Displays 54 (2018) 34–46

Contents lists available at ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

Design and characterization of the lateral actuator of a bimodal tactile display with two excitation directions[☆]

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ARTICLE INFO

Keywords:
Tactile display
Load model
Piezoelectric
Bimorph
Perception threshold

ABSTRACT

In this paper, a bimodal tactile display used to stimulate the mechanoreceptors is proposed. The use of tactile displays to provide tactile sensations has become the object of increasing interest in recent years. Most of these displays have only one actuator type to generate the tactile perceptions and the spatial resolution of many displays is too rough for good tactile impression. Hence, for the proposed tactile display, two types of actuators for lateral and vertical (normal) excitation are combined. The resolution of the 4 × 4 array is 2.4 mm. Due to its design concept, the presented display is easily expanded. The normal actuator is based on the reluctance principle and the lateral actuator is based on the piezoelectric effect. This contribution focuses on the design and characterization of the piezoelectric actuator. The lateral actuator is mounted on the normal actuator. This has a significant impact on the design of the piezoelectric actuator. To describe the dynamics of this actuator, a Transfer Matrix Method (TMM) Model is created. The mechanical boundary condition at the connection to the normal actuator is included utilizing discrete elements. The model is validated by experiments. Using the model, the geometry of the actuator elements is designed. For performance tests, several experiments have been carried out. The behavior of the lateral actuator has been analyzed in the two end positions of the normal actuators for different load conditions. In terms of performance, the lateral actuators achieve sufficient deflection, even under high load conditions, using imitation human skin as the contact material and with a weight of 50 g. It is shown in a subject test that the lateral actuator works well under real conditions. A measurement of the combined movement has been performed using a Micro System Analyzer (MSA-100-3D) at different frequencies.

1. Introduction

Currently, users of a computer (PC) receive information acoustically and visually. They can control the PC with haptic inputs via mouse, keyboard or touchpad. With the proposed tactile display, we want to simulate real surface structure impressions in the fingertip of the user. Via the addition of an information transfer possibility and the use of the tactile stimuli of the user, our aim is that the PC can send tactile information back to the user.

There are four types of mechanoreceptors in the skin of the fingertip: the Merkel receptor, the Ruffini corpuscle, the Meissner corpuscle and the Pacinian corpuscle. Each is sensitive to specific stimuli. The Merkel receptor, also called SA-I (SA means slowly adapting), is a slowly adaptive receptor. It is stimulated with quasi static pressure vertical (normal) to the fingertip. The Ruffini corpuscle, called SA-II, is the second slowly adaptive receptor type. It is stimulated by skin shearing. The Meissner corpuscle and the Pacini corpuscle are important for the proposed tactile display. They are also called RA-I and RA-II where RA means rapidly adapting. The Meissner corpuscle reacts to the excitation depending on the speed and the Pacini corpuscle reacts to the excitation depending on the acceleration [1–3]. According to [4–6], the SA-I receptors have their maximum sensitivity frequency range in the range of ~0.3–100 Hz and the SA-II receptors in the range of ~7–400 Hz. According to [7,4–6], the RA-I receptors have their maximum sensitivity frequency range in the range of ~3–200 Hz and the RA-II receptors in the range of ~10–800 Hz. The position of the individual receptors in the finger also influences sensation. However, the position of the receptors is not quite as important as the identifiability of the individual pins as such in this work. If the subject can identify the individual pins, the distance from pin center to pin center is too great. There are different approaches for the development of tactile displays. They can be classified into three stimulation types: the

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[☆] This paper was recommended for publication by Pen-Cheng Wang.

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https://doi.org/10.1016/j.displa.2018.09.002
Received 15 March 2018; Received in revised form 1 August 2018; Accepted 5 September 2018

simulation of physical characteristics, the electrical activation of the mechanoreceptors, and the stimulation of the mechanoreceptors [8]. The focus of this paper is on the stimulation of the mechanoreceptors.

For development of the tactile display, it is important to know the load conditions of a tactile display. It has been shown that impedance measurements of the finger can be used for this purpose. These measurements have already been carried out by other researchers. In [9] an impedance curve is shown which was performed with a test pen. With only a few measuring points, the authors were able to show that there is a minimum in the range of 200–300 Hz. In [10], impedance measurements on the finger were performed with another system. In this case, the subjects did not have to hold a test pen, but had to place their fingers on an actuator. The contact surface was the fingertip. While this shows a similar course as in [9], some differences were also present which may be due to the other contact conditions. However, the authors were able to create a substitute model for their tactile actuator from the impedance measurements and use it for further work. In addition to the load conditions, it is important to know which performance is required as a minimum by the tactile display under the load conditions. Here, the tactile detection threshold has proved to be a useful measure of the required amplitude. If a tactile display is not able to reach the tactile detection threshold under load conditions, the subject will not feel anything. Tactile detection threshold measurements were performed by [9–11]. It was shown [9] that above a frequency of 100 Hz the tactile detection threshold is already below 1 μm and that, as with the impedance measurements, a minimum lies in the range of 200–300 Hz. Similar behavior was found in [10] and the authors were able to make a good prediction of the amplitude in which the tactile detection threshold was to be reached. This behavior is also shown in [11]. In addition, the authors were able to show that older subjects need larger amplitudes for detection. Furthermore, the frequency range can be mentioned as a development parameter for a vibro-tactile display. In [1], the required frequency range is specified with up to 1 kHz. It is shown in [12] that an optimal pin spacing is between 1 mm and 2 mm. The individual pin can no longer be assigned to an individual receptor with a distance greater than 2 mm. If the distance is less than 1 mm, adjacent pins are perceived as one pin.

In the past, various tactile displays were suggested. They worked with different actuator types to ensure the required deflection at different frequencies. For example, there are pneumatic tactile displays where small bubbles are deflected [13–15]. There are also phase change actuators in which a liquid is evaporated and thus a pneumatic pressure is used to deflect the actuators [16]. There are smart fluid actuators in which the deflection of the actuators is controlled electrically or magnetically via liquids [17,18]. There are polymer actuators that can be controlled thermally or electrically [19,20]. Piezoelectric actuators are also used for tactile displays. Piezoelectric bending actuators are proposed in [4,21–24] and piezostacks with a hydraulic amplification in [25,26]. Shape memory alloys (SMA) are used in [27,28]. Electrostatic force actuators are used in [29,30]. Electromagnetic power actuators are used in [31–33]. A dielectric elastomer actuator is proposed in [34] and a multimodal actuator for a flexible tactile display with normal and rotational excitation is proposed in [35]. Finally, there are thermal tactile displays such as in [36] and direct electrical stimulation of the receptors with displays such as in [37].

The tactile display in [31] generates a normal excitation to the finger and works up to a frequency of 800 Hz with a maximum free amplitude of 100 μm. The displays proposed in [22,4,24] for generating braille information already have a very good spatial resolution of only 1 mm and produce skin shearing in a wide frequency range. The flexible display with the multimodal actuators made of [35] could already work up to a frequency of 250 Hz with an actuator size of only 47.5 × 12 × 27 mm. One of the best known tactile displays is probably the Optacon [21], which transmits a translation of graphic information about photocells to piezoelectric bimorphs, which are then deflected according to the information. This leads to very good detection rates after a corresponding training phase of the subjects. In [38], the authors used piezoelectric bimorphs to measure the quasi-static mechanical parameters of the fingertip in a test setup. To describe the results they used a second order linear viscoelastic material model, similar to [39]. However, this study was the first to investigate relaxation and creep in the living glabrous skin. In [40,41] the authors describe a further development of the tactile display with piezoelectric bending actuators presented in [24]. While [40] shows the functionality with a free excursion amplitude of up to 100 μm in a frequency range up to 250 Hz, [41] shows that the display is very well suited for the identification of two continuous lines. One is horizontal and the other diagonal to it. They received the best detection rate at their specified maximum voltage of 90 V. The system is very compact with an area of 150 cm^2 and a weight of 60 g.

All these approaches to tactile displays are already leading in the right direction. However, we suppose that if one wants to imitate real surfaces with a vibro-tactile display, one cannot avoid choosing a multimodal approach similar to that in [35] to activate the corresponding receptors. The innovation in our proposed tactile display is a combined actuator that can stimulate the fingertip with both normal and shear stimulation. To stimulate the SA receptors, it is equipped with an actuator called “”normal actuator”, which is an electromagnetic force actuator used especially for low frequencies up to 150 Hz and normal excitation. In order to stimulate the RA receptors, it has an actuator called a “lateral actuator”, which is especially used for high frequencies up to 1 kHz and shear excitation. As already mentioned, piezoelectric bending actuators in the braille range performed well, which is why they are used for the shear actuators. The display presented here has been designed to create a distribution of stress and strain in the finger that corresponds to that which occurs when the finger is traversed over a defined surface. The display is not intended for direct reproduction of the surface properties of a surface, such as extending and retracting pins to generate braille. However, for the generation of a stress and strain distribution in the finger that corresponds to an extending or retracting pin. This should be realized over different frequencies, different excitation directions and deflection amplitudes, as shown in previous works with only one excitation direction, e.g. laterally in [24]. An analytical description of the finger under such loads is not explained here, but a replacement model from impedance measurements is created and used to ensure the functionality of the display. We assume that the bimodal excitation possibility can contribute to a better modelling of the stress and strain distribution in the finger. In [42] the authors show that a reference perception excitation perpendicular to the finger can also be obtained with a tangential excitation with less displacement but higher force. This shows that both normal and tangential excitation of the finger can result in the same feeling but it shows also that the actuators don’t need the same force and displacement for the same feeling. We assume that the stress and strain field in the finger can be modelled better with a bimodal actuator. As already mentioned, an actuator distance of less than 1 mm is optimal to reproduce real surface structures. However, this results in the actuators having to be correspondingly small, which is only possible to a limited extent, since the required deflection or force must be achieved. With a second actuator coupled, the respective individual actuators could be designed to match a specific frequency range. For example, the normal actuator for low frequencies with a high deflection but small force, and the tangential actuator for high frequencies with a small deflection but high force. This could not only help to further reduce the size of the actuators, but also to transmit the signal to be transmitted in more detail to the finger.

Both types of actuators were assembled to form an actuator called “tactile generator”. In a field of 4 × 4 there are 16 tactile generators with a good resolution of 2.4 mm. We propose a load model designed using impedance measurements of the fingertip for the development of the lateral actuator. In our impedance measurements, we measured up to a frequency of 1 kHz and with a pin that has almost the same contact