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A flexible multimodal tactile display for delivering shape and material information

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ABSTRACT

The growing complexity of telemanipulation tasks calls for increased realism and intuitiveness of the interaction between the user and the master control. Humans perceive multiple haptic features of an object such as its stiffness, temperature, and shape, and rely on this multimodal information to achieve dexterous manipulation. However, to date, remote manipulators rarely provide haptic information to the operator. Moreover, current multimodal displays are often too rigid and bulky to be integrated into the manipulator. Thus, to improve the quality of teleoperation, there is a high demand for flexible devices that are capable of matching the skin's curvature while delivering multimodal haptic information to the operator. In this paper, we present a flexible tactile display delivering tactile and thermal stimuli to the user's skin. We propose a hybrid electromagnetic-pneumatic actuation to operate a 2×2 array of tactile cells. Each cell provides a repetitive stimulation with a force and an indentation that are above the human perception threshold for the finger, palm, and forearm. In addition, the temperature of the display's surface is controlled using a Peltier element attached to an air-cooled heatsink. By providing a reproducible cooling gradient, our display simulates common materials encountered in the daily environment. User study results show that (1) the tactile stimulation is perceived well and (2) the identification rates of objects simulated with the display were comparable to those obtained with real objects. Unlike previous devices, the thermal stimulation is delivered while the display is in constant contact with the user's skin, a necessary requirement for teleoperation. These results demonstrate the potential of our device as a promising tactile display for providing haptic feedback in teleoperation.

1. Introduction

With advancements in ubiquitous computing, human–machine interaction (HMI) is becoming an important field of research. The growing number of tasks that can be performed through a teleoperated manipulator, such as robots or less automated devices, and their increasing importance, are continuously requiring more intuitive and reliable human-machine interfaces. Teleoperation allows the remote control of a manipulator in restricted or unfriendly environments; teleoperation not only allows the user to filter their tremor, and to scale their movements up or down, as well as the force they apply, but it also has the potential to enhance the user's perception by increasing the strength of a stimulus through visual or tactile feedback. Currently, accurately controlled teleoperated robots are used to inspect nuclear reactors, offer rescues in catastrophic situations, and perform complex surgical procedures. Robotic surgery, in particular, is a promising field in which errors in the bidirectional communication with the user are critical and should be minimized.

While these robotic systems have facilitated humans' performance in extreme environments [1–3], they currently provide only visual feedback. Haptic information, which is an important form of feedback for surgeons, is often absent in these systems [4]. Haptic feedback can be divided into force and tactile feedback, which are both essential for dexterous manipulation. Without force feedback, surgeons using position-controlled teleoperated robots are subject to the serious risk of damaging internal tissues by applying too much force. In addition, previous works [5,6] have emphasized the benefits of introducing force feedback in robotic surgical systems

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in terms of usability and reduction of cognitive load. By palpating the tissues, surgeons can find hidden arteries based on pressure (pulse) cues and discern cancerous tissues based on temperature alone [7]. Thus, multimodal tactile perception is an essential feature that allows us to discriminate the objects we manipulate based on their texture, compliance, shape, and thermal characteristics.

However, existing tactile displays are primarily focused on presenting a single tactile feature, such as the shape [8,9], texture [10–12], or material [13–15] of an object, by delivering distributed tactile or temperature cues to the skin. Some multimodal haptic devices do exist. They provide tactile and kinesthetic feedback [16,17] by mounting similar tactile displays on force feedback devices. Fewer devices deliver multiple tactile features simultaneously [7,18,19]. These multimodal devices are limited in terms of size and rigidity, restricting their usage to predefined areas of the body and making their integration with other devices, such as the master controller of a teleoperated system, challenging. For example, most thermal displays are still bulky and require the user to actively touch the display for the thermal sensation to be delivered, a crucial lack for teleoperation applications where the skin of the operator is always in contact with the master console. Flexible displays can overcome these limitations by adapting to any shape and curvature of the body, thus enabling comprehensive tactile feedback. Different actuation mechanisms have been used to create flexible tactile arrays. These include pneumatic systems that are actuated by a remote pump, enabling the design of flexible displays with no rigid parts. Pneumatic actuation provides large forces but suffers from a limited bandwidth, and requires multiple valves to control distributed tactile arrays, which results in an increase in overall complexity and size [9,20]. Electromagnetic actuators offer wide bandwidth and are suitable for integration due to their compact size, but they are subject to small actuation forces and displacements [21,22]. Recently, tactile displays based on dielectric elastomers [23,24] have shown promising results in terms of miniaturization and flexibility. However, they suffer from low actuation forces, narrow bandwidth, and high actuation voltages. At this time, there are no displays combining both thermal and tactile stimulations in a compact and flexible body that can be easily integrated with commercial master consoles.

In this paper, we present a flexible multimodal display that is capable of delivering both distributed tactile and temperature stimuli to the skin of the user. The device consists of two modules: a tactile array and a thermal unit. The tactile array uses a hybrid pneumatic and electromagnetic actuation (based on a previous design [25]), optimized to increase force and deflection performance. The design of each module and their integration are presented. Their physical characterization is then performed, and compared to human perceptual thresholds. Finally, the psychophysical performance of the device is assessed through two user studies: a tactile pattern identification task and a thermo-tactile material identification task.

2. Design

The proposed multimodal tactile display delivers shape information for an object by applying different pressure patterns to the operator's skin. The tactile display also delivers material information by modulating the temperature of the skin using a thermal module. Indeed, the rate of temperature change of the skin depends on the material of the touched object. For example, the skin temperature decreases more rapidly when touching a slab of metal, as compared with a piece of wood, owing to the different thermal properties of the materials, such as heat capacity and thermal conductivity, the geometric properties of the object, and the thermal contact resistance between the object and the material [26].

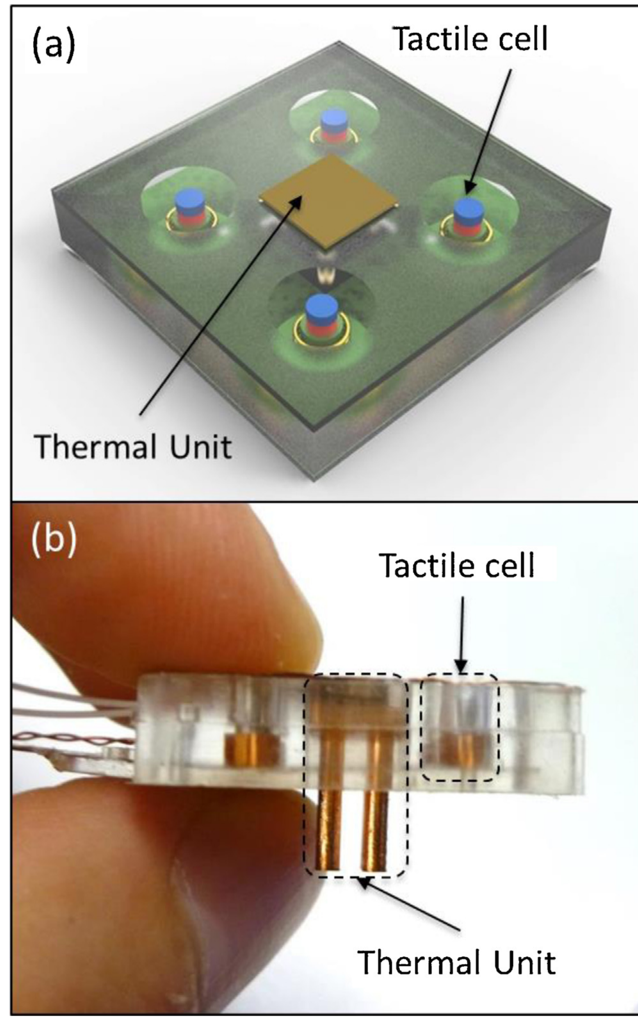

Fig. 1. Display design: (a) schematic diagram of the proposed tactile display, and (b) photograph of the side view of the display.

The display, illustrated in Fig. 1a, is divided into two parts: a tactile module and a thermal module. These modules work independently and are readily integrated. The tactile module consists of a flexible elastomeric (polydimethylsiloxane, PDMS) body with an array of four tactile cells. The thermal display module is composed of a Peltier element (PE), a thermistor, a heatsink, and a heat spreader. As illustrated in Fig. 1b, the thermal display is inserted inside the through hole of the tactile display.

2.1. Tactile module

The main components of the tactile display are a thin PDMS membrane, a flexible PDMS body with four chambers, a flexible PCB (FPCB), four permanent magnets, four coils, and four cores, as illustrated in Fig. 2a. Each permanent magnet is attached to the 100 μm thick flexible PDMS membrane and is aligned with an electromagnet, which consists of the coil and the core placed inside a chamber in the main body. Microchannels integrated in the PDMS body provide uniform pneumatic pressure inside the chambers. These microchannels merge into a single input port. Thus, the pressure is the same in all of the chambers. The combination of a magnet, an electromagnet, and a pressurized chamber constitutes a tactile cell. Each cell has dual electromagnetic and pneumatic actuation. There are four tactile cells forming a 2×2 array. The distance between adjacent cells is 12 mm. This spacing leaves room to insert the ther-