A Novel Stimulation Method Based on a Neuromorphic Mechanoreceptor Model for Haptic Illusion

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Abstract. Vibrotactile stimulation system that generates haptic illusion by employing a RA mechanoreceptor model is developed. The developed stimulator consists of an array of 6 by 4 tiny ultrasonic linear motors [1, 2] with nominal pitch of 2.9mm. Distal pad of human finger with RA mechanoreceptors is modeled using Bensmaia's RA model [3]. In addition, stimulation characteristics of the motor are calibrated and modeled by measuring a trajectory using laser displacement sensor. Optimization algorithm with subgradient method derives the corresponding spatio-temporal stimulation patterns for 24 motors to provide a specified haptic illusion such as edge.

Keywords: vibrotactile stimulator, texture display, RA model, haptic illusion

1 Introduction

Significant improvement in human-computer interface (HCI) has been achieved toward the system with higher intuitiveness and enriched sensory stimulation (e.g. touchscreen and 3D vision system). In order to further improve the perceived veracity of the sensory experience during HCI, the search for the next level of innovation in the interface system is being focused on tactile based user interface [4]. Especially, vibrotaction has been used widely, primarily because it is relatively easily generated and it seems natural to stimulate mechanoreceptors with such a stimulus (i.e. sequenced pressure) [1-5]. One of the common goals of those attempts is to provide a tactile feeling of the shape and texture of a random object to the user. For those researches, first of all, a proper vibrotactile stimulator is required.

One of the most intuitive methods is aligning many individually controlled linear motors in array [5]. However, since conventional linear motors have large size and more than enough force and speed, J. H. Killebrew implemented a relatively small linear motor optimized for the human finger stimulation.

The resulting stimulator consists of an array of 20 by 20 shafts connected to linear motors with 0.5mm pitch. Nevertheless, the total size is still large, and its heavy weight and noise limit the usage. Recently, linear motor based vibrotactile stimulator with improved mobility by adapting non-straight shafts was proposed [6]. However, even though the use of non-straight shafts reduces the size, motor speed is seriously limited, and thus the maximum vibration frequency is limited under 25 Hz.

One solution is employing a different type of linear motors which has a small size and moderate force and speed. TULA35 (Piezoelectric Technology, Seoul) is a tiny ultrasonic linear motor which consists of a piezoelectric disk with a radius and thickness of 2mm and 0.4mm, respectively, and a shaft with a radius of 0.5mm [2]. Once the voltage inputs of opposite polarity are applied alternately, piezoelectric effect makes disk shrink and stretch, which transmits the vibration to the shaft attached on the disk. As a result, the vibration of the shaft moves a slider that wraps around the shaft or, equivalently, the shaft is moved when the slider is fixed. Since this motor is able to vibrate up to 300Hz while maintaining an amplitude of few um, it is appropriate to stimulate human finger [7].

H. Hernandez [1] developed 2 by 3 and K. Kyung [2] developed 3 by 3 vibrotactile stimulator with TULA series. Their goal was to display Braille or a course shape of displayed objects directly with static or low frequency stimulation. For example, to present a line, only pins that correspond to the path of the line come up. This strategy might be good enough to represent symbols such as Braille, but once we attempt to display the detailed characteristics of objects such as a pointed tip of a needle, the obvious limitation appears.

Considering that we are able to distinguish the stimulus not only with different amplitudes but also with different temporal and spatial patterns, it is reasonable to predict that, for a given stimulator, there is a proper stimulation pattern that closely reconstructs the tactile sensation of a specific object. However, such a pattern can hardly be derived mathematically because the problem is highly complicated. Recently developed electrostatic friction based stimulator [8] attempted to provide a texture of displayed object using brute force approach. For each combination of frequency and amplitude, corresponding texture was determined through human experiments. Although this method is clear, all combinations cannot be tested practically and thus the optimum stimulation for a given texture is hard to be discovered. Hence, even coarse estimation of such parameters would boost up the process and increase the similarity.

In this paper, 6 by 4 pin array vibrotactile stimulator employing TULA35 is implemented, and an appropriate stimulation pattern is derived from computer simulation. For the simulation, Bensmiai’s RA mechanoreceptor model [3] that incorporates velocity sensitivity of RA mechanoreceptor in the conventional RC mechanoreceptor model with refractory period and hyperexcitability is used. Other mechanoreceptors such as SA and PC are not considered in this preliminary research because of absence of known simple models for arbitrary stimulus. Nevertheless, RA is the most densely distributed mechanoreceptors in finger [7], which implicates the importance in tactile discrimination, and RA has been known that it is sensitive to edge contours and Braille-like stimuli [9]. These properties make RA mechanoreceptors ideal when they are stimulated by pin array type vibrotactile stimulator. Furthermore, stimulation characteristics of each motor are modeled using laser displacement sensor. Subgradient method, essentially gradient descent method, is applied for optimizing the spatio-temporal patterns of the stimulator for a target tactile sensation. In this paper, the stimulation pattern is assumed to always be periodic with specified amplitude.

Fig. 1. Implemented 6 by 4 pin array vibrotactile stimulator that has 2.9mm pitch. The stimulator consists of four layers (left) and the motors are placed over two layers (middle) for the minimum pitch. Frame is built using acrylic resin material and total dimension is 40mm x 40mm x 17mm (right).

2 Vibrotactile Stimulator

2.1 Implementation

Vibrotactile stimulator consists of 6 by 4 array of TULA35 with 2.9mm pitch, Fig. 1. Motors are positioned over two layers to achieve 2.9mm pitch because the disk of the motor has a diameter of 4mm [2]. Second layer from the top holds the slider that wraps around the shaft of the motor so that the motor moves vertically using the friction between the slider and the shaft. Dimension is idealized to stimulate a distal phalanx of human finger, and it is 40mm x 40mm x 17mmm, Fig. 1.

For driving, twelve LT3572 that is possible to drive two motors per one chip are used. Also, four LT1935 which supplies 30V to three LT3572 are employed to reduce the size of driving board. Each motor is individually controllable through NI PCIe-6536 and PC. Normally, 85kHz pulse with about 20% of duty ratio is applied for the motors to move upward, and pulse train with 80% duty ratio is used for downward movement.

2.2 Modeling

Laser Doppler displacement sensor, LK-G30 (KEYENCE corporation, Osaka) is utilized to characterize and calibrate the motor by measuring its trajectory for a given control pulse train. Fig. 2 shows that measured results when the motor is driven by several consecutive blocks of 70 pulses with one second time step between the blocks.

The result shows that motor amplitude is possible to be reliably controlled with standard deviation of about 10%. The linear relationship with the slope of 0.95/7 between the number of pulses and measured amplitude is shown in Fig. 2 and Fig. 3. In addition, since seventy 85kHz pulses achieve 9.5μm movements, the speed of motor can be determined as

$$Motor\ speed = \frac{amplitude}{time} = \frac{9.5\mu m}{70 \times 1/85kHz} \approx 11.5\ mm/s \qquad (1)$$

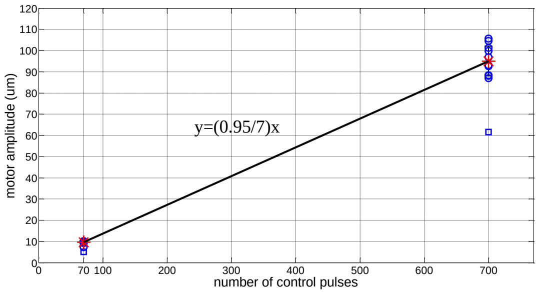

Fig. 2. The number of control pulses versus measured motor amplitude. Asterisk represents a mean of consecutive trials (circles) and error bars show one standard deviation point. Rectangular symbol represents the point where the motor is in transient (excluded in calculation of mean and standard deviation).

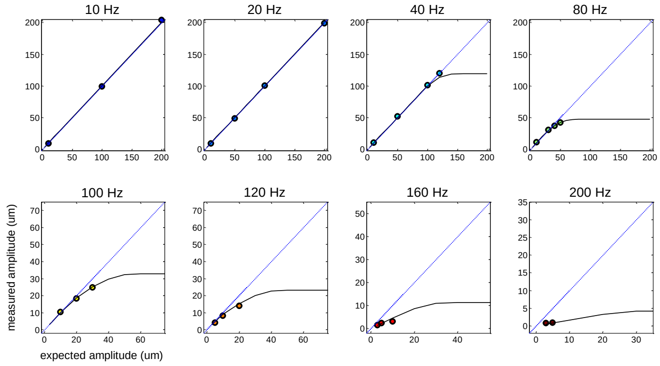

Fig. 3. Comparison of measured amplitude and model simulation when the motor is driven by periodic stimulus with specified amplitude. Filled circles represent measured points and black solid line represents model response. Model has two parameters, maximum motor speed, 11.5mm/s (from equation (1)), and the window length of moving average filter, 4.3ms.

Motor speed limitation causes the saturation of the amplitude for a given frequency, Fig. 3. Saturation point rapidly decreases as frequency increases, and the deviation from linear line becomes apparent. However, only motor speed limitation cannot explain the deviation far before the saturation point because the saturation effect due to the motor speed limit would occur at a sudden point. Hence, moving average filter with window length of 4.3ms is inserted into the model. Therefore, the model consists of square wave generator with fixed ramp rate (i.e. motor speed, equation (1)) for a given amplitude and frequency of the stimulus and moving average filtering of the generated square wave. Note that when the frequency and/or amplitude are high enough, square wave becomes triangular wave with reduced amplitude.

3 RA Mechanoreceptor Model

Known RA mechanoreceptor model [3] is employed for computer simulation.

The model responds only sensitive to the velocity of stimulus and it is appropriate particularly because the response can be defined from arbitrary stimulus, equation (2).

$$\mathrm{P}_t = \mathrm{P}_{t-1} + \alpha v_t - (\mathrm{P}_{t-1} - \mathrm{P}_r)\frac{dt}{\tau} \qquad (2)$$

where P_t is a membrane voltage at time t, P_r is a resting membrane voltage, τ is a time constant, 44ms, v_t is a velocity of the stimulus at time t. For refractory period, hyperexcitability period, and threshold noise standard deviation, the reported values, 1ms, 44ms, and 0.05, respectively, are adopted [3]. α is adjusted to match the previously reported human experiment and electrical recording data, which proved the correctness of the model. RA receptors are randomly placed over a distal phalanx with a density of 140cm^{-2} for top and 40cm^{-2} for bottom part [9], Fig. 4. Sensitivity variation over the receptive field is modeled by varying α.

4 Simulation

Fig. 4 shows the result of optimization. Solid line represents a target illusion edge, and thus we can assume that if the receptors that includes the edge in their receptive field (i.e. ON receptor) have higher response, we will feel a sharp edge since RA is known to be sensitive to edge contour [9]. Hence, the cost function of subgradient method is determined as the difference between the mean response of ON receptors and other receptors (i.e. OFF receptors). Motors near ON receptors tend to have near 60Hz stimulus as the iteration proceeds, Fig. 4 (center), and other motors have higher or lower frequencies. Note that, the amplitude change does not affect much as expected from equation (2). The resulting impulse rates of receptors are shown in Fig. 4 (right) and prove the effectiveness of the method. As expected, ON and OFF receptors have higher and lower impulse rate, respectively, to present the target illusion.

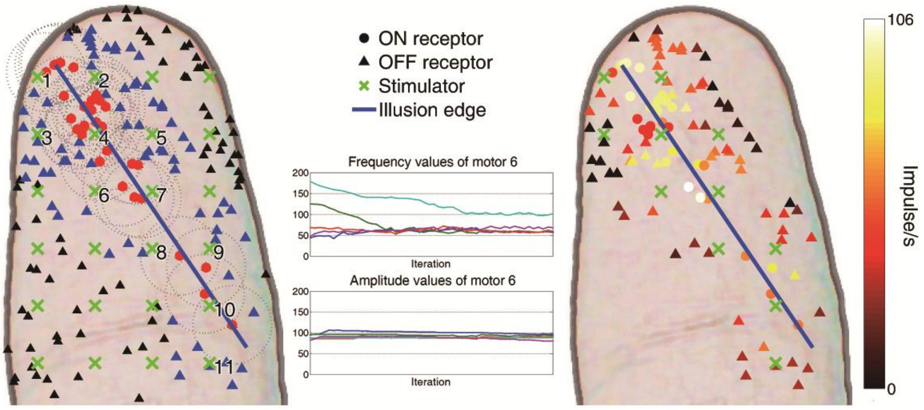

Fig. 4. Simulated distal phalanx model with overlapped 6 by 4 stimulator and target illusion edge (left). After the optimization (center), stimulator patterns are tuned to increase the impulse rate of ON receptors and decrease that of OFF receptor (right).

5 Conclusion

In this paper, a vibrotactile stimulator is implemented and its computational model is derived. In addition, optimal spatio-temporal stimulation patterns for the sensation of a specified edge are obtained using a model of distal phalanx employing RA mechanoreceptor model. Obviously, more detailed modeling of mechanoreceptors and skin [10] and improved optimization method will improve the system. Nevertheless, this preliminary result implicates the important possibility to generate haptic illusion. Not by scanning all possible combinations of stimulus through human experiments, one can considerably shrink the range of combinations before the human experiments. Furthermore, hints for complicated haptic illusions, which are not able to be just anticipated by researcher, can be derived. Once various illusions are reliably generated, the method will be applied to numerous fields from haptic UI to prosthetic skin [11].

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