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Encoding and presentation of surface textures using a mechanotactile display

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A B S T R A C T

Tactile displays can present virtual tactile sensations to the user by stimulating tactile receptors, which are distributed spatially within the skin and are classified into four types based on their characteristic temporal pattern of impulses. The mechanotactile displays can stimulate different types of the receptors selectively by changing the displacement and frequency of the skin deformation. In our previous work, we developed an array of large-displacement microactuators composed of hydraulic amplification mechanism (HDAM) and piezoelectric actuators, which is capable of stimulating all the four types of the tactile receptors. We controlled the driving parameters that were the driving voltage, vibration frequency, and actuation patterns of the actuators, and successfully presented various surface textures. However, in practical applications, the control parameters are to be tuned according to the surface textures that we want to present. In addition, the input signals to the piezoelectric actuators would consist of multiple frequency components and are difficult to create through trial and errors. To solve this inverse problem, in this work, we encoded the sample surface textures to voltage signals by sliding the sample over the HDAM and using the piezoelectric actuators as sensors. First, we attempted to reproduce the surface textures. The encoded signals were amplified to drive the mechanotactile display. The perception tests indicated that this approach was effective. Secondly, we attempted to correlate the encoded signals with hardness of the samples. The encoded signals were investigated among the samples of different hardness. In addition, we fabricated moicropatterned tactile samples that have the same physical properties except Young's modulus to isolate hardness from other parameters. The encoded signals were compared to extract the characteristic signals to determine the hardness. These signals were used to drive the tactile display in the perception tests, which verified the effectiveness of the approach. These two approaches that were proposed and experimentally verified in this paper are readily applicable to solve the inverse problem in tactile display applications.

1. Introduction

A tactile display is a device that can present virtual tactile sensations to the user by stimulating tactile receptors in the human skin. Tactile receptors are mechanosensitive nerve terminals that are distributed spatially within the skin. They respond the stimulation with trains of electrical impulses and are classified into four types associated with their characteristic temporal patterns of impulses [1,2]. Various kinds of tactile displays have been developed in different approaches to date [3–7]. Mainly, electrical stimulation or mechanical deformation of the skin is used to stimulate the receptors to present tactile sensation. Electrotactile displays that stimulate the receptors electrically are lightweight, low cost, scalable and consume much less power than mechanotactile displays that mechanically deform the skin to activate the receptors [7]. To further reduce the power consumption, needle-type electrodes were developed, which can penetrate through the high-impedance stratum corneum [8–10]. This needle-electrode display could successfully present surface texture feeling, such as roughness [9].

It is known that mechanotactile displays are better at presenting tactile sensations than electrotactile display [11–13]. The mechanotactile displays stimulate different types of tactile receptors selectively by changing the displacement and frequency of the skin deformation. Four tactile receptors are classified into SA (Slow adapting) type and FA (Fast adapting) type; SA type receptors have relatively high sensitivity at a low frequency and FA type recep-

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tors can react to small displacement at a high frequency [14–16]. For example, the skin deformations to stimulate SA type receptors can be achieved by pin-arrayed solenoid valves [4], while ultrasonic vibration [5] or electrostatic force actuator [6] can be used to stimulate FA type receptors. However, in those approaches, it was difficult to stimulate both SA and FA types of tactile receptors with one actuator due to the different working ranges. To do so, the actuators capable of producing displacement greater than 100 μm at 10 Hz and 1 μm at a high frequency up to 200 Hz are needed. To satisfy these requirements, we developed an array of large-displacement micro-actuators that were composed of hydraulic amplification mechanism (HDAM) and piezo-electric actuators, as shown in Fig. 1 [17,18]. The HDAM amplifies the displacement created by the piezoelectric actuators at the top, where the subject place his/her fingertip. It was found that the display could present various kinds of surface textures to the subjects. We attempted to quantitatively correlate the parameters of the display, which were the driving voltage, vibration frequency and actuation patterns of the actuators, to the presented tactile sensations using a sample comparison method [19,20]. The results indicated that roughness had a strong correlation with the driving voltage. Hardness and wetness could also be correlated to the parameters though the correlation was weaker than the roughness.

In these works, we perturbed the control parameters of the tactile display and investigated the presented surface textures. However, in practical applications, first, surface textures that we want to present are given and then, the control parameters are to be tuned for them. In addition, the input signals to the piezoelectric actuators would consist of multiple frequency components and are difficult to create through trial and errors. To solve this inverse problem, in this work, we conducted two experiments. First, we attempted to reproduce the surface textures of given tactile samples. This mandates that the surface textures need to be encoded. Encoding of surfaces have been attempted by many researchers, mainly in the field of textile engineering [21,22]. The surfaces are quantified with respect to mechanical property and correlated to the tactile feeling by measurement instruments, such as Kawabata Evaluation System. However, in this work, the surfaces need to be encoded to determine the control parameters of the display. Our tactile display is composed of HDAM and piezoelectric actuators. When the samples are slid on the HDAM, deformation of HDAM associated with the surface textures is transferred to the piezoelectric actuators, which work as sensors to detect the deformation and encode the textures. The encoded textures, which are in the form of voltage, are properly amplified to drive the piezoelectric actuators and to reproduce the surface textures.

Second, we attempted to correlate the encoded signals with the characteristics of the surface textures, such as roughness and hardness. It is reasonable to presume that the roughness can be controlled by the display. However, though HDAM cannot control its own hardness, the hardness was found to have some correlation with the control parameters [19,20]. We encoded the tactile samples, which were used for the sample comparison method, and attempted to extract the characteristic signals. In addition, to further focus on the hardness, we fabricate 5 kinds of micro-patterned tactile samples that have the same pattern but different Young's modulus. Using these samples, we could isolate the effect of hardness from other parameters and thus, could successfully extract the characteristic signals to determine the hardness. The signals were used to drive the display in the perception tests and experimentally proved to have strong correlation with the hardness.

These two approaches that were proposed and experimentally verified in this paper are readily applicable to solve the inverse problem in tactile display applications.

2. Design and fabrication

2.1. Tactile display

The tactile display we used in this work consists of nine piezoelectric actuators and a hydraulic amplification mechanism (HDAM) that can amplify the input displacement hydraulically [18]. To stimulate both SA and FA receptors in the skin, large output

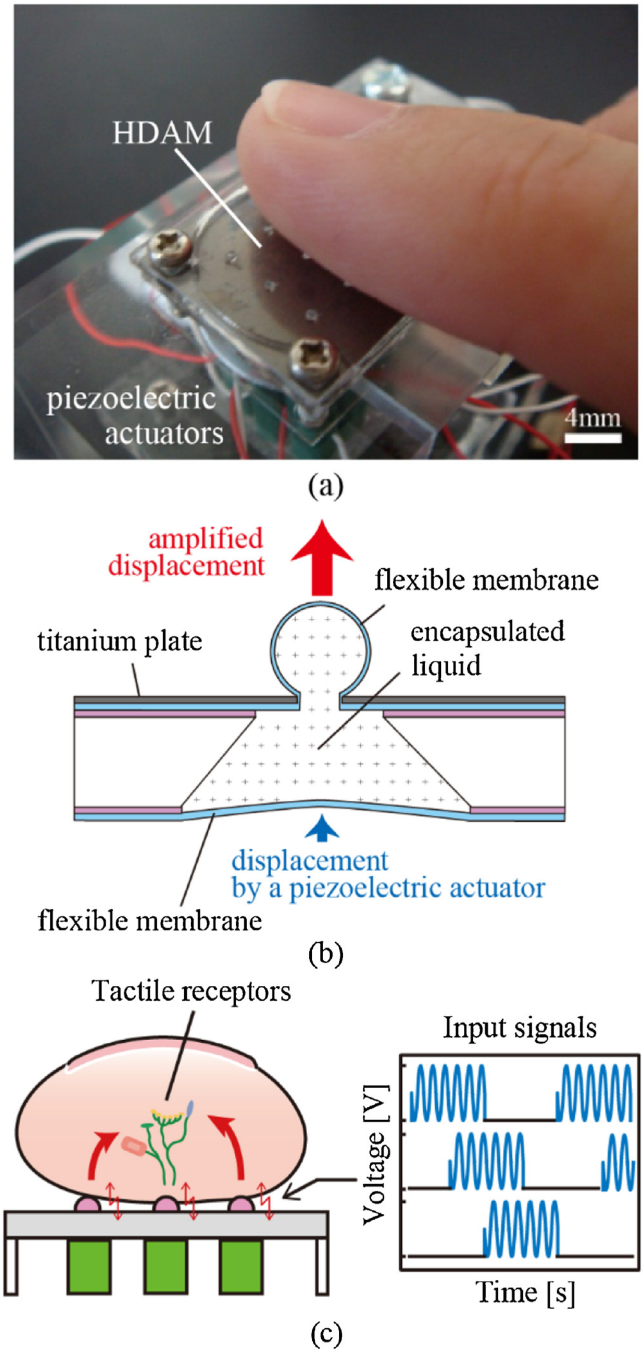

Fig. 1. (a) Mechanotactie display composed of HDAM and piezoelectric actuators. 9 piezoelectric actuators are positioned below the 3×3 cells of HDAM. A subject place his finger onto the HDAM. (b) Conceptual sketch of HDAM. HDAM encapsulates incompressible fluid inside with flexible membranes. Small displacement at the bottom applied by the piezoelectric actuator is hydraulically amplified at the top surface of the HDAM due to the differences between the opening areas. (c) The display can present various tactile sensation to the subject by driving the 9 piezoelectric actuators individually.