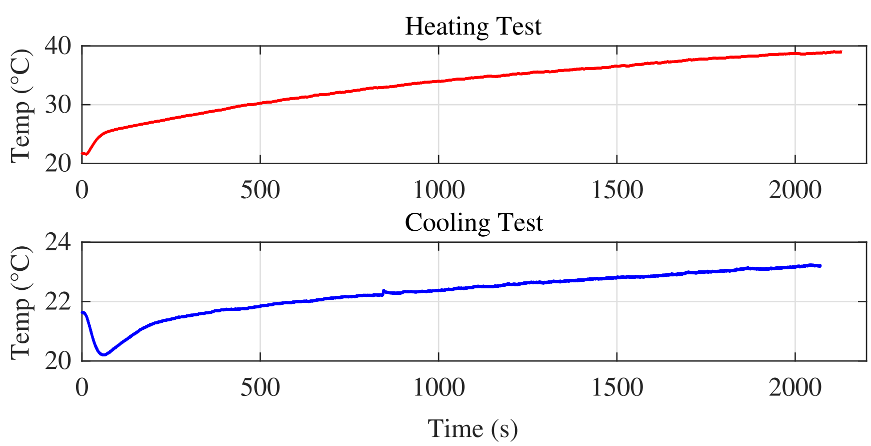

Fig. 4. Graphs of temperature change over time with heated and chilled water

5 Discussion

The prototype demonstrated a good range of achievable stiffness. The stiffness measure selected, initial contact stiffness, is more susceptible to the low surface stiffness of the thermal skin, but was needed to avoid manual actuation of the jamming effect. Stiffness was also highly controllable, with consistent responses to torque in the 0-1 Nm range. Hysteresis was initially high due to the elasticity of the thermal skin being able to build potential energy when depressed into the softer jamming substrate, but reduced quickly and was consistent throughout. As a haptic interface, this would have a noticeable effect on tactile sensation [25].

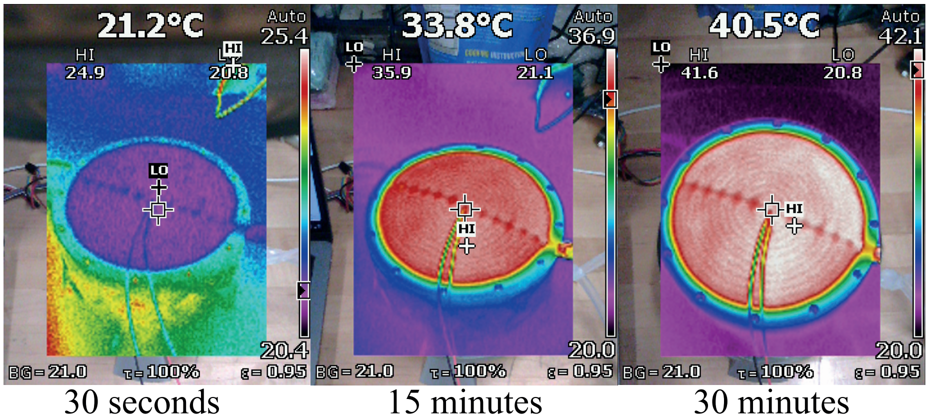

Fig. 5. Thermal images of the display during during warm-up and at its maximum temperature

Thermal performance indicated that there were several limitations. The display initially demonstrated good performance in heating, with surface temperature rising quickly to a moderate level. The rate of increase then slowed substantially. Whilst the maximum achievable temperature demonstrated a useful range, it was slow to reach higher temperatures. Possible reasons for this include heating a large volume of water in the reservoir, causing energy loss, and the relatively large area of the display. A larger Peltier element and closed water loop may improve this performance in the future. Cooling was broadly ineffective. Future iterations of the technology will improve heat dissipation at the thermoelectric element to improve this.

Surface uniformity was generally very good, with little evidence of the water losing energy as it flowed through the thermal skin. Temperature was also generally consistent above and between channels, indicating that the copper-silicone composite was effective in conducting heat. There was no evidence of significant heat loss to the jamming substrate, indicating that the non-composite silicone was effective at concentrating heat transfer to the display.

5.1 Future work

Future work will seek to improve response rate by reducing the overall thermal mass of the system and moving to a more powerful thermoelectric element. Cooling performance will also be improved by better dissipating heat from the thermoelectric element.

Scientific work will be able to apply the new interface to address known challenges in the creation of multisensory experiences, as well as to investigate crossmodal correspondences involving both softness and temperature. Such experiences include medical simulation, where softness, heat and cold are important indicators of infection, malignancy, and vascular disease, as well as affective haptic experiences that benefit from softness and warmth. Scientific investigations will explore the crossmodal perception of haptic interactions, such as the recognition of physical materials by their compliance and thermal emissivity or the interaction of softness, temperature and weight - a variation of Weber's Illusion [9].

6 Conclusion

This work demonstrates that particle jamming can be used as a foundation for multimodal tactile interfaces that can combine otherwise incompatible technologies to produce multiple distinct sensations simultaneously. This is evidenced through the combination of softness- and temperature-change in a desktop-scale haptic device. Future research will work to improve the rate of temperature change and with a view to using this capability to explore the perceptual characteristics and application areas of these crossmodal haptic interactions.

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Disclosure of Interests. The authors have no competing interests to declare.

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