ThermalTex: A Two-Modal Tactile Display for Delivering Surface Texture and Thermal Information

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Abstract. We present a two-modal surface display that can simultaneously display thermal and texture stimuli to the user's fingers. The texture is generated by electrovibration effect on a flexible film with a high thermal conductivity. The temperature of the film is controlled by Peltier element attached with a water-cooling heatsink. The performance of the prototyped device is evaluated by the temperature response to the step signal and the maximum electrostatic force of the display. The application of the display is demonstrated in a virtual reality environment where users can feel the two modal haptic property of the virtual object.

Keywords: Haptics · Electrovibration · Temperature · Thermal stimuli

1 Introduction

Human tactile perception systems contain diverse types of receptors, such as mechanoreceptors and thermoreceptors [1]. These receptors work in an integrated manner to perceive a haptic sensation [2]. For example, when human explores the tactile properties on the surface of real object, the texture and temperature are always perceived synchronously. This fact appears indicating that the simultaneous presentation of texture and temperature information is beneficial for the reproduction of surface characteristics.

Some researchers have tried to add temperature feedback to surface haptic feedback devices by combining pin-array and the thermal feedback [3–5]. The pin-array stimuli

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were actuated by piezoelectric bimorphs and the thermal feedback was created by a Peltier thermoelectric element. To improve the quality of teleoperation, Gallo et al. [6] presented a flexible tactile display delivering pattern and thermal stimuli. The pattern was realized by a hybrid electromagnetic-pneumatic actuation and the temperature is controlled by a Peltier element. More recently, Strese et al. [7] presented a tactile mouse to display the hardness, friction, warmth and roughness of virtual objects. The hardness, friction and roughness were actuated by the electromagnet, servo and voice coil actuator, and the thermal stimuli were created by a Peltier element.

We aimed to develop a new tactile interface, which can provide electrovibration and thermal stimuli. The electrovibration stimuli was generated on a high thermal conductivity film. The Peltier element provides the thermal stimuli through heating and cooling the film. Furthermore, we evaluated the performance of the prototyped device by measuring temperature change ability and the maximum electrostatic force. Finally, a special demo was designed to show the proposed display ability in presenting surface properties.

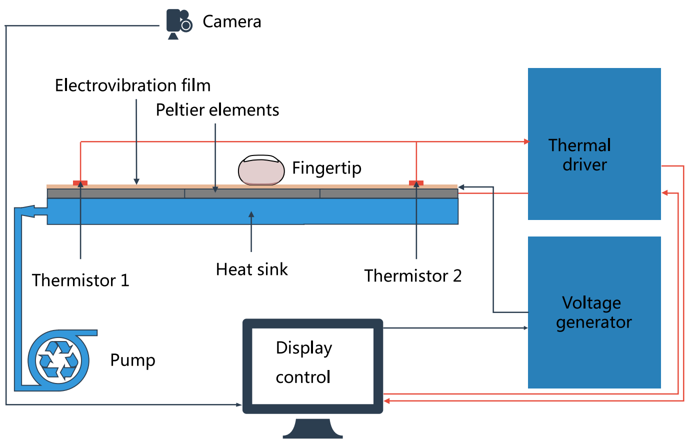

Fig. 1. The proposed tactile display: the system diagram

2 Design

The proposed display consists of two parts: a texture module and a thermal module. These modules work independently and are readily integrated. The texture module generates electrovibration effect by a flexible film. The thermal module controls the temperature by the Peltier effect. The display design was shown in Fig. 1.

2.1 Texture Module

In order to efficiently control the temperature of the texture module, the electrovibration actuator in the texture module needs to be thin and has high thermal conductivity. Therefore, we designed a thin electrovibration film with a high thermal conductivity.

Generally, the electrovibration actuator composed of three layers, including the base layer, conductive layer and insulating layer. Nano-carbon copper foil (NCF) is very thin and has high thermal conductivity, so we used it as the base layer and conductive layer. The NCF consists of a base layer of Nano-carbon and a copper layer, which are about 0.15 mm. The insulating layer is a key part of generating electrovibration stimulus, which needs to have high electrical resistance and is easy to coat on the copper layer. We coated a layer of Polyimide (PI) on top of the copper layer as the insulator, which is roughly 2 μm and has 0.12 w/(m.k) thermal conductivity. Totally, Electric vibrating film length 120 mm, width 80 mm, thickness 0.15 mm. Totally, electrovibration film is 120 × 80 × 0.15 mm.

A voltage controller was used to generate a periodic voltage applying to the conductive layer. This controller can output square wave, 0–350vpp and 10–5000 Hz voltage. The amplitude error of the input voltage was no more than ±4% and the frequency error of the input voltage was no more than ±0.2%. The user's wrist is grounded through an electrode.

As the voltage was applied, an electrostatic force appeared between the finger and the touching surface of the proposed display. While we modulated the voltage based on the time or touching position, the electrostatic force would induce a dynamic friction, which then perceived as a tactile texture.

2.2 Thermal Module

Combining the thermal module with the texture module imposes three specific constraints: 1) the thermal module must be fit in the area of the texture module (8 cm * 12 cm). 2) The thermal module should respond quickly to switch between elevated and reduced temperatures. 3) Its achievable range of temperature spans from 20 °C to 35 °C, which is sufficient for simulating heat transfer phenomena between a fingertip.

The Peltier element acted as a thermal actuator because it is only electrically driven and responds quickly to switch between elevating and reducing temperatures. In order to estimate the power density of the Peltier element, the maximum heat flux Q generated when a hand touched the entire haptic module area can be derived from two semi-infinite body models:

$$Q = \frac{T_e - T_d}{R_{e-d}} \tag{1}$$

where T_e is the environmental temperature, T_d is the targeted temperature of the device, and R_{e-d} is the thermal contact resistance between the environment and the device. The value of R_{e-d} at a contact force of approximately 2 N can be approximated as a function of the thermal conductivity of the tactile surface material (κ_d), shown as follows:

$$R_{e-d} = \frac{0.37 + \kappa_d}{1870 \times \kappa_d} \quad (2)$$

The resting temperature of the skin of the hand often varies between 25 °C and 36 °C [8]. We chose an average value and assumed the hand temperature is 30 °C. When the texture module is kept at 20 °C, the derived maximum heat flux is 6.1 kW/m^2. The whole area of the contact area is 8*12 cm^2. The maximum heat pumping capacity is 58.2 W.

We choose six 40 * 40 * 4.6 mm Peltier elements (TEC1-12704T125, Beijing Huimao Refrigeration Equipment Co., Ltd., China) with a maximum cooling capacity of 40.1 W was selected. The total area of the six Peltier elements is fit with the tactile contact area and the total heat cooling capacity is about 240 W, which is four times larger than the estimated values because the maximum cooling capacity of Peltier element is obtained at a temperature difference between the two plates of the Peltier element of 0 °C. Thus, the real maximum Qc depends on the heatsink performance. Since performance of Peltier thermoelectric module depends, we designed a water-cooling system to increase their performance. The water-cooling system consists of a pump, a water tank and a water-cooling block that is attached to the heat generation side of Peltier elements a piece of thermally conductive silicone.

As our device have a narrow working temperature range from 18 °C to 38 °C, and need a fast-transient response to simulate the finger contact with a material, we chose two NTC thermistor temperature sensors for our system. The thermistor is a $\Phi 1.6 \times 4.5$ mm cylinder with a thermal sensitivity of ±0.1 °C (between 0 °C and 70 °C).

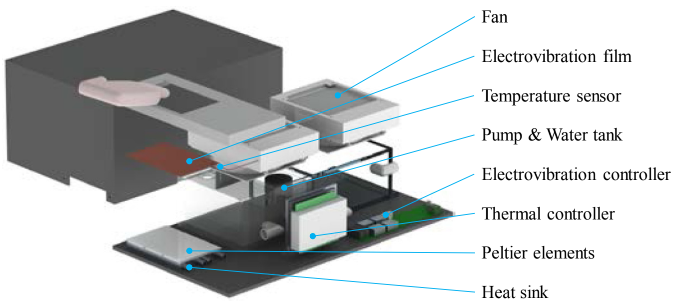

Fig. 2. The components of the ThermalTex

3 Fabrication and Assembly

The electrovibration film was fabricated by a molding process, e.g. the NCF was spin-coated with a fluorine PI, and then baked at 200 °C for 2 h.

The six Peltier elements are arranged as shown in Fig. 2 to form an 8 * 12 cm plane. The bottom surface of the Peltier elements was glued onto the heatsink and the top surface was glued onto the electrovibration film by the thermal grease. The thermal grease could reduce the thermal resistance between the Peltier elements, the heatsink and electrovibration films. Two NTC thermistor temperature sensor was attached to the top surface of the electrovibration, aiming to directly measure the temperature of the electrovibration film. In order to accurately measure the temperature of the electrovibration film, the temperature sensor needs to be closely attached to the top surface of the electrovibration film. We use thermal grease to wrap the temperature sensor and fix it on the top surface of the electrovibration film with adhesive tape.

4 Performance Measurements

The ThermalTex depends on the temperature and the electrostatic force applying to the fingertip. Different tactile sensations can be created by controlling the amplitude and frequency of electrostatic force and the variation of the temperature. Therefore, it is essential to know capacity of the proposed display in variation of the temperature and the generating electrostatic force.

We conducted two experiments with ThermalTex. In the first experiment, we measured temperature change ability. The maximum electrostatic force at different temperature was measured in the second experiment.

4.1 Temperature Response

To evaluate temperature change ability of the proposed display, we recorded the temperature response while applying step signals of temperature. The step signals of temperature were from the room temperature (25 °C) to the minimum working temperature (20 °C) and to the maximum working temperature (35 °C). The temperature was measured by the thermal sensors of the proposed display with 10 Hz sample rate.

The result was shown in Fig. 3. When the temperature dropped from 25 °C to 20 °C, it took about 20 s to stabilize the temperature within the range of 20 ± 0.5 °C. We noticed that the first drop in temperature to a minimum (temperature sensor 1: 20.52 °C, temperature sensor 2: 20.26 °C) took only about 7.5 s, which indicated that the temperature could decrease faster, but it took longer to stabilize to the target value. When the temperature rose from 25 °C to 35 °C, there was a similar trend. It took 30 s to stabilize within 35 ± 0.5 °C, and the first rise to the maximum value (temperature sensor 1: 35.93 °C, temperature sensor 2: 36.25 °C) took only about 9 s.

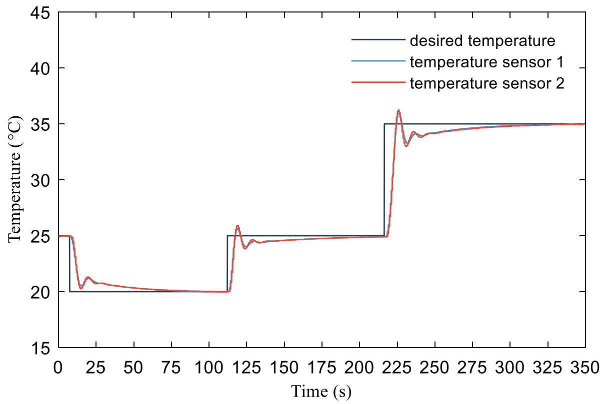

Fig. 3. The behavior of the proposed display for temperature steps

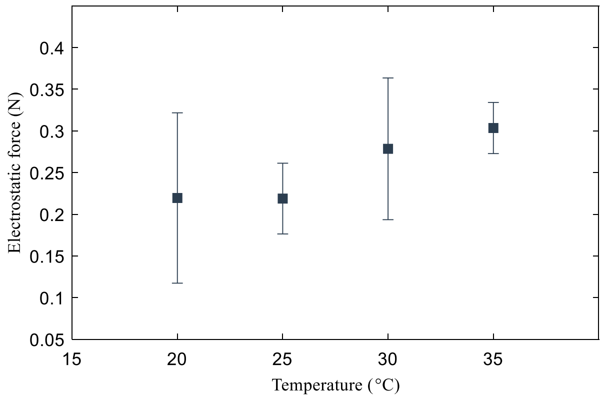

Fig. 4. The electrostatic force was estimated while applying the voltage amplitude of 350 Vpp at 140 Hz

4.2 Electrostatic Force

We used an apparatus to measure the maximum electrostatic force generating on the proposed display. Detail information of the apparatus can be seen in [9, 10]. The maximum electrostatic force occurred while applying the maximum amplitude of the voltage (350 Vpp square voltage). Thus, we choose the 350 Vpp amplitude of applying voltage. The frequency is 140 Hz, which located in the sensitive range of the electrovibration display [11, 12]. Four temperature levels (20, 25, 30, 35 °C) cover the working range of the proposed display.

A participant joined this experiment. To decrease the hydration level of the fingertip, talcum powder was used to dry the fingertip. We recorded the normal force and the tangential force while participant slid her index finger with a 0.5 N normal force. The applying voltage was turned on every 500 ms for 250 ms each time. For each temperature, the sliding was repeated five times. The calculation of the electrostatic force refer in [9].

The estimated electrostatic force with respect to the temperature was shown in Fig. 4. The average of the maximum electrostatic force varies between 0.22 N and 0.30 N. The voltage amplitude and the electrostatic force are positive related [13]. Thus, the electrostatic force can be adjusted from 0 to the maximum value by controlling the voltage amplitude.

5 Application

The ThermalTex can be applied to many situations, such as teleoperation, remote palpation and virtual shopping, etc. Figure 5 demonstrates an application in virtual shopping. In this scenario, we set up two kinds of clothes with zipper, one of which was made of metal and the other was made of plastic. When the user pulls the zipper, he/she can differentiate between the two zippers by the thermal feedback while feel the tactile sensation of zipper.

Fig. 5. Application of the proposed display. Users can see the virtual products by the VR headset and perceive the tactile sensations of the zipper in the virtual store by the proposed display

6 Conclusion

The paper presented a new tactile interface to provide feedback of surface properties of fine texture and temperature. The performance of the thermal and the texture feedback was assessed by the temperature response to the step signals and the maximum electrostatic force of the display, respectively. The results show that the temperature can change rapidly, but it takes about 30 s to stabilize to the target value. The maximum electrostatic force varies between 0.22 N and 0.30 N, when the normal force of 0.5 N was applied by the sliding finger. Potential application was demonstrated by a virtual shopping scenario.

The performance evaluation of the ThermalTex shows two challenging issues to be addressed. The temperature response time is slow and needs to improve for the requirements of real-time display. Furthermore, there is a large variation in the electrostatic force at 20 and 30 °C, and the reason needs to be explored in the future.

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