Special Issue on Surface Haptics

THIS special issue is focused on recent research advances in the area of surface haptics. Haptics for interactive touch surfaces, also known as *surface haptics*, is a new area of research in the field of haptics. The goal of surface haptics is to generate haptic effects on physical surfaces such as the touch surfaces used in mobile phones, tablets, kiosks, information displays, and the front panels of new generation home appliances and cars.

This special issue begins with a paper written by the four guest editors (C. Basdogan, F. Giraud, V. Levesque, and S. Choi) that reviews surface haptics by focusing on the three most popular actuation methods: vibrotactile, electrostatic, and ultrasonic.[1] The paper covers the current state of the art in terms of a) *machine haptics* (actuation technologies and methods enabling tactile feedback on touch surfaces), b) *human haptics* (studies investigating human tactile perception and contact mechanics between the fingerpad and touch surfaces displaying tactile feedback), and c) *human-machine haptics* (including tactile rendering algorithms for displaying virtual textures and shapes on touch surfaces, the design of user interfaces and experiences with surface haptics, and applications of surface haptics).

In the area of machine haptics, one of the challenges is multi-touch and multi-user interactions with touch surfaces, which require distinct feedback to individual fingers, and therefore the localization of haptic stimuli on the surface. Dhiab and Hudin demonstrate theoretically and experimentally that vibrotactile stimuli produced by a piezoelectric or electromagnetic actuator can be confined on a narrow plate using the geometry of the waveguide. They further show that the vibrations are not attenuated when a finger applies pressure to the surface. Pantera and Hudin also aim to generate localized tactile stimulation on a touch surface. To cope with the reverberation and the propagation of the vibration waves on the surface, they use several actuators that are controlled by an inverse filtering technique. The idea behind this technique is to calculate the inverse of the transfer functions between the signals driving the actuators and the vibrational displacements to achieve the desired displacements at multiple points on the surface, thereby allowing multi-touch tactile interactions with the fingers. Xu *et al*. investigate the power consumption of the TPad (Tactile Pattern Display), which utilizes ultrasonic transverse vibrations to modulate friction between the human finger and a touch surface made of glass. The authors investigate the relation between the physical and mechanical parameters of the glass surface and the friction reduction to improve the power consumption of their device.

The papers in the group on human haptics focus on modeling the contact interactions between the human finger and a touchscreen under electroadhesion. An oscillating electroadhesive force (also known as electrovibration) is generated between the finger and the screen in the normal direction when an alternating voltage is applied to its conductive layer, leading to an increase in friction between the screen and the sliding finger. Though the practical implementation of this approach is straightforward, our knowledge of the underlying contact mechanics is still limited. To address this shortcoming, Argatov and Borodich propose a theoretical model for investigating the nature of electroadhesive contact between a human finger and a touch surface. They utilize the DMT contact model to account for the adhesive stresses acting on the finger due to electrovibration. They also take into account the nonlinear elastic behavior of the human finger in their model using the framework of the Winker-Fuss approach. The authors suggest that this nonlinear behavior causes a reduction in the apparent contact area that was observed in earlier experimental studies. Basdogan *et al*. suggest another model supported by their experiments conducted with a custom-made tribometer. The authors extend the well-known JKR model to electroadhesive contacts in the normal direction and suggest an empirical approach for handling the frictional contacts in the tangential direction. The unknown parameters of the model are estimated via optimization by minimizing the error between the measured tangential forces and the ones generated by the analytical model. None of the contact modeling studies introduced above consider the effect of environmental factors and the properties of the fingerpad skin on electroadhesion, and thus the tangential friction force. To examine this, Li *et al*. investigate the effect of relative humidity and finger hydration level on the electroadhesion force due to the resulting changes in the effective elastic modulus, contact angle, and capillary forces. Their results show that electrowetting can contribute up to 60% of the increase in friction force with electroadhesion.

The human-machine haptics section opens with a survey paper, written by Costes *et al*., focusing on the rendering of "haptic images" on touch surfaces, which enables the user to touch and feel visual images having textures. The survey reviews the existing literature in this area in terms of a) haptic data and b) hardware technologies enabling the rendering of these data on touch surfaces. The authors emphasize the lack of a generic format for representing haptic data and the hardware solutions that successfully handle the trade-off between expressiveness and usability in rendering the haptic data. The work done by Bernard

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1. Papers submitted to this special issue by the Guest Editors were handled by the journal's Editorial Board.

et al. is an example of the concept of haptic images introduced in the above survey paper. The authors render haptic textures by modulating the friction between the human finger and a touch surface using ultrasonic actuation techniques. In this technique, the touch surface is vibrated at ultrasonic frequencies to generate an air cushion between the finger and the surface, leading to a reduction in friction. By modulating the amplitude of these vibrations, virtual textures can be generated on the touch surface. The authors investigate the detection thresholds of friction-modulated sinusoidal gratings and conclude that they are temporally integrated in the brain, since the threshold values are not affected by the scanning speed. They also find that friction-modulated grating detection thresholds follow similar trends to those of vibrotactile detection, supporting the results of earlier studies. Xu *et al*. render button clicks on a touch surface based on the concept of active lateral force feedback, which is achieved by synchronizing in-plane ultrasonic vibrations and out-of-plane electroadhesive forces. The results of their psychophysical experiments show that the proposed approach has the ability to generate a range of realistic button click sensations that can match subjects' individual preferences.

Finally, this special issue would not be possible without the reviewers. We received several submissions and the review process of all submissions was completed in a timely manner. We also acknowledge the support provided by Editor-in-Chief, Lynette Jones, and Samantha Jacobs of IEEE Publishing Operations.

We hope that you will enjoy reading this special issue.

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