Proceedings of IMECE2004
2004 ASME International Mechanical Engineering Congress and RD&D Expo
November 13-19, 2004, Anaheim, California USA

IMECE2004-59874

A TWO DOF CONTROLLER FOR A MULTI-FINGER TACTUAL DISPLAY USING A LOOP-SHAPING TECHNIQUE

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ABSTRACT

The design and evaluation of a new controller for a multi-finger tactual (kinesthetic and cutaneous) display, the TACTUATOR, is discussed. A crucial performance requirement is that the relative amplitude of spectral components be preserved in terms of perceived intensity as judged by human users. In this article, we present a two degree-of-freedom controller consisting of a feedback controller and a pre-filter, and its digital implementation. The overall system was evaluated with frequency-response function measurements and with human psychophysical experiments. The measurement results confirm that the steady-state frequency response closely follows the design specifications. The psychophysical results indicate a deviation in the model of the human detection threshold curve at frequencies below 30 Hz. Future work will compensate for this deviation by reshaping the pre-filter. Our work demonstrates the validity of designing controllers that take into account not only the electromechanical properties of the hardware, but the sensory characteristics of the human user.

1 INTRODUCTION

This work was motivated by the desire to develop a tactual[1] display that can assist hearing-impaired individuals with speech communication. That such a goal is attainable is demonstrated by a living tactual communication method called Tadoma used by deaf-and-blind people [2]. In this method, the user puts the hand on a speaker's face to receive multidimensional tactual information such as lip motion, mouth opening, muscle tension, airflow, and laryngeal vibration. Research has shown that Tadoma users can receive oral speech at 12 bits/sec — roughly half the rate at which normal conversations are conducted [3]. In comparison, most tactile aids for the hearing-impaired can only transmit < 5 bits/sec. The difference in performance is perhaps not surprising considering the fact that users of the Tadoma method have access to a rich set of signals associated with speech production whereas most tactile aids can only deliver vibratory signals. The TACTUATOR was therefore developed to be a three-channel (for stimulating the thumb, index, and middle fingers), broad-band (0 to 300 Hz) tactual stimulator capable of delivering signals along the entire kinesthetic (low-frequency large-amplitude motions) to cutaneous (high-frequency small-amplitude vibrations) continuum [4]. Previous experiments using synthetic signals with the TACTUATOR have demonstrated an information rate of 12 bits/sec, which is roughly comparable to that achievable with the Tadoma method [5].

Unlike many current haptic interfaces that are mostly open-loop force-feedback devices, the TACTUATOR is a closed-loop position display. Efforts are now under way to assess user performance using pre-processed speech signals with the TACTUATOR. For example, recorded speech signals for different phonemes can be band-limited to 300 Hz (to match the frequency range of the TACTUATOR) and used as the position reference signals for the controller. When broad-band input signals are used with the TACTUATOR, it is crucial that the relative amplitude of spectral components be preserved in terms of perceived intensity as judged by human users. In other words, if we take into account the frequency response of the

[1] Our definitions of the terms "tactile," "kinesthetic," and "tactual" follow those provided by [1]. The term "tactile" refers to information acquired through surface contact factors via cutaneous sensors in the skin (e.g., information on texture obtained by relative stroking motion between skin and object, information obtained from vibratory arrays, etc.). The term "kinesthetic" relates to information about finger position, motion, and force obtained via sensors in the internal components of the hand, wrist, and arm such as muscles, joints, and tendons. The term kinesthetic is intended to include proprioceptive, and the term "tactual" includes both tactile and kinesthetic.

actuator assembly as well as human sensory characteristics, then the objective of the controller design is to achieve a flat frequency response over the frequency range 0-300 Hz.

In this article, we present a two degree-of-freedom (DOF) controller consisting of a feedback controller and a pre-filter. The feedback controller was designed to counter the low-frequency disturbance due to a user's finger loading the device, to eliminate control-loop resonance, to increase the closed-loop bandwidth, and to reduce the effect of high-frequency noise. It operates on the error signal based on the sensed position of the actuator assembly, and outputs a command signal to the motor. The feedback loop involving the controller and the actuator assembly is preceded by a pre-filter. The pre-filter serves to shape the overall frequency response of the actuator system so that it precisely matches, and therefore cancels, the human detection threshold curve across the frequency range 0-300 Hz. The two DOF controller design has been implemented in a DSP environment with a 4 kHz sampling rate using a bilinear transformation.

The rest of the article is organized as follows. In Sec. 2, we outline the design objectives and method. In Sec. 3, we model the TACTUATOR assembly, position sensor and noise. In Sec. 4, we present the design of the feedback controller and pre-filter in continuous time. The digital implementation is presented in Sec. 5. The evaluation results are presented in Sec. 6. We end the article with a brief summary and discussion in Sec. 7. Given the similarity among the three channels of the TACTUATOR assemblies, we focus our discussion on a single channel.

2 OBJECTIVES

To understand the main objective of the controller design, it is important to first consider the unique characteristics of the human somatosensory system. The "dynamic range" of the mechanoreceptors in the human skin can be defined by the minimum displacement that can be reliably perceived (*detection threshold*) and the maximum displacement that does not cause pain or discomfort. Figure 1 shows a typical human detection-threshold (HDT) curve as a function of sinusoidal stimulus frequency [6]. The inverse of the detection-threshold curve can be regarded as the sensitivity curve, or equivalently, the "frequency response" of the human user. The maximum displacement that is comfortable to the touch is usually 50-55 dB above the detection threshold at the corresponding frequency [7]. Finally, the *perceived intensity* of a signal is roughly determined by the distance between the physical intensity of the signal and the detection threshold at the corresponding frequency [7]. This quantity is called dB sensation level (SL) in the psychophysics literature.

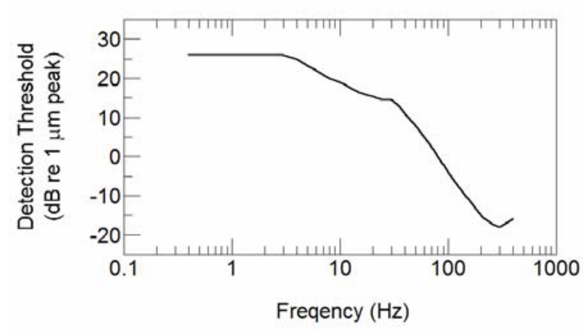

Fig. 1. Human detection threshold (HDT) curve (from Fig. 1 in [6]).

It now follows that to preserve the relative intensity of spectral components of the reference signal in terms of perceived intensity, the main objective of this work was to design a controller such that the combined frequency response of the closed-loop system and the human sensitivity curve was flat across the operating frequency range of the TACTUATOR. Therefore, when a broad-band signal such as that derived from a speech signal is used as the reference input to the overall system, the relative signal strengths will be preserved in terms of dB SL when received by a human user. Figure 2 shows a pictorial explanation of how different spectral components are amplified equally with the intended closed-loop response of TACTUATOR. In the figure, instead of multiplying the frequency responses of the TACTUATOR and the human sensitivity function, we have instead shown the *addition* of their logarithmic transformations for ease of graphic illustration. The result on the right of the equality sign is the overall system response (a constant gain) that is independent of frequency (top blue line). Also shown is the 0 dB SL line (bottom red line).

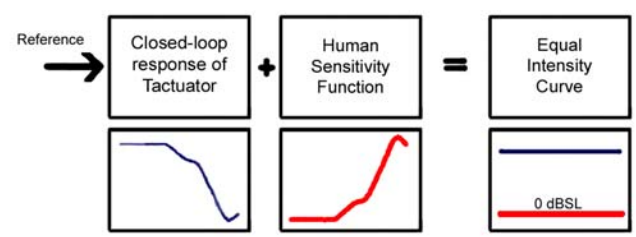

Fig. 2. Pictorial explanation of design objective.

The design objectives were then laid out as follows:

i) Steady-state response of the closed-loop system followed a target frequency function in the range DC to 300 Hz.
ii) In-line 60-Hz noise and high-frequency harmonics were below the HDT levels at the corresponding frequencies.
iii) The level of control-loop resonances was reduced to be below the HDT level.

iv) Low-frequency finger load influenced the overall system response as little as possible.

Classical control design approach was taken because of its comprehensibility in the frequency domain and in input-output analysis. Bode plots were used to represent and analyze the steady-state response of system components that could be modeled as linear time invariant (LTI) systems [8]. The choice of a closed-loop controller enabled us to achieve stability and resistance to parametric uncertainty. An additional prefilter was used to shape the spectral components of the reference signal.

3 SYSTEM AND ENVIRONMENT MODELING

Three major components were considered in system modeling: a single-channel TACTUATOR motor assembly, position sensor, and noise. Figure 3 shows the hardware of a single channel. The frequency response of the motor assembly was obtained by measuring the input-output voltage ratio over the frequency range DC to 400 Hz. Figure 4 shows the measured open-loop magnitude and phase plots. The open-loop response of the motor assembly was well modeled by a second-order linear time-invariant system, which was consistent with earlier work [4]. The parameters of the nominal model were then estimated by a recursive least square algorithm [9]. The stringent condition of persistent excitation (PE), for the parameters to converge to their real value, was fulfilled by using a combination of several signals, such as step, delimiter, random noise and sinusoids, as the inputs to the TACTUATOR motor assembly. The estimated transfer function for the motor assembly is $P(s) = 2875 / \left(s^2 + 94s + 290 \right)$ (shown as Continuous Model in Fig. 4).

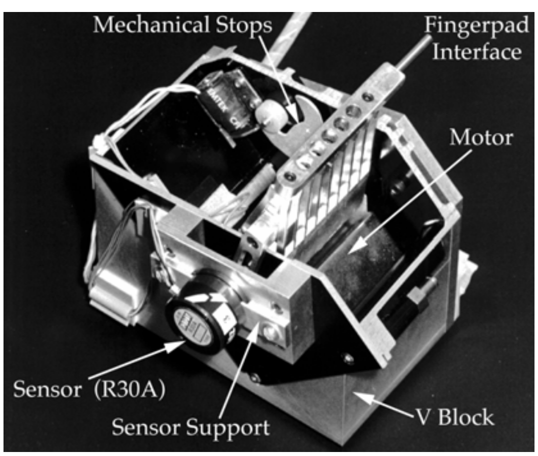

Fig. 3. A single-channel TACTUATOR motor assembly, modified from the head-positioning motor of a hard-disk drive. The user's finger rests on the pin labeled "Fingerpad Interface" in the upper-right corner.

The position sensor, a rotary variable differential transformer, was carefully mounted to be co-axial with the voice-coil motor. The displacement at the fingerpad interface, where the fingertip rests, was roughly linear with the angular movement of the motor. Figure 5 shows the relation between the output of the sensor (in V) and the displacement at the fingerpad interface (in mm, measured with a dial gauge). The sensor gain, estimated from the slope of the best-fitting LSE line, was 0.19898 V/mm.

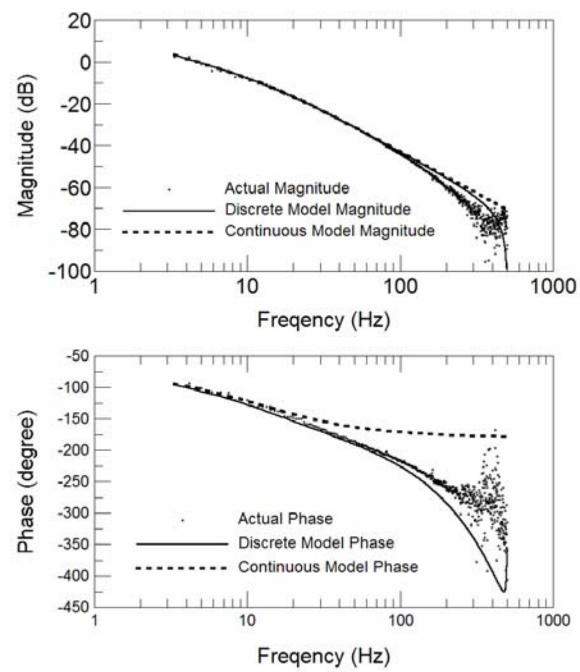

Fig. 4. Open-loop magnitude and phase responses of the TACTUATOR motor assembly *P*(*s*).

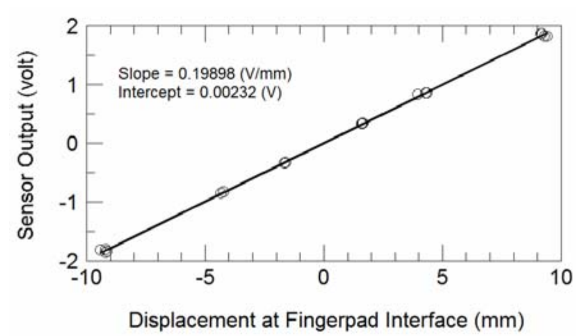

Fig. 5. Calibration of sensor gain.

Expected noise sources were identified in the frequency range of interest by using a proportional controller in a unity feedback loop, where the proportional gain was gradually increased. At low frequencies, friction in the motor assembly reduced the output response of low-amplitude reference signals. Loading due to human finger resting on the fingerpad interface had similar effects on the output. At higher frequencies, in-line 60 Hz noise and its harmonics were above human detection thresholds. It was also observed that the frequency of control-loop resonances increased with the bandwidth of the closed-loop system.

4 CONTROLLER DESIGN

A two DOF controller design similar to that proposed in [10] was chosen to satisfy both performance and robustness requirements. A signal diagram is shown in Fig. 6. The reference position signal, $r(t)$, was first passed through a pre-filter, $F(s)$. The output of the pre-filter was then compared to the measured position signal to form an error signal, $e(t)$, for the feedback controller, $C(s)$. The command signal, $u(t)$, was used to drive the motor assembly, $P(s)$, to achieve a position trajectory of $y(t)$ at the Fingerpad Interface. The effect of finger loading and sensor noise were represented by $d_0(t)$ and $n(t)$, respectively.

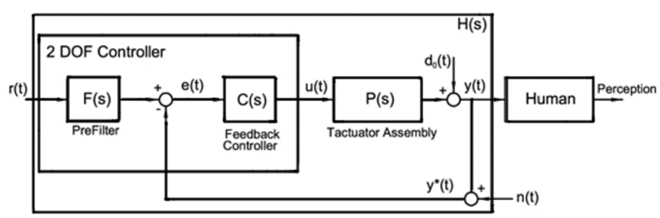

Fig. 6. Closed-loop signal block diagram.

With the assumption of a linear system, the Laplace transform of the finger position $y(t)$ could be expressed as

$$Y(s) = H(s)R(s) + S(s)D_O(s) - T(s)N(s) \quad (1)$$

where

$H(s) = F(s)C(s)P(s)/[1 + C(s)P(s)] = HDT(s)$ (see Fig. 1 for *HDT* function)

$S(s) = 1/[1 + C(s)P(s)]$

$T(s) = C(s)P(s)/[1 + C(s)P(s)]$

and $R(s)$, $D_o(s)$ and $N(s)$ are the Laplace transforms of $r(t)$, $d_0(t)$ and $n(t)$, respectively. The corresponding frequency responses were obtained by setting s to $j\omega$.

From the continuous models described in the previous section, a controller was required to reject low-frequency load disturbances, eliminate control-loop resonances by adjusting the closed-loop bandwidth, and reduce the effect of high-frequency noise. The Nichols chart technique [8] was adapted for its frequency response representation. Open-loop and closed-loop responses can be seen on the same graph. Controller influence on the open-loop response is directly depicted on the closed-loop grids of the same Nichols chart. From Eq. (1), low sensitivity $S(s)$ at low frequencies and high sensitivity at high frequencies would eliminate the effects of disturbances and noise. A compromise in the sensitivity value was needed in the mid-frequency region where the 60 Hz noise was a major source of disturbance.

The feedback controller $C(\omega)$ was designed using the Nichols chart of the plant model $P(\omega)$ (dash-dot) and open-loop response $L(\omega) = C(\omega)P(\omega)$ (dashed), shown in Fig. 7. An integrator was used in the controller to reduce steady-state error in the output signal. Control-loop resonances were reduced by selecting the appropriate bandwidth and thus the response time. The drop in magnitude and phase responses due to the integrator was compensated for by a lead-lag type compensator. The compensator lifted the frequencies so that the low-frequency segment stayed close to the closed-loop 0-dB grid, and the high-frequency segment dropped steeply after achieving a cut-off frequency of 20 Hz, as shown in Fig. 7. System stability required that the frequency response stay to the right of the '+' sign, which is the origin of the Nichols chart. This '+' sign corresponds to the 0 dB magnitude and –180° phase of the open-loop response. The phase margin is therefore indicated by the horizontal distance between the '+' sign and the open-loop response, and the gain margin is determined by the vertical distance between the two. The final design of the feedback controller is

$$C(s) = 12.264\frac{s^2 + 111s + 530}{s(s + 260)}.$$

The prefilter $F(\omega)$ was used to achieve the required frequency response $H(\omega)$. From the block diagram of Fig. 6, we have $H(s) = F(s) \cdot T(s)$. Taking the log of both sides of the equation and expressing the results in dB scale, we obtain

$F(\omega)\ (\mathrm{dB}) = H(\omega) - T(\omega)\ (\mathrm{dB})$.

Its Laplace transform is

$$F(s) = 565.49\frac{s^3 + 199.81s^2 + 17923s + 1.786\times10^5}{s^4 + 1420s^3 + 336711s^2 + 1.12\times10^7 s + 1.01\times10^8}$$

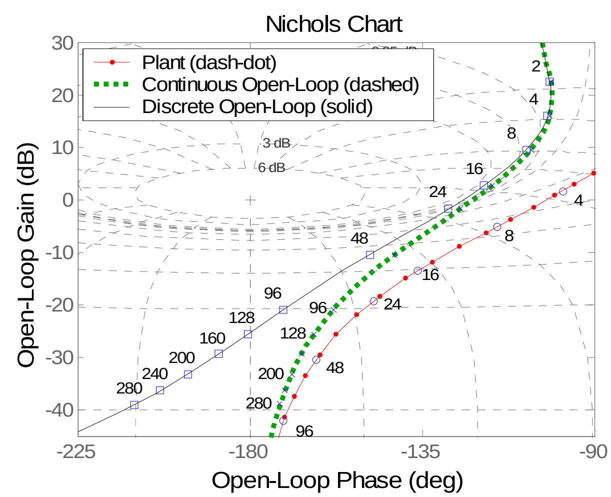

Fig. 7. Loop shaping in Nichols chart.

5 DIGITAL IMPLEMENTATION

The two DOF controller design has been implemented on a SBC6711 standalone card (Innovative Integration, Simi Valley, CA) with four 16-bit A/D and four 16-bit D/A channels (Fig. 8). Given the working frequency range of the TACTUATOR (DC to 400 Hz), a sampling rate of 4kHz to 8kHz was desired [9]. However, a higher sampling rate required higher resolution of the digital controller parameters. Truncating the decimal points in these parameters could potentially lead to system instability. Therefore, the lowest desirable sampling rate of 4kHz was chosen for digital implementation of the two DOF controllers.

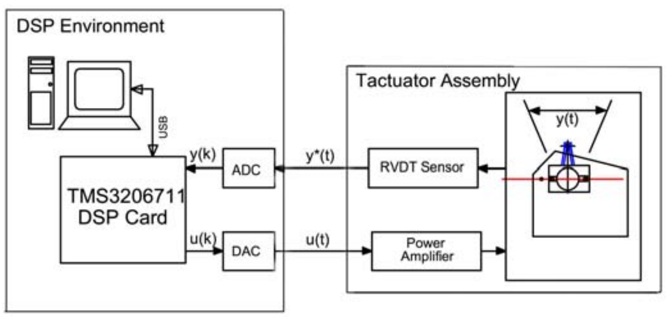

Fig. 8. A diagram of the DSP environment.

The continuous model for the plant $P(s)$ was converted to its ZOH (zero-order hold) equivalent (shown as Discrete Model in Fig. 4). The controllers $C(s)$ and $F(s)$ were converted to discrete functions by bilinear transformation. In a typical ISR (interrupt service routine), the computed controller command is delayed by one sampling period. This delay reduces the stability margin for controller design. In anticipation of this problem, a sufficient stability margin was incorporated into our controller design, as shown by the solid line labeled Discrete Open-Loop in Fig. 7.

6 EVALUATION

Implementation of the two-DOF controller design was evaluated in two ways. First, the closed-loop frequency response function was measured under unloaded and loaded conditions. Specifically, a constant reference input level was used at several frequencies and the position-sensor readings were recorded. Ideally, the position outputs for a fixed input level should be perceived as equally intense across the entire frequency range tested. In other words, the recorded sensor outputs should lie on a curve that is parallel to the human detection threshold (HDT) curve shown in Fig. 1. The measurement results for unloaded condition are shown in Fig. 9. The bottom solid curve in Fig. 9 corresponds to the HDT curve as shown in Fig. 1, after converting units from displacement in μm to sensor output in V. The circles show the measured output at 0 dB SL at selected frequencies. There was generally a close match between the measured data points (circles) and the expected output (bottom solid curve). Deviations at a few frequencies were likely due to signal noises at such a low signal level. The top three solid curves in Fig. 9 are the HDT curve shifted by 10, 30 and 50 dB, respectively. Again, the measured data points at these signal levels followed the predictions closely. These results indicated that we were able to deliver signals with intended perceived intensity values in dB SL. Therefore, the two-DOF controllers were successful at compensating for the frequency response of the motor assembly and the HDT curve. Figure 10 shows similar data for the condition where an index finger rested lightly on the Fingerpad Interface as shown in Fig. 3. The results were essentially the same as those shown in Fig. 9, indicating that the feedback controller was doing a good job at rejecting the low-frequency disturbances caused by the finger load at higher amplitude levels.

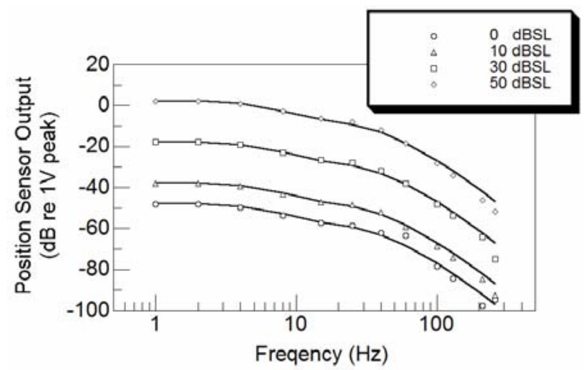

Fig. 9. A comparison of the measured sensor outputs (individual data points) and the predicted output levels (solid lines) at 0, 10, 30 and 50 dB SL, under unloaded condition.

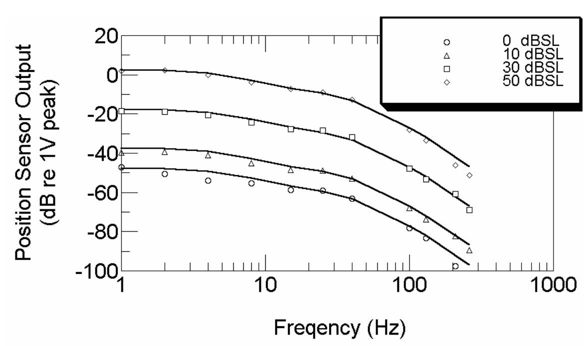

Fig. 10. A comparison of the measured sensor outputs (individual data points) and the predicted output levels (solid lines) at 0, 10, 30 and 50 dB SL, under loaded condition.

Second, psychophysical experiments were conducted to estimate the human detection thresholds for sinusoidal movements with the new controller. This was necessary because detection thresholds are known to vary when conditions such as contact area and body site change [7]. The controller presented in this article was designed based on detection thresholds measured on the thenar eminence [6]. We wanted to estimate the detection thresholds with the TACTUATOR and the two-DOF controller in order to fine-tune the desired frequency response $H(\omega)$.

Detection thresholds were determined with a three-interval forced choice (3IFC) paradigm combined with a one-up three-down adaptive procedure (see [11] and a review of adaptive procedures [12]). Thresholds obtained this way correspond to the 79.4 percentile point on the psychometric function [11]. On each trial, the subject felt three stimuli: two of the stimuli contained a zero-amplitude signal, and the other one contained a sinusoidal position signal. The subject's task was to indicate which of the three intervals ("1", "2" or "3") contained the non-zero signal. The magnitude of the position signal was reduced after the subject had made three consecutive correct responses. The magnitude was increased after each incorrect response. The initial magnitude of the position signal was always set to be higher than the anticipated detection threshold at the corresponding frequency. It changed initially by 4 dB and then by 1 dB after the first three reversals. A reversal occurred when the magnitude of sinusoidal vibration was changed from increasing to decreasing, or vice versa. An experimental run was terminated after 12 reversals at the 1-dB step size. Each run typically lasted 60-90 trials. The average magnitude from the last 12 reversals was taken as an estimate of the threshold.

The results from three human subjects are shown in Fig. 11. The subjects reported no known sensory or motor impairments. Compared with the original HDT curve used in controller design (solid line in Fig. 11), the newly measured thresholds were somewhat higher at lower frequencies and lower at higher frequencies. These results were consistent with other threshold data taken with the TACTUATOR [4] [13]. A new HDT curve, shown as dashed line in Fig. 11, was obtained. The prefilter controller $F(s)$ will be reshaped using this new HDT curve.

7 DISCUSSION AND FUTURE WORK

In this article, we have presented the design, implementation and evaluation of a two-DOF controller system for a multi-finger tactual display called the TACTUATOR. Our design specifications were based on not only the electromechanical characteristics of the actuator, but also the human sensory capabilities as well. We took existing data from the literature on human detection threshold (HDT), and formulated it in the form of a transfer function in the frequency domain. The data from [6] are widely cited and used in psychophysical studies that involve the measurement of displacement detection thresholds under a variety of conditions. After the implementation of the controllers, we re-evaluated the HDT function with the TACTUATOR using three human subjects. Note that it is always a tradeoff to balance the number of subjects and the amount of data collected per subject in any psychophysical experiment. We had chosen to use a small number of well-trained subjects from our laboratory and to collect a large amount of data from them. As can be seen from Fig. 11, we were able to obtain fairly consistent data with a small standard deviation.

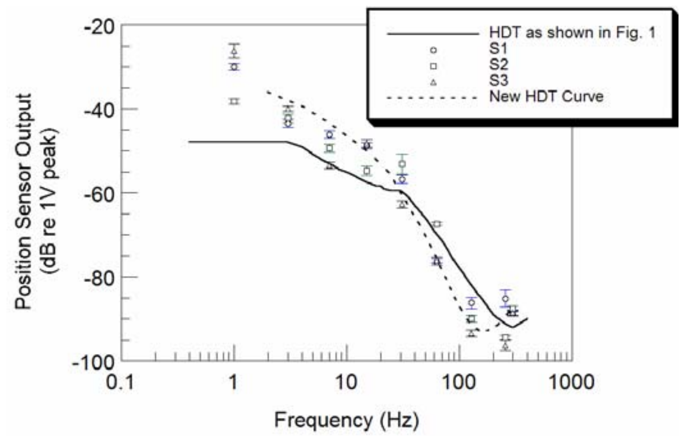

Fig. 11. Detection thresholds for sinusoidal movements measured with the two-DOF controllers. Shown here are individual data points from the three subjects (S1, S2, and S3) along with the standard errors. The HDT curve shown in Fig. 1 is reproduced here (solid line). Dashed line shows the new HDT curve based on the new data taken.

The discrepancy between data from [6] and those measured with the TACTUATOR was likely due to the differences in hardware and in experimental setup. In [6], the location of the body site stimulated was the thenar eminence. Subjects rested their hand on a rigid annulus surround that restricted the extent of skin excitation. Subjects performed experiments in a sound-insulated booth and temperature of the skin contact was maintained at 30˚ C. In the current study, we estimated detection thresholds on an unsupported fingertip with no rigid surround to limit the amount of skin being stimulated. We chose this setup because that is how the TACTUATOR is intended to be used. Brisben et al. ([14], page 1553, last 6 lines of column 2) showed that thresholds for skin contact with no surround at lower frequencies were higher than those evaluated with annulus surround. Despite the expected discrepancy of threshold measurements, our work demonstrates the validity of designing haptic controllers that take into account the unique sensory characteristics of the human user.

In the near future, we will use the new HDT curve (shown as the dashed line in Fig. 11) to re-shape the prefilter $F(s)$ and finalize the controller implementation for the single channel of motor assembly that this study was based on. We will then generalize the methodology presented here to design and implement digital controllers for the remaining two channels of the TACTUATOR. Additional psychophysical data will be collected, using both normal-sensing subjects as well as hearing-impaired individuals (i.e., intended users of the TACTUATOR), to demonstrate that the closed-loop response of the TACTUATOR will indeed follow the human displacement detection thresholds.

One of the original goals for developing the TACTUATOR system was to use it as a multidimensional tactual display for speech communication as an aid to hearing-impaired individuals. To date, studies that have been conducted with the TACTUATOR have used combinations of single-frequency sinusoidal inputs with proper single-point compensations for hardware transfer function and human perception sensitivities. With the new controllers presented in this article, we are now ready to present broad-band speech signals to the TACTUATOR and test its effectiveness in transmitting "rich" information to three digits of the hand. This new capability will allow us to measure, for example, a user's ability to discriminate tactual representations of phonemes based on processed acoustic speech signals. These new studies will bring us closer to achieving the ultimate goal of a tactual speech communication system for people with hearing impairments.

ACKNOWLEDGMENTS

This publication was made possible by Grant Number R01-DC00126 from the National Institute on Deafness and Other Communication Disorders, National Institutes of Health. The third author was also partly supported by the National Science Foundation under Grant No. 9984991.

REFERENCES

[1] J. M. Loomis and S. J. Lederman, "Tactual Perception," in *Handbook of perception and human performance: Cognitive processes and performance*, vol. 2, K. R. Boff, L. Kaufman, and J. P. Thomas, Eds. New York: Wiley, 1986, pp. 31/1–31/41.

[2] C. M. Reed, W. M. Rabinowitz, N. I. Durlach, L. D. Braida, S. Conway-Fithian, and M. C. Schultz, "Research on the Tadoma Method of Speech Communication," *Journal of the Acoustical Society of America*, vol. 77, pp. 247–257, 1985.

[3] C. M. Reed and N. I. Durlach, "Note on information transfer rates in human communication," *Presence — Teleoperators & Virtual Environments*, vol. 7, pp. 509–518, 1998.

[4] H. Z. Tan and W. M. Rabinowitz, "A new multi-finger tactual display," in *Proceedings of the International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, American Society of Mechanical Engineers Dynamic Systems and Control Division*, vol. 58, K. Danai, Ed. NY: The American Society of Mechanical Engineers, 1996, pp. 515–522.

[5] H. Z. Tan, N. I. Durlach, C. M. Reed, and W. M. Rabinowitz, "Information transmission with a multifinger tactual display," *Perception & Psychophysics*, vol. 61, pp. 993–1008, 1999.

[6] S. J. Bolanowski Jr., G. A. Gescheider, R. T. Verrillo, and C. M. Checkosky, "Four channels mediate the mechanical aspects of touch," *The Journal of the Acoustical Society of America*, vol. 84, pp. 1680-1694, 1988.

[7] R. T. Verrillo and G. A. Gescheider, "Perception via the sense of touch," in *Tactile Aids for the Hearing Impaired*, *Practical Aspects of Audiology*, I. R. Summers, Ed. London: Whurr Publishers, 1992, pp. 1–36.

[8] N. S. Nise, *Control systems engineering*, 2nd Edition ed. Menlo Park, Calif.: Addison-Wesley, 1995.

[9] G. F. Franklin, J. D. Powell, and M. L. Workman, *Digital Control of Dynamic Systems*, Second Edition ed. Reading, MA: Addison-Wesley Publishing Company, 1990.

[10] A. C. Zolotas and G. D. Halikias, "Optimal design of PID controllers using QFT method," in *IEEE Proceedings of Control Theory and Applications*, vol. 146(6), 1999, pp. 585 - 589.

[11] H. Levitt, "Transformed up-down methods in psychoacoustics," *Journal of the Acoustical Society of America*, vol. 49, pp. 467-477, 1971.

[12] M. R. Leek, "Adaptive procedures in psychophysical research," *Perception & Psychophysics*, vol. 63, pp. 1279-1292, 2001.

[13] G. Denesvich, "Identification of Frequency and Amplitude through Cutaneous Stimulation," in *Dept. of EECS*. Cambridge, Massachusetts: Massachusetts Institute of Technology, 1995, pp. 32.

[14] A. J. Brisben, S. S. Hsiao, and K. O. Johnson, "Detection of vibration transmitted through an object grasped in the hand," *Journal of Neurophysiology*, vol. 81, pp. 1548-1558, 1999.