Data-Driven Rendering of Fabric Textures on Electrostatic Tactile Displays

Jian Jiao, *Student Member, IEEE*, Yuru Zhang, *Senior Member, IEEE*, Dangxiao Wang, *Senior Member, IEEE*, Yon Visell, *Member, IEEE*, Dekun Cao, Xingwei Guo, and Xiaoying Sun, *Member, IEEE*

Abstract—**Due, in part, to the popularity of online shopping, there is considerable interest in enabling consumers to experience material touch via internet connected devices. While there have been several efforts to render texture via electrostatic tactile displays, the textures involved have typically consisted of synthetic patterns, such as shapes, shadings, or gradients of photographic textures. In this paper, we propose a data-driven algorithm for the haptic rendering of fabric textures on an electrostatic tactile display. We measure the friction force, normal force, and displacement during the swiping of a finger across real fabric using a new measurement apparatus introduced here. Using these measurements, we compute friction coefficients derived from the recorded frictional and normal forces. We then reproduce the friction coefficients by controlling the voltage applied to an electrostatic tactile display in order to render the tactile texture of the measured fabric. In order to evaluate this rendering method, we conducted a psychophysical experiment that assessed the visual and haptic similarity of ten real and simulated fabrics. The experimental results show that the virtual textures generated using this electrostatic rendering algorithm were perceptually similar to the corresponding real textures for all fabrics tested, underlining the promise of electrostatic tactile displays for material simulation.**

***Keywords*: Electrostatic touchscreen, texture rendering, fabric textures, tactile display, friction coefficient**

I. INTRODUCTION

Due, in part, to the popularity of online shopping [1], [2], there is growing interest in enabling consumers to touch and feel fabrics via internet connected devices [3]. To address this, new methods for rendering tactile textures of fabrics need to be developed via a surface tactile display device of the network terminal. Surface haptic displays create tactile perception by modulating frictional forces between the finger and surface as a finger slides across the surface of display device [4], [5]. There are essentially two established methods for modulating surface friction: ultrasonic vibration [6], [7] and electrostatic vibration [8], [9], [10]. Ultrasonic vibration reduces friction force between the finger and the surface, whereas electrostatic vibration increases friction forces between a finger and the surface. Bueno et al. [11] preliminarily rendered tactile texture on a high frequency vibration stimulator (STIMTAC) using the frictional force and displacement signals occurring due to a flat sole slider swiping across a real velvet. In this paper, we rendered the haptic textures of fabrics on a surface tactile display using electrostatic attraction. The operating principle of the device is that electrostatic forces are generated between a finger and a surface consisting of a conductor covered with a thin insulating layer as a finger slides on an electrostatic screen surface. When an alternating voltage is applied to the conductor, the capacitive layer between the finger and the device is charged, creating an electrostatic attraction that increases surface friction [12], [13]. The lateral force felt by the finger in motion is modified by a modulation of the attractive force. The modulation is due to the electrostatic force that appears between the finger and the polarized surface [14]. By modulating the applied signal, users are able to experience different touch sensations. Several prior research groups have employed periodic signals, such as sinusoidal or square waves, to drive electrostatic displays to elicit sensations of roughness. These signals are tuned by varying their amplitude and frequency in order to model different textures [4]. Based on this method, some prior researchers rendered the imaginary tactile texture based on the shading and gradients of image by controlling the applied voltage according to the finger movement position on a periodic signal electrostatic tactile display [13], [15].

In previous work [11], haptic texture rendering based on real materials has been performed using frictional force signals occurring due to scanning a rigid probe across a surface via a piezoelectric vibration flat. To date, most electrostatic surface tactile display devices are driven by synthetic periodic signals [16], [17], [18]. In this paper, we propose a data-driven algorithm for rendering fabric textures on an electrostatic tactile display. Using measured signals from real materials, we modulate the applied voltage signals of the electrostatic tactile display to reproduce texture of fabric. In this process, the difficulty lies in how the perceptual information is captured and how it is encoded in the driving signal of the electrostatic surface display.

In this paper, we propose a data-driven algorithm for the haptic rendering of fabric textures on an electrostatic tactile display. The main contributions of this work can be summarized as follows:

1) A novel data-driven tactile texture rendering algorithm was proposed, which depended on finger motion displacement. The movement speed of finger

J. Jiao, Y. Zhang, D. Wang, and X. Guo are with the State Key Lab of Virtual Reality Technology and Systems, Beihang University, No. 37 Xueyuan Road, Haidian District, Beijing, 100191, China. (phone: 010-82338273; fax: 010-82338273; e-mail: jiaojian2jiaojian@163.com, yuru@buaa.edu.cn, hapticwang@buaa.edu.cn).

Y. Visell is with the Department of Electrical and Computer Engineering, Media Arts and Technology Program, California NanoSystems Institute, University of California at Santa Barbara, Santa Barbara, CA 93106, USA. (yonvisell@ece.ucsb.edu).

D. Cao and X. Sun are with the College of Communication Engineering, Jilin University, Nanguan District, Changchun, 130022, China. (sunxy@jlu.edu.cn).

Corresponding author: D. Wang.

is not required when human experienced tactile textures. In the designed system, periodic applied voltage signals were used in haptic texture rendering.

2) Due to the small circuit board used to generate periodic signal, the whole electrostatic tactile display system is miniaturized and low cost.

II. Related Work

In recent years, electrostatic surface haptic displays based on bare finger interaction are receiving increasing attention [19], [20], [21]. Meyer *et al.* presented model for rendering tactile signals via both ultrasonic and electrostatic surface haptic devices, characterizing their dynamics and their bandwidth for rendering haptic effects. The results indicated that, compared with ultrasonic devices, electrostatic devices yield faster responses, facilitating wide-bandwidth forces for texture rendering [4]. Texture rendering on electrostatic devices is achieved by modulating the electrostatic attraction between a bare finger and touch screen. Bau *et al.* found that textures can readily be simulated by accounting for the motion of the finger and controlling the applied voltage, so as to change the friction between the finger and touchscreen [22].

Several prior studies have presented methods for rendering electrostatic textures based on synthetic patterns, such as shapes, shadings, or gradients of photographic textures. Wang *et al.* proposed an electrostatic tactile rendering algorithm for image-based shape features resulting from Gaussian bumps. This algorithm extracts heights of images shape by using the method of shape from shading [15]. Wu *et al.* presented a method for image-based rendering of textures based on gradients of image textures computed via a Roberts filter, with the resulting signals used to modulate friction between the finger and touchscreen [13]. Kim *et al.* presented a tactile rendering algorithm for simulating 3D geometric features, such as bumps, on touch screen surfaces. This was achieved by modulating friction forces between the user's finger and the touch screen [17]. Wang *et al.* presented an electrovibration haptic feedback pen (EV-Pen) for electrostatic touchscreens and used it to carry out the tactile texture simulations [23]. Nakamura *et al.* designed a prototype multitouch. Using this system, several rendering algorithms were implemented for rendering static objects, textured surfaces, and dynamic objects [8]. Later, the method was extended to multi-finger interaction, including softness sensations that were realized by using electroadhesion brakes that were controlled as a function of the normal force [24].

Data-driven haptic rendering is an approach, in which interaction signals are recorded from real objects using a measurement device and reproduce them via haptic feedback device [12], [25], [26]. Culbertson et al. [27], [28] rendered realistic haptic textures, using tool-surface interaction data collected by a haptic recording device, via the TexturePad system which consisted of a Wacom tablet and a stylus augmented with a Haptuator. Pai et al. [29] rendered haptic force of 3D object and tactile texture of its surface with force-feedback device by scanning physical interaction behavior. Abdulali et al. [30] proposed a data-driven approach for modeling haptic responses of textured surfaces with homogeneous anisotropic grain using the signals recorded through sliding a rigid tool across real textures in an unconstrained manner. Concerning haptic texture rendering based on real materials on electrostatic tactile displays, Ilkhani et al. [12] proposed a haptic rendering algorithm for electrostatic textures, in which a function generator is used to replay acceleration signals captured from real textured surfaces.

In this paper, to display the realistic tactile information of fabrics to customers via internet connected devices online shopping, we presented a data-driven texture rendering algorithm for soft fabrics on an electrostatic tactile display using periodic applied voltage signals. In the proposed method, the friction coefficients from real fabrics were amplified as input voltage signals. The applied voltages were used to modulate finger friction on electrostatic tactile display according to finger displacement.

III. Measurement of Finger-Fabric Interaction

A. Apparatus

In order to measure force and displacement signals occurring due to scanning a finger across a real texture surface, we designed a force-displacement measurement system. In our device (Figure 1), we use a cable linkage and a high resolution encoder to track the motion of the fingertip. To measure synchronous displacement of the fingertip movement on the fabric, a high resolution linear encoder (MII1630S-20, MicroE Systems, US, resolution 1 μm) was mounted on the top of base plate. The probe of the encoder is moved on a sliding rail. A cable line connected the probe and fingertip carriage, via a pulley, and moved synchronously with the fingertip. The displacement of the latter was thus recorded during sliding on fabric surfaces. To measure the frictional and normal force, a six-axis force/torque sensor (ATI Nano17, ATI Industrial Automation Inc. US) is mounted on the base plate. The accuracy of the force sensor was 0.003 N, and the maximum sampling rate was 1000 Hz. The fabric was placed on a tray that was fixed on top of the force sensor.

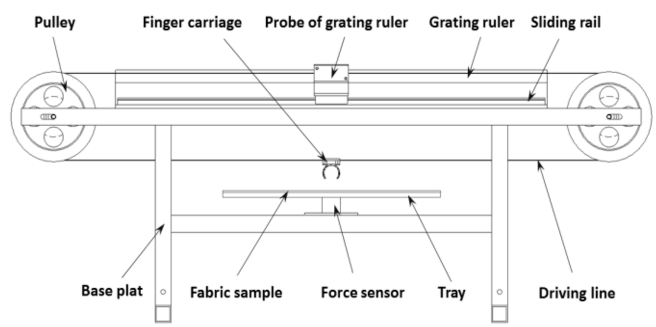


Figure 1. Force-displacement measurement device.

The custom software used to capture the force and displacement signals was developed in C++. The software ran on a computer (3.60 GHz Intel Dual Core i7-4790 CPU PC, Windows 7 operating system).

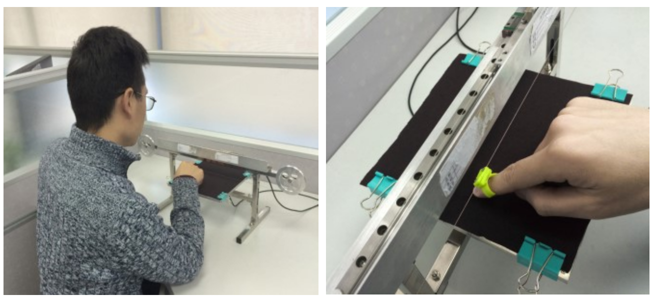
B. Fabric Samples

As shown in Figure 2, we collected 10 fabric samples. These fabrics were cut into the same square shape as the tray. A mark on the back of the fabric was used to label them. We placed them in numbered order, from 1 to 10, and fixed them to the tray via binder clips, to prevent the fabric sample from moving as a fingertip scanned its surface.

Figure 2. Ten fabric samples for haptic texture rendering.

C. Procedure

As shown in Figure 3, a user is seated in front of the force-displacement measurement device at a convenient height and angle. He took the fingertip carriage on the fingertip and moved his fingertip across the fabric surface with a consistent and smooth hand motion during the experiment.



(a) (b)

Figure 3. Force-displacement measurement system. (a) Full view of experiment. (b) Posture of fingertip scanning across a fabric surface.

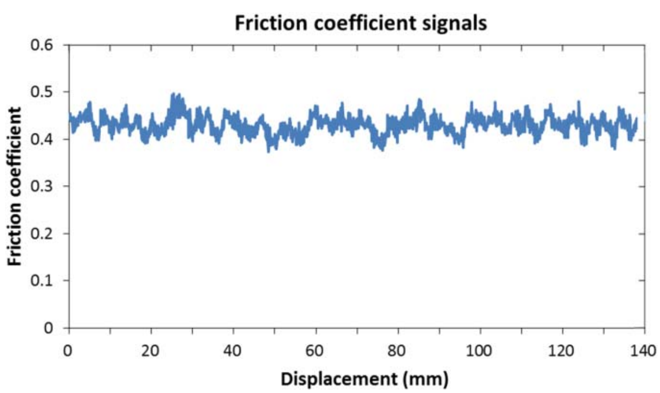


Figure 4. A recorded original friction coefficient signal data for one of the ten fabric samples.

As shown in Fig.3, one user scanned his fingertip across a fabric sample from one side of the texture to another side. In order to eliminate artifacts in the whole experiment, he kept the direction of the fingertip moving on the fabric surface parallel to the line of motion, and carefully regulated the exploration at an approximately normal force of 1N [4], [12] and speed of 50 mm/s [4], [20] using visual bars displayed on a monitor. After each trial, he lifted his finger from the fabric surface and paused while the fabric was changed by the experimenter to the next sample. When he scanned his fingertip across the fabric surface again, the next trial began. This process was repeated four times for each of the ten fabric samples. The whole measurement procedure lasted for more than half an hour for each participant. Figure 4 shows a recorded original friction coefficient signal data for one of the ten fabric samples for swiping once.

IV. Texture Rendering

A. Electrostatic Display

For texture rendering, a custom designed electrostatic tactile display was utilized as shown in Figure 5. The display is based on the physical principle that the Coulomb force exerted on a finger affects the attractive and frictional force felt by the finger sliding through a surface, as developed and validated in our prior work [31].

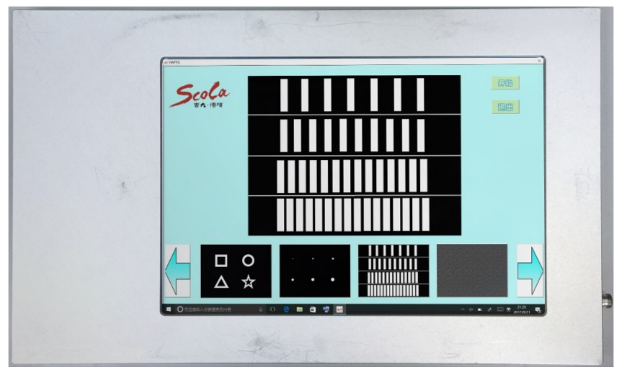


Figure 5. Custom-designed electrostatic tactile display device used in this study, described and validated in our prior research [31].

The display includes a Microsoft Surface, a Micro-touch screen, a tactile controller module and a finger tracking module. The resolution of the Microsoft Surface screen is 2160 x 1440 dpi and the size of Micro-touch screen is 12 inches. The controller module generates the electrostatic driving signals and loads them to the Micro-touch screen, allowing the corresponding tactile sensation to be provided to the fingertip. The tactile excitation signal generator is a programmable voltage source and generates voltages of four waveforms (sinusoidal, square, triangular and sawtooth wave), which provides voltage amplitudes ranging from 0 to 350 V with the accuracy of 2V and frequencies ranging from 1 to 10 kHz with 1 Hz resolution. An optical sensor (GSC0320, TMDTOUCH, China) acquires the finger position signals, which offers 0.1 mm accuracy with a 1 kHz update rate. The graphical user interface and software platform were based on custom software written in C++.

B. Haptic Rendering Algorithm

We chose relatively steady one from the four repeatedly collected friction coefficient signals for each real texture. The selected signals was low-pass filtered at 100 Hz to reduce noise [32]. These filtered friction coefficient signals were amplified in the form of voltage and played back on the electrostatic tactile display to render the tactile texture of fabric. In the present proposed rendering method, the applied voltage signals were computed in the following way.

Firstly, a position-dependent friction coefficient $f(x)$ at the fingertip is calculated using the measured frictional force and normal force, via

$$f(x) = \frac{F_f(x)}{F_n(x)} \tag{1}$$

where x is the displacement of finger, $f(x)$ is the friction coefficient between finger and fabric at position x of displacement, $F_f(x)$ and $F_n(x)$ are the frictional and normal force applied to fingertip at position x respectively.

Secondly, for the applied voltage signals, we use a carrier frequency of 240 Hz since this corresponds to the frequency of greatest sensitivity [33]. The friction coefficient was used in order to specify the nominal voltage to be supplied to the electrostatic display, via

$$V(x) = bf(x)Y(t) \tag{2}$$

where $V(x)$ is the amplitude of square wave voltage applied to the electrostatic tactile display at position x, b is voltage amplification factor from friction coefficient, t denotes time, $Y(t)$ denotes the carrier square wave function, and

$$Y(t) = \begin{cases} 1, & \frac{n}{f_0} \le t < \frac{n}{f_0} + \frac{1}{2f_0} \\ 0, & \frac{n}{f_0} + \frac{1}{2f_0} \le t < \frac{n+1}{f_0} \end{cases}$$

$$f_0 = 240$$

where n is an arbitrary integer, f_0 is the frequency of applied voltage.

The factor b allowed us to match the real and rendered textures. We preliminarily set a value of $b = 400$, with its final value determined in a psychophysical experiment, described below.

Therefore, at any given time during the tactile rendering process, the voltage supplied to the electrostatic touchscreen was determined by the position x of users' sliding motion.

V. Psychophysical Evaluation

We performed a psychophysical evaluation experiment to assess the fabric texture rendering capabilities of the proposed haptic rendering algorithm on the electrostatic tactile display. Two experiments were performed. Experiment I was used to establish an appropriate value for the input voltage amplification factor on the electrostatic tactile display (Equation 2). Experiment II assessed the perceptual similarity between the rendered and real fabric samples.

A. Participants

Fourteen participants, including seven females and seven males, were invited to take part in experiment I or II. All participants were right handed. None of the participants had any prior experience with electrostatic tactile display devices. These participants were all graduate students at Beihang University. Each participant gave written informed consent to participate in the study, and the experiments were performed consistent with the human participant testing regulations of the authors' institution.

In order to make rendering and rating more objective, the participants were divided into two groups for the two experiments. Among them, four participants (one female, three males, age range: 25-30 years, mean: 28 years) took part in Experiment I, and the other ten participants (four females, six males, age range: 22-27 years, mean: 25 years) participated in Experiment II.

B. Experimental Procedures

Before formal testing, all human participants were given an opportunity to familiarize themselves with the experimental apparatus and procedure. Each participant was instructed to sit down in the chair. The two wrists and the forearms of the participant were resting on a table (Figure 6). The electrostatic tactile display was placed on the table and each fabric was placed on right side of the electrostatic device according to the order of testing. Participants were asked to put their left hand on the aluminum shell of the electrostatic tactile display device, to close the voltage loop. When the amplitude of the applied voltage signal was increased or decreased, the participants slide their right index finger across the touchscreen to feel the rendered fabric and assess the perceived realism and roughness.

(a) (b)

Figure 6. Experiment system of voltage amplification factor rating. (a) A participant during testing. (b) Detailed view of voltage amplification factor experiment.

During familiarization, participants were allowed to look at the texture surface that they were touching. After that, the formal psychophysical evaluation experiment began. In order to eliminate the interference of surrounding noise, each participant wore noise insulating earmuffs (PELTOR H10A, 3M Inc, USA) in the whole experiments.

In order to reduce the effect of the external environment on experiment results, participants were instructed to wash their hands with soap and rinsed with water, and dry them to avoid sweating. The screen of the display was cleaned by isopropyl alcohol before experiment. Indoor temperature and humidity in the laboratory were kept at 23 ℃ to 28 ℃ and 35% to 55%, respectively.

1) Experiment I—Adjustment of Voltage Amplification Factor: In this experiment, the goal was to find the amplification factor of applied voltage that each participant judged to provide the most realistic rendering for each fabric sample. In the experiment, the process was repeated for each fabric sample, and was conducted in a different random order for each participant in the experiment. Participants were asked to choose whether the virtual or the real sample beside the screen felt rougher, using a 1-up, 1-down adaptive staircase algorithm [34], [35], [36]. The initial value of the voltage amplification factor was set as 400. If the real surface was evaluated as rougher, the amplification factor of the applied voltage was increased by a step size of 10. If the virtual surface was evaluated as rougher, the voltage amplification factor was decreased by the same step size.

By changing the amplification factor of the applied voltage step-by-step, the voltage amplification factor converged to a value for each participant where participant felt that the virtual surface and real surfaces were similar in roughness. After the first two reversals, the average value from the next four reversals was taken as the final value for the amplification factor of applied voltage. The values for each participant were saved and used in Experiment II.

2) Experiment II—Evaluation of Similarity: In current experiment, the goal was to evaluate the perceptual realism of the haptic texture rendering of the fabric surface using the voltage amplification factors acquired from Experiment I. The evaluation was carried out in a multimodal (haptic and visual) condition and in a purely haptic condition.

Fabric samples were randomly ordered for each of the ten participants. Participants evaluated the similarity of each virtual texture with the corresponding real fabric sample. A 7-point Likert scale was used to rate the similarity from 1 (most dissimilar) to 7 (most similar). In order to eliminate the subjective bias of the participants, we adopted an anonymous approach for evaluating the simulation similarity during the experiment. Each participant was required to autonomously operate the electrostatic tactile display device and write the scores of similarity evaluation in forms on a piece of paper in an independent room. After the experiment, the papers with the results of the evaluation were put into a box by the participants themselves.

C. Experimental Results

1) Adjustment of Voltage Amplification Factor: For a given fabric sample, the preferred amplification factor of applied voltage scaling level for each participant was determined using the adaptive staircase algorithm. Then we can derive the averages and standard deviations of the voltage amplification factor for each fabric sample. As shown in Figure 7, the applied voltage amplification factors determined by participants varied greatly depending on the fabric surface texture.

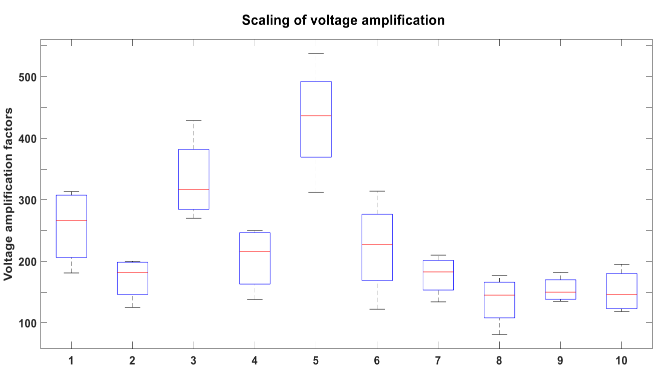


Figure 7. Voltage amplification factor for each participant.

Since the real fabric samples 1, 3, and 5 were much rougher than the other seven samples, the three voltage amplification factors are notably higher than the others. Moreover, several real fabric samples (e.g., the samples 8 and 9) are finer than the others. Their corresponding voltage amplification factors are correspondingly lower. In other words, the rougher the surface texture of real fabric is, the larger the voltage amplification factor is, and vice versa. In addition, most of the voltage amplification factors were between 150 and 200 (Figure 7). These correspond to the fine textures. This illustrates that it may be appropriate to use a voltage amplification factor of less than 200 when rendering a fine texture.

2) Evaluation of Similarity: After taking the average of similarity evaluation for ten participants, the mean values and standard deviations of similarity evaluation for ten different samples were calculated across all ten participants, as shown in Figure 8. In the visuo-haptic similarity evaluation, the mean similarity scores for haptic texture simulation were between 5 and 6 for all fabric samples. For the haptic only condition, the mean scores of similarity were between 5 and 6.5 for all fabric samples.

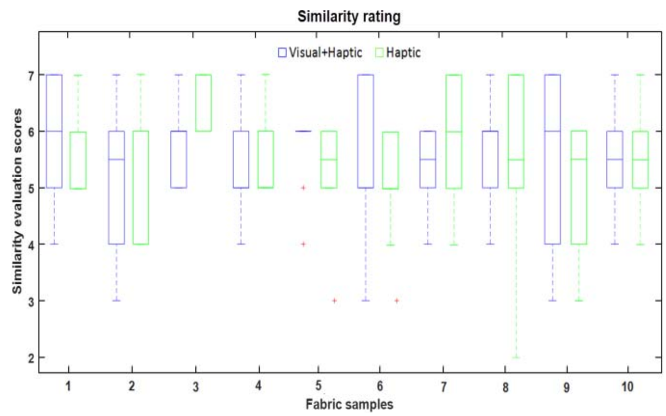


Figure 8. Similarity scores for each fabric samples.

We further analyzed the differences in mean scores of the similarity rating for the tactile texture simulation of fabric between the unimodal and multimodal condition using one-way repeated-measures ANOVA analysis. There were no significant differences between the two conditions, with $F(1,9)=0.009$, $p>0.05$. This indicates that, in the absence of visual feedback, the proposed tactile texture rendering algorithm is able to achieve a similar fidelity as when visual feedback is present. Because the scores nearly saturated the response range, it also suggests that the proposed data-driven haptic texture rendering algorithm is a viable method for simulating fabric textures on electrostatic tactile displays.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a data-driven algorithm for haptic rendering of fabric textures on electrostatic tactile displays. It is achieved by modulating the frictional force between a finger and touchscreen using the amplified friction coefficients as input voltage signals. The frictional and normal force, and corresponding displacement signals, due to the sliding of a finger across a real fabric surface were measured using a customized force-displacement measurement system. We calculated position-dependent friction coefficients based on the measured frictional and normal forces. Subsequently, the friction coefficients were amplified and mapped into input voltages for the electrostatic tactile display for rendering the virtual tactile textures.

We performed two psychophysical experiments to evaluate the fidelity of haptic texture rendering of fabric, and assessed the realism of the rendering in both haptic and visuo-haptic conditions. The experimental results show the virtual textures generated with the data-driven haptic texture rendering algorithm were similar to the real fabric textures. In addition, we observed no significant differences in the realism of simulation between the two conditions.

In the future, motivated by applications in virtual online shopping, we plan to establish a database based on bare finger interaction to cover the force/motion information on large-scale fabric samples. Moreover, we plan to build a bare finger interaction model that might further improve our texture rendering algorithm and enhance the realism of haptic simulation for fabrics, by accounting for more parameters affecting the interactions.

ACKNOWLEDGMENT

This work is supported by the National Key Research and Development Program of China under Grant No. 2017YFB1002803, the National Natural Science Foundation of China under the grant No. 61631010 and No. 61572055. YV acknowledges support from US National Science Foundation grants CNS-1446752 and IIS-1527709.

REFERENCES

[1] K. Jeong, S. Jang, J. Chae, G. Cho, and G. Salvendy, "Use of Decision Support for Clothing Products on the Web Results in No Difference in Perception of Tactile Sensation Than Actually Touching the Material," *International Journal of Human-Computer Interaction,* vol. 24, no. 8, pp. 794-808, 2008.

[2] Y. C. Chou and C. Liang, "The influences of virtual experiences and purchase situations on consumer behavior: A case study of online apparel shopping," in *E-Case & E-Tech International Conference*, 2013, pp. 1-9.

[3] C. S. Nam, P. Richard, T. Yamaguchi, and S. Bahn, "Does Touch Matter?: The Effects of Haptic Visualization on Human Performance, Behavior and Perception," *International Journal of Human-Computer Interaction,* vol. 30, no. 11, pp. 839-841, 2014.

[4] D. J. Meyer, M. Wiertlewski, M. A. Peshkin, and J. E. Colgate, "Dynamics of ultrasonic and electrostatic friction modulation for rendering texture on haptic surfaces," in *Haptics Symposium*, 2014, pp. 63-67.

[5] M. Wiertlewski, J. Lozada, and V. Hayward, "The spatial spectrum of tangential skin displacement can encode tactual texture," *IEEE Transactions on Robotics,* vol. 27, no. 3, pp. 461-472, 2011.

[6] M. Biet, F. Giraud, and B. Lemaire-Semail, "Implementation of tactile feedback by modifying the perceived friction," *European Physical Journal - Applied Physics,* vol. 43, no. 1, pp. 123-135, 2008.

[7] R. F. Friesen, M. Wiertlewski, and J. E. Colgate, "The role of damping in ultrasonic friction reduction," in *Haptics Symposium*, 2016, pp. 167-172.

[8] T. Nakamura and A. Yamamoto, "Multi-finger surface visuo-haptic rendering using electrostatic stimulation with force-direction sensing gloves," pp. 489-491, 2014.

[9] A. Israr, O. Bau, S.-C. Kim, and I. Poupyrev, "Tactile feedback on flat surfaces for the visually impaired," in *CHI'12 Extended Abstracts on Human Factors in Computing Systems*, 2012, pp. 1571-1576.

[10] D. J. Meyer, M. A. Peshkin, and J. E. Colgate, "Fingertip friction modulation due to electrostatic attraction," in *World Haptics Conference*, 2013, pp. 43-48.

[11] M. A. Bueno, B. Lemaire-Semail, M. Amberg, and F. Giraud, "A simulation from a tactile device to render the touch of textile fabrics: a preliminary study on velvet," *Textile Research Journal,* vol. 84, no. 13, pp. 1428-1440, 2014.

[12] G. Ilkhani, M. Aziziaghdam, and E. Samur, "Data-Driven Texture Rendering on an Electrostatic Tactile Display," *International Journal of Human–Computer Interaction,* pp. 1-15, 2017.

[13] S. Wu, X. Sun, Q. Wang, and J. Chen, "Tactile modeling and rendering image-textures based on electrovibration," *Visual Computer,* pp. 1-10, 2016.

[14] E. Vezzoli, M. Amberg, F. Giraud, and B. Lemaire-Semail, "Electrovibration modeling analysis," in *Eurohaptics*, 2016, pp. 369-376.

[15] T. Wang and X. Sun, "Electrostatic tactile rendering of image based on shape from shading," in *International Conference on Audio, Language and Image Processing*, 2015, pp. 775-779.

[16] C. D. Shultz, M. A. Peshkin, and J. E. Colgate, "Surface haptics via electroadhesion: Expanding electrovibration with Johnsen and Rahbek," in *World Haptics Conference*, 2015, pp. 57-62.

[17] S.-C. Kim, A. Israr, and I. Poupyrev, "Tactile rendering of 3D features on touch surfaces," in *Proceedings of the 26th annual ACM symposium on User interface software and technology*, 2013, pp. 531-538.

[18] Y. Vardar, B. Guclu, and C. Basdogan, "Effect of Waveform on Tactile Perception by Electrovibration Displayed on Touch Screens," *IEEE Transactions on Haptics,* pp. 1-1, 2017.

[19] C. Xu, A. Israr, I. Poupyrev, O. Bau, and C. Harrison, "Tactile display for the visually impaired using TeslaTouch," in *CHI'11 Extended Abstracts on Human Factors in Computing Systems*, 2011, pp. 317-322.

[20] Y. Vardar, I. Aykut, M. Saleem, K., and C. Basdogan, "Roughness perception of virtual textures displayed by electrovibration on touch screens," *2017 IEEE World Haptics Conference (WHC),* pp. 263-268, 2017.

[21] T. Nakamura and A. Yamamoto, "A Multi-User Surface Visuo-Haptic Display Using Electrostatic Friction Modulation and Capacitive-Type Position Sensing," *IEEE Transactions on Haptics,* vol. 9, no. 3, pp. 311-322, 2016.

[22] O. Bau, I. Poupyrev, A. Israr, and C. Harrison, "TeslaTouch:electrovibration for touch surfaces," in *ACM Symposium on User Interface Software and Technology, New York, Ny, Usa, October*, 2010, pp. 283-292.

[23] Q. Wang, X. Ren, and X. Sun, "EV-pen: an electrovibration haptic feedback pen for touchscreens," in *SIGGRAPH ASIA 2016 Emerging Technologies*, 2016, pp. 8-9.

[24] T. Nakamura and A. Yamamoto, "Extension of an electrostatic visuo-haptic display to provide softness sensation," in *Haptics Symposium (HAPTICS), 2016 IEEE*, 2016, pp. 78-83.

[25] R. Hover, M. D. Luca, and M. Harders, *User-based evaluation of data-driven haptic rendering*. ACM, 2010, pp. 1-23.

[26] J. Lang and S. Andrews, "Measurement-based modeling of contact forces and textures for haptic rendering," *IEEE Transactions on Visualization & Computer Graphics,* vol. 17, no. 3, pp. 380-391, 2011.

[27] H. Culbertson, J. Unwin, B. E. Goodman, and K. J. Kuchenbecker, *Generating haptic texture models from unconstrained tool-surface interactions*. 2013, pp. 295-300.

[28] H. Culbertson, J. Unwin, and K. J. Kuchenbecker, "Modeling and rendering realistic textures from unconstrained tool-surface interactions," *IEEE Transactions on Haptics,* vol. 7, no. 3, p. 381, 2014.

[29] D. K. Pai *et al.*, "Scanning physical interaction behavior of 3D objects," in *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, 2001, pp. 87-96: ACM.

[30] A. Abdulali and S. Jeon, "Data-Driven Modeling of Anisotropic Haptic Textures: Data Segmentation and Interpolation," in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*, 2016, pp. 228-239.

[31] G. Liu, X. Sun, D. Wang, Y. Liu, and Y. Zhang, "Effect of Electrostatic Tactile Feedback on Accuracy and Efficiency of Pan Gestures on Touch Screens," *IEEE Transactions on Haptics,* vol. PP, no. 99, pp. 1-1, 2017.

[32] H. Culbertson, J. J. Lopez Delgado, and K. J. Kuchenbecker, "One hundred data-driven haptic texture models and open-source methods for rendering on 3D objects," in *Haptics Symposium*, 2014, pp. 319-325.

[33] Y. Vardar, B. Güçlü, and C. Basdogan, "Effect of Waveform in Haptic Perception of Electrovibration on Touchscreens," in *Proceedings, Part I, of the 10th International Conference on Haptics: Perception, Devices, Control, and Applications - Volume 9774*, 2016, pp. 190-203.

[34] T. N. Cornsweet, "The staircase method in psychophysics," *American Journal of Psychology,* vol. 75, no. 3, pp. 485-491, 1962.

[35] H. Levitt, "Transformed up-down methods in psychoacoustics," *Journal of the Acoustical Society of America,* vol. 49, no. 2, pp. 467-477, 1971.

[36] M. R. Leek, "Adaptive procedures in psychophysical research," *Attention, Perception, & Psychophysics,* vol. 63, no. 8, pp. 1279-1292, 2001.