31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Electro-Tactile Preference Identification Using Fuzzy Logic

M. Sami Fadali, Yantao Shen, Saeed Jafarzadeh, and Jingang Yi

Abstract— **Electro-tactile based rehabilitation systems must be capable of self-tuning to suit the tactile preference of different users. However, tactile preference is difficult to assess in practice. We propose a Takagi-Sugeno-Kang (TSK) fuzzy logic modeling and control approach for the on-line assessment of tactile preference. The method relies on real-time measurements of voltage and power absorbed by the fingertip. Our results show that the fuzzy logic approach successfully models user tactile preference. We are currently developing an electro-tactile based Braille display (E-Braille) for assisting the Blind and Visually Impaired (BVI) that exploits our fuzzy model.**

I. INTRODUCTION

The goal of our work is to develop a user-friendly electro-tactile technology for rehabilitation applications. An electro-tactile (also called electrocutaneous) display is a tactile device that directly activates nerve fibers within the skin with electrical current from surface electrodes, thus generating fast tactile sensations without the use of complicated mechanical actuators [1], as shown in Figure 1. Electro-tactile display technology has been extensively researched [1]-[8]. It was shown that an electrode can produce tactile sensations with the appropriate electronic signal to stimulate the multiple receptors in the human skin [1][2][6][7][9]. Human skin includes 7 classes of mechanoreceptors, 2 classes of thermoreceptors, 4 classes of nocioceptors, and 3 classes of proprioceptors [1][7]-[10]. Different receptors sense different tactile modalities such as pressure, texture, vibration, temperature, electric voltage and current. Among the different classes of mechanoreceptors the most commonly investigated include: Merkel cells for pressure sensation, the Meisner corpuscle for low frequency vibration and the deep Pacinian corpuscle for high-frequency vibration [7]-[10], as illustrated in Figure 2 (adapted from [7]). Mechanical or electronic stimulations to these mechanoreceptors produce tactile feelings in humans [1][8]-[10].

Currently, although electro-tactile display technology has been extensively researched, the quality control of tactile sensation/preference is still an open research problem [1][5][8][9]. Associated with the sensation quality, the stimulation signal needs to be carefully and accurately controlled following user tactile preference so as to avoid unpleasant sensations. The first step in developing such a tactile preference control system is to obtain a suitable model that characterizing the electrode-skin interface and correlates it to human tactile perception. Because human perception is fuzzy, we use fuzzy logic to model this correlation and show how this fuzzy model can be incorporated in the user interface of a custom-built electro-tactile system to accommodate user preferences. We apply a fuzzy logic modeling approach due to Fadali and Sonbol [11][12] to obtain the fuzzy model from experimental data. The fuzzy model uses Takagi-Sugeno-Kang (TSK) rules with algebraic consequents. Additional rules can be similarly developed and added to the interface to allow the selection of data frequency and other device parameters. The significance of our work is that it greatly improves the rendering performance of electro-tactile systems. The proposed method can be applied to an electro-tactile based Braille display (E-Braille) that we are currently developing for assisting the Blind and Visually Impaired (BVI).

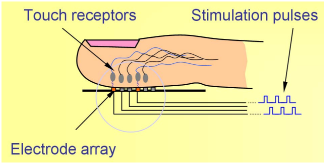

Fig. 1. Illustration of electro-tactile mechanism.

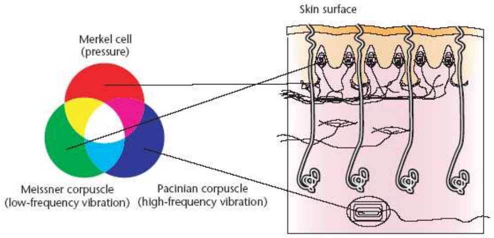

Fig. 2. The mechanoreceptors in human skin. Adapted from [7]

This paper is structured as follows. The electro-tactile display system used to obtain experimental data is described in Section II. The proposed TSK fuzzy logic modeling approach for the identification of tactile preference is introduced in Section III. In Section IV, we demonstrate the modeling approach and present its results. Finally, we provide conclusions and suggestions for future work in Section V.

II. CUSTOM-BUILT ELECTRO-TACTILE DISPLAY FOR DATA COLLECTION

To administer the voltage step-function signals for electro-tactile data collection, we have developed an electro-tactile display terminal illustrated in Figure 3. The tin-coated electrode areas are 0.454 mm^2 with a density of 32 electrodes

This work was partially supported by the IBRAF grant (NSHE-09-X27) from the Nevada System of Higher Education.

M. Sami Fadali, Yantao Shen, and Saeed Jafarzadeh are all with Department of Electrical and Biomedical Engineering, University of Nevada, Reno, Nevada, 89557 USA {fadali,ytshen}@unr.edu

Jingang Yi is with the Department of Mechanical and Aerospace Engineering, Rutgers University, Piscataway, NJ 08854 USA jgyi@rutgers.edu

978-1-4244-3296-7/09/$25.00 ©2009 IEEE

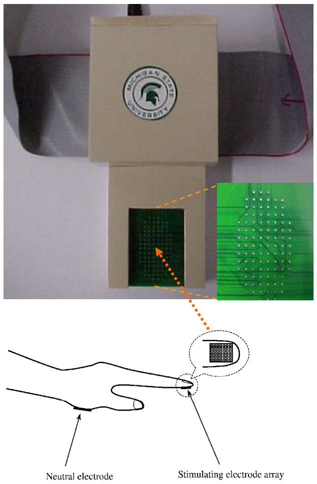

Fig. 3. Electro-tactile display terminal and electrode array.

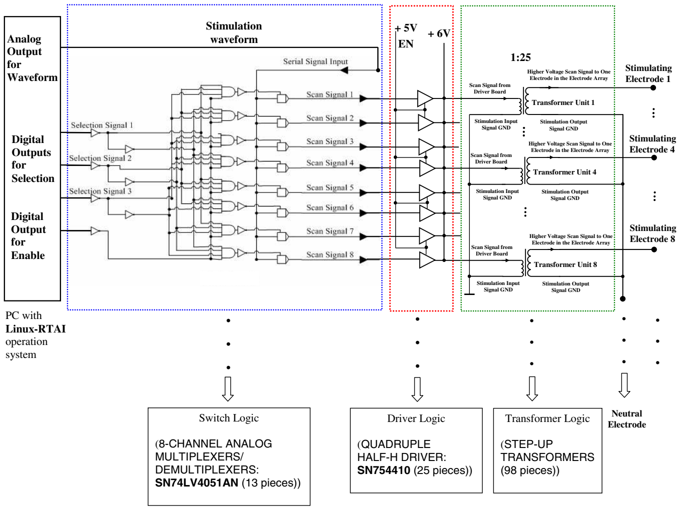

Fig. 4. Logic diagram of the electro-tactile display system.

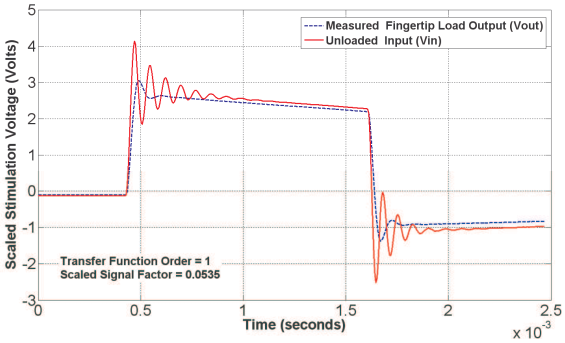

Fig. 5. Typical V_{in} (unloaded input voltage, red solid) and V_{out} (output voltage after finger loading, blue dashed).

per cm^2 and spaced 2 mm apart from one another. These values are roughly consistent with reported spatial resolution of relevant tactile receptors at the fingertips [1][5][10]. The board is custom manufactured PCB. The electrode fingertip-shaped cross section helps conform to the index fingertip. In addition, Figure 4 presents our simplified schematic of a repeatable structure for concurrent row scanning of 8 channel signals on to the respective electrodes of the display terminal. There are a total of 13 of these structures allowing for 104 addressable electrodes (we used 98-electrode array). The analog output channel from the computer acts as input to the current drivers. Each current driver delivers its output to its respective input of one of the 1:25 step up transformers. Three digital output lines and one of the 13 select lines address the analog demultiplexer to pass the analog signal to the ”on” current drivers for a particular 8 bit row scan. The current drivers feature voltage output amplitude level programmability allowing for variable stimulation amplitudes displayed on the electrodes. The design is relatively simple but involves significant tradeoff concerning power efficiency, poor open-loop phase margin, and portability.

Extensive data has been collected using the developed display system. Figure 5 shows the typical stimulus voltage signals (Unloaded: V_{in} and loaded: V_{out}) of one electrode in the array before human finger contact and during human finger contact. In this record, V_{in} was set in a frequency 50Hz, duty circle 5%. From the recording signals ($\sim$195KHz sampling rate, pulse width: 1.2ms), the fingertip skin serves as a functioned electrical damping device to effectively reduce the oscillation of the stimulus signal from V_{in} to V_{out} when the fingertip contacts the active electrode.

III. FUZZY MODELING FOR IDENTIFICATION OF ELECTRO-TACTILE PREFERENCE

The stimulating current induced by the applied voltage must be carefully and accurately controlled to avoid unpleasant sensations and improve electro-tactile display quality. In this paper, we explore the use of fuzzy logic to exploit qualitative data regarding the comfort level and sensitivity of users of the display. Fuzzy logic is particularly appropriate since both measures of performance are subjective and are not easily quantifiable. The parameters must be identified online and used to automatically tune the current to a desired sensation level for the user.

We use the approach of Sonbol [11][12] for the fuzzy modeling of unknown tactile preference functions. We assume that fuzzy systems are multi-input-single-output (MISO) mappings $f : U \subset R^n \rightarrow V \subset R$ where $U = U_1 \times U_2 \times \times U_n \subset R^n$ is the input space and $V \subset R$ is the output space. Hence, we use the TSK fuzzy systems with a rule base of the form:

$$R_{i_1 \ldots i_n} : IF \;\; \mathbf{x} \; is \; \mathbf{A}_{i_1 \ldots i_n} \;\; THEN \;\; y^{i_1 \ldots i_n} = a^{i_1 \ldots i_n} \qquad (1)$$

where

$$\mathbf{x} = [x_1 \cdots x_n]^T, \;\; \mathbf{A}_{i_1 \ldots i_n} = [A_1^{i_1} \cdots A_n^{i_n}]^T,$$

$$i_j = 1, \ldots, N_j, \;\; j = 1, \ldots, n$$

For example, $\mathbf{A}_2^3$ denotes the third fuzzy set of the fuzzy variable x_2. We assume that $\mathbf{A}_{i_1 \ldots i_n}$ are fuzzy sets with normal, complete, and consistent triangular membership functions. Triangular membership functions satisfying these properties are shown in Figure 6.

Sonbol [11][12] derived the following bound on the TSK fuzzy approximation error of a function $g(\mathbf{x})$ which we

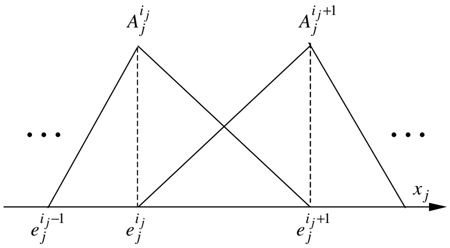

Fig. 6. Triangular membership functions.

restate here without proof.

Theorem 1.
Assume that $\forall \mathbf{x} \in U$:
$g(\mathbf{x})$ is $\mathscr{C}$, $f(\mathbf{x})$ is a fuzzy TSK approximation of $g(\mathbf{x})$ with the rule set in Eqn. (1), and

$$\begin{aligned} g(\mathbf{x}^*) &= f(\mathbf{x}^*), \\ \mathbf{x}^* &= (x_1^{j_1+k_1}, x_2^{j_2+k_2}, \ldots, x_n^{j_n+k_n}) \end{aligned} \tag{2}$$

where $k_i = 0,1,\ i = 1,2,\ldots,n$, and $j_i = 1,2,\ldots,N_i - 1$.

Then the error in approximating $g(\mathbf{x})$ with $f(\mathbf{x})$ is bounded by

$$|g(\mathbf{x}) - f(\mathbf{x})| \leq \frac{1}{2}\sum_{i=1}^{n} h_i^{j_i}(|g'_{x_i}(\alpha_i^{j_i})| + \varepsilon_{i,l}^{j_i} \tag{3}$$

where

$$\varepsilon_{i,l}^{j_i} = \min_{x_i^{j_i} \leq \alpha_i^{j_i} \leq x_i^{j_i+1}} \ \max_{x_i^{j_i} \leq \alpha_i^{j_i} \leq x_i^{j_i+1}} |g_{x_i}^{(l)}(x_i) - g_{x_i}^{(l)}(\alpha_i^{j_i})| \tag{4}$$

$$i = 1,\ldots,n,\quad j_i = 1,\ldots,N_i - 1,$$

$$\alpha_i^{j_i} \in [x_i^{j_i}, x_i^{j_i+1}],\quad h_i^{j_i} = x_i^{j_i+1} - x_i^{j_i}$$

The following steps are used to obtain the fuzzy interface model:
1) Specify the input and output variables.
2) Obtain the input-output data pairs and numerically estimate the partial derivatives of the output with respect to all input variables.
3) Use Theorem 1 to design the membership functions of the inputs.
4) Construct the rule base from the set of measurements corresponding to the input values determined from the membership functions of Step 3.

IV. IDENTIFICATION RESULTS AND DISCUSSION

The objective of this section is to find the preferred voltage V_s (output of the driver or input of the step-up transformer) in the schematic of our electro-tactile structure shown in Figure 4. By adding the fuzzy controller, the structure has been simplified to the block diagram showed in Figure 7 for a particular subject. The peak value of the signal in the absence of a subject/user (in the unloaded case) is V_{in}. When the subject places his/her index fingertip on the display finger port, the peak is reduced. The peak value of the signal in presence of subject/user (in the loaded case) is V_{out}. The signals V_{in} and V_{out} with the peaks are shown in Figure 8 for $V_s = 4.1$.

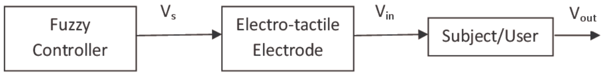

Fig. 7. Block diagram of fuzzy-based controllable electro-tactile system.

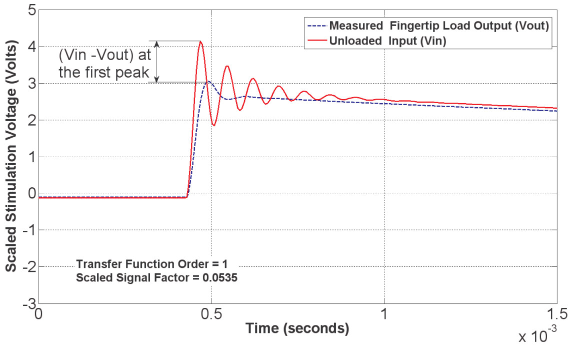

Fig. 8. V_{in} and V_{out} signals, scaled by 0.0535.

To generate the appropriate level for V_s, we evaluate user preference based on the collected experimental data. In practice, the first peak value of $\frac{V_{in}-V_{out}}{V_{in}}$ does not change significantly with input voltage for the same subject/user. We therefore used this parameter to characterize subject preference. Our experiments showed that a certain V_s value or range of values can be assigned to the subject as the input signal to the display system. A summary of representative data points for female subjects is plotted in Figure 9.

As observed from the figure, female preference characteristics are normally in the range 0.05 to 0.25. On the other hand, large input voltages exceeding 7 Volts are unacceptable for all subjects regardless of gender. To control the preference level, we design a fuzzy user interface or controller to represent the experimental data. The TSK fuzzy approach of [11][12], described in Section III, is used for this purpose. The result of applying this approach is shown in Figure 10. The model requires six fuzzy sets which we label as: Extremely Weak, Very Weak, Weak, Medium, Strong, Very Strong. These membership functions are shown in Figure 11.

Figure 11 shows that the widths of the membership

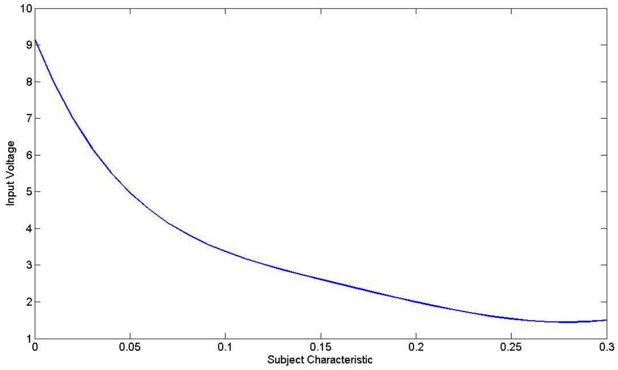

Fig. 9. Summary of experimental data for female subjects.

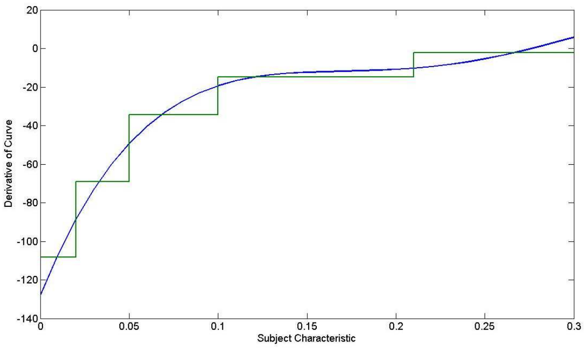

Fig. 10. Derivative of preference curve.

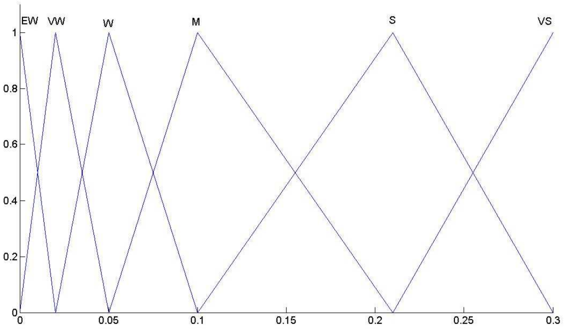

Fig. 11. Fuzzy membership functions for modeling the experimental data.

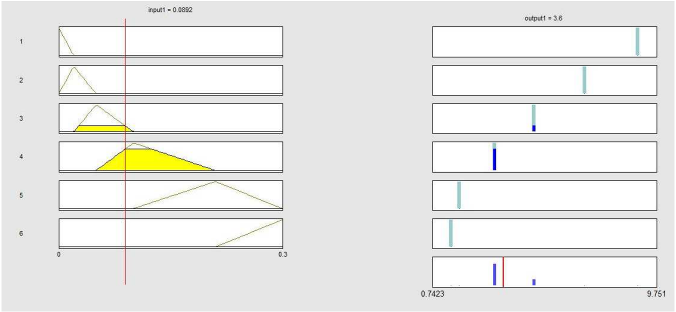

Fig. 12. MATLAB plots for the input-output relations of the controller.

functions are variable with more fuzzy sets required to model rapid changes in the experimental data. This guarantees the estimation error to be less than the specified error bound while reducing the number of required membership functions. A sample input and output for this controller shown in Figure 12.

As shown in Figure 13, the surface for the fuzzy model successfully approximates the user preference data. Decreasing the approximation error requires more fuzzy sets, and consequently more computation. The design of the user interface is typically a compromise between approximation accuracy and computational efficiency.

V. CONCLUSIONS AND FUTURE WORKS

In this paper, we demonstrate how an electro-tactile system can be designed to suit user tactile preferences using fuzzy logic. We use a simple TSK fuzzy logic user interface to identify the electro-tactile preference for female subjects. We demonstrate how fuzzy logic can be used to design an electro-tactile interface that can be set to meet the requirements of individual users. Future research will focus on the implantation of electro-tactile based Braille display and the development of rules to accommodate more BVI user preferences, such as the frequency of the excitation waveform.

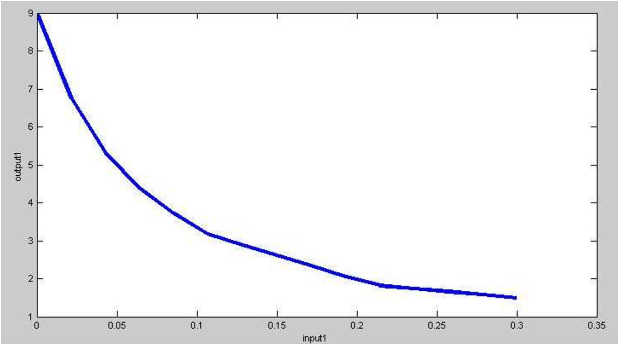

Fig. 13. Fuzzy approximation of the experimental data.

REFERENCES

[1] K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita, and W. J. Tompkins, "Electro-Tactile and Vibrotactile Displays for Sensory Substitution Systems", *IEEE Transactions on Biomedical Engineering*, Vol. 38, pp. 1-15, 1991.

[2] K. A. Kaczmarek, M. E. Tyler, and P. B. Rita, "Electro-tactile Haptic Display on the Fingertips: Preliminary Results", *Proc. 16th Int'l Conf. IEEE Eng. Medicine and Biology*, pp. 940-941, 1994.

[3] C. J. Poletto and C. L. Van Doren, "A High Voltage, Constant Current Stimulator for Electrocutaneous Stimulation Through Small Electrodes", *IEEE Transactions on Biomedical Engineering*, Vol. 46, pp. 929-936, 1999.

[4] A. Y. J. Szeto and F. A. Saunders, "Electrocutaneous stimulation for sensory communication in rehabilitation engineering", *IEEE Transactions on Biomedical Engineering*, Vol. 29, pp. 300- 308, 1982.

[5] L. R. Bobich, J. P. Warren, J. D. Sweeney, S. I. Helms Tillery, and M. Santello, "Spatial Localization of Electro-tactile Stimuli on the Fingertip in Humans", *Somatosensory and Motor Research*, Vol. 24, No. 4, pp. 179-188, 2007.

[6] O. Yarimaga, J. Lee, B. Lee, and J. Ryu, "Tactile Sensation Display with Electro-tactile Interface", *ICCAS 2005*, KINTEX, Gyeonggi-Do, Korea, June 2-5, 2005.

[7] H. Kajimoto, N. Kawakami, S. Tachi, and M. Inami, "SmartTouch: Electric Skin to Touch the Untouchable", *IEEE Computer Graphics and Applications: Emerging Technologies*, Vol. 24, No. 1, pp. 36-43, 2004.

[8] H. Kajimoto, N. Kawakami, T. Maeda, and S. Tachi, "Electrocutaneous Display with Receptor Selective Stimulations", *Electronics and Communications in Japan, Part 2*, Vol. 85, No. 6, pp. 40-49, 2002.

[9] N. Asamura, N. Yokoyama, and H. Shinoda, "A Method of Selective Stimulation to Epidermal Skin Receptors for Realistic Touch Feedback", *Proc. IEEE Virtual Reality Conf., IEEE CS Press*, pp. 274-281, 1999.

[10] A. B. Vallbo and R. S. Johansson, "Properties of Cutaneous Mechanoreceptors in the Human Hand Related to Touch Sensation", *Human Neurobiology*, Vol. 3, pp. 3-14, 1984.

[11] A. Sonbol, "TSK Fuzzy Approximation and Stability Analysis", *Ph.D. Dissertation (M. S. Fadali, Advisor), University of Nevada, Reno, NV*, March 2004.

[12] A. Sonbol, M. S. Fadali, "Fuzzy Lyapunov Stability Analysis of Discrete Type II TSK Systems", *2003 IEEE CDC*, Maui, HI, Dec. 2003.