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Recently, haptics research has grown into an interdisciplinary field, covering perception, psychophysics, virtual reality, mechanism design, and control. Haptics research is considered to have originated from teleoperator systems. In these initial explorations, increasing the transparency level of the mechanical master/slave manipulator system was the main issue [1]. As computer graphics technology has emerged to realize a wide range of virtual reality applications, the development of control technologies and haptic master device designs have adapted to focus mainly on interaction with virtual environments. Numerous breakthroughs in visual, sound, and haptic modeling technologies enable the real-time display of contact with virtual objects, including capabilities such as shape deformation and reactive force. There have been attempts to model and display the fine details of touched surfaces to enhance virtual presence [2]. Research in neuroscience and psychophysics has led to discoveries in the human perceptual processes underlying haptic sensations. Drawing on this understanding, researchers have begun to examine efficient

Mechatronics Technology in Mobile Devices

The State of the Art in Tactile Actuators and Related Applications

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methods of building tactile display units that are capable of rendering feelings of roughness, softness, and temperature [3].

In recent years, the communication industry has largely commercialized mobile phones. Recognizing that visual information is one of the most dominant sensory inputs, advancing industries are focusing on increasing the size of the visual display unit in mobile devices. To increase the size of the visual display window, the mechanical keypad has been replaced with a touch screen.

To compensate for the absence of physical feedback that had been provided by the keypad, haptic feedback has been adapted to mobile devices [4]. Currently, most physical haptic feedback is carried in the form of vibrations in mobile devices. Previous generations of physical haptic feedback was based on crude eccentric motors. Hence, mobile companies have been developing a linear vibration motor for enhanced vibrotactile feedback [5]. Current developments in haptic technology are promising to open up new areas in the communication and display industries. This article presents various prominent haptic actuators and related mobile applications.

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Tactile Actuators for Mobile Devices

Voice Coil Motor-Type Actuator

Previously, most commercial vibration actuators were eccentric motors, which generated vibrations using electromagnetic and centrifugal forces. There have been many instances of fruitful research using vibration motors as a media for delivering haptic information to users. Chang et al. developed a mobile system (ComTouch) for providing vibrotactile feedback coupled with auditory information [6]. The ComTouch system allows rich communication among users by converting hand pressure into vibrational intensity. Oakley et al. developed a hardware platform in which a user provides a command to a device with a motion sensor [7]. In their system, a user senses vibrotactile feedback according to scrolling and/or tilting motion. Immersion Corporation developed the VibTonz system that generates vibrotactile sensation [8]. Although the VibTonz system presents a favorable method to increase the quality of communication, current commercial vibration motors cannot sufficiently express the plentiful haptic feedback offered by the VibTonz system. The commercial eccentric motors generate vibration using an electromagnetic and centrifugal force. As an unbalanced mass in the eccentric motor rotates while interacting with a permanent magnet, the intensity of the vibration is coupled with the frequency, and the respond rate to stimulate the user's finger is slow. Therefore, using the eccentric motor limits the ability to discriminate diverse vibrotactile sensation.

To overcome these limitations, voice coil motor (VCM)-type actuators have been developed. Samsung Electro-Mechanics developed a new linear resonance actuator using resonance frequency to generate vibrations [5]. The linear resonance actuator consists of an elastic spring, a plunger, a permanent magnet, and a solenoid coil. When electric current is applied to the solenoid coil, the permanent magnet attached beneath the spring is vertically actuated. This actuation generates a fast vibration. To stimulate highly sensitive human mechanoreceptors, the vibration should be faster, and its frequency and intensity should be decoupled.

Yang et al. developed a crispy vibrator, a compact inertial type of vibration actuator, consisting of an elastic spring, permanent magnet, solenoid coil, and solenoid core [Figure 1(b)]. Figure 1(a) shows the driving principle of the proposed crispy vibrator. The solenoid steel core attracts the permanent magnet, which is connected to the elastic spring, causing the elastic spring to deform from the initial state. This deformation of the elastic spring generates elastic returning force. When one square wave of electric current flows into the solenoid, repulsive force between the solenoid and the permanent magnet is generated. The repulsive force causes the permanent magnet to rise up, and this movement generates inertial force. This inertial force creates one crispy vibration. Likewise, when continuous two square waves of electric current flow into the solenoid, the two crispy vibrations are produced. In this way, a series of the crispy vibrations can be generated, and the frequency of the vibration can be modulated by changing the duty and the duration

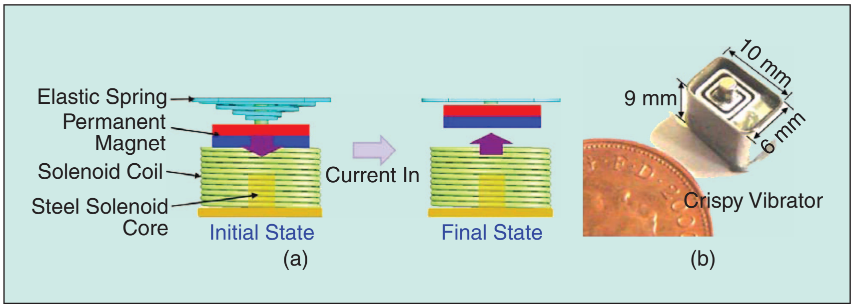

FIGURE 1 – (a) Driving principle and (b) developed figure of crispy vibrator.

Ionic EAPs are actuated by the movement of ions inside the polymer and can be operated at a low voltage.

of the square wave. In addition, if the voltage level of the square wave is controlled, the intensity of vibration can be adjusted independently. Therefore, the frequency and the intensity of the crispy vibrations can be decoupled.

Piezoactuator

To generate more delicate tactile sensations on the touch panel, various piezoactuators were incorporated into mobile devices. SMK Corporation embedded a piezoelectric transducer (PZT) substrate into the touch panel [9]. A PZT substrate is attached beneath the movable touch panel (Figure 2). When pressure is detected on the touch panel, a drive voltage flows into the PZT substrate. In response, the PZT substrate causes the touch panel to vibrate, providing tactile feedback. As the touch panel directly vibrates without an independent vibrating source, there is no energy loss or transmission delay caused by transmitting the vibration.

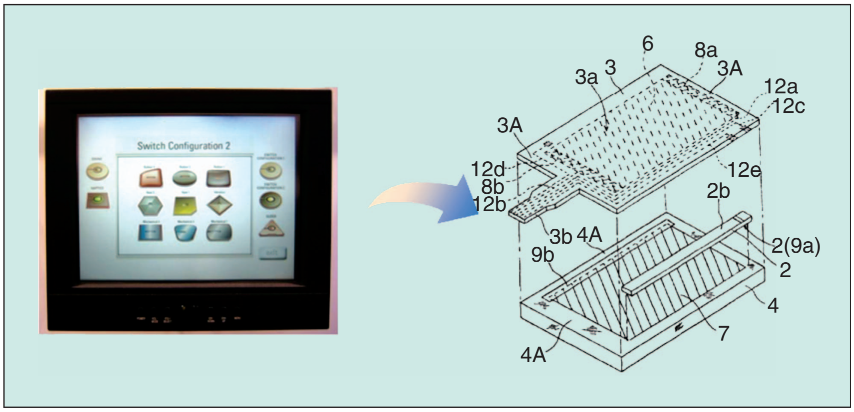

FIGURE 2 – Disassembled haptic touch panel with piezoactuator inside. (Developed by SMK.)

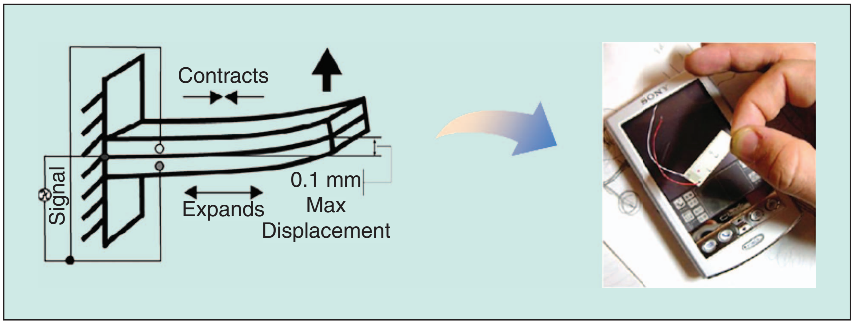

FIGURE 3 – Multilayered PZT actuator.

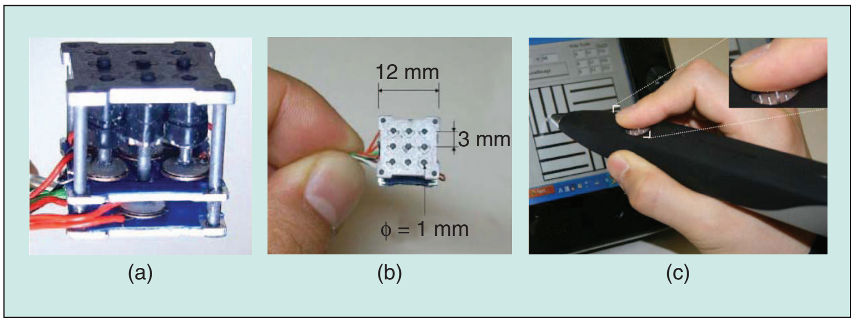

FIGURE 4 – Miniature pin-array tactile module using ultrasonic actuator.

Poupyrev et al. developed a multilayered piezoactuator for mobile devices [10]. The piezoactuator is constructed as a sandwich of 0.28-μm piezoceramic films with adhesive electrodes in between, resulting in a 0.5-mm beam (Figure 3). The piezoceramic material works as a solid-state muscle by either shrinking or expanding depending on the polarity of the applied voltage. The piezoactuator is attached beneath the touch panel of mobile devices. When the piezoactuator is shrinking and expanding, vibrations are created. These vibrations transmit through the touch panel. Therefore, when a user presses the touch panel, the vibration is generated and stimulate the user's tactile sensation.

One of the disadvantages in a conventional piezoactuator is small stroke. Hence, to increase the stroke of piezoactuator, Wagner et al. developed a helically wound PZT ceramic actuator, called the helimorph [11]. As these actuators can actuate over a broad bandwidth, these actuators can convey various tactile sensations, such as the clicking of a button, the surfing of menus, and exploration of a rough surface.

Piezoelectric Technology Corporation developed an ultrasonic actuator [12]. The ultrasonic actuator is composed of a PZT transducer and an inertial mass. When the PZT transducer is actuated in the range of ultrasonic frequencies, it generates a flexural vibration. This vibration generates inertial force to inertial mass, causing the inertial mass to move up and down. Kyung and Lee developed a miniature pin-array tactile module using ultrasonic actuators and a penlike tactile display

(Ubi-pen) using the tactile module (Figure 4) [13]. In their system, nine ultrasonic actuators are arranged to provide tactile sensations. This operating property can be applied to areas of portable devices, such as mobile phones.

The piezoceramic material works as a solid-state muscle by either shrinking or expanding depending on the polarity of the applied voltage.

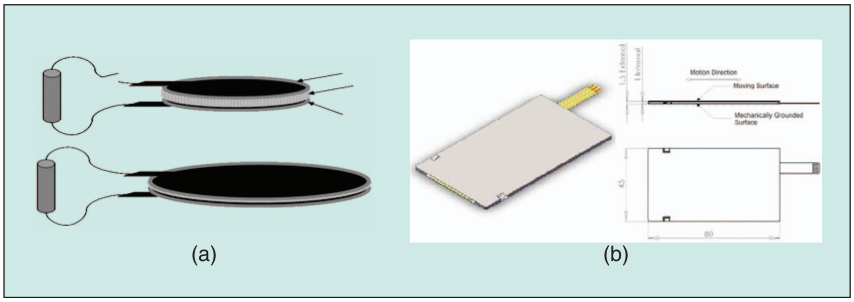

FIGURE 5 – (a) Basic construction of an EPAM device and (b) X-Reflex using EPAM. (Image courtesy of Artificial Muscle, Inc.)

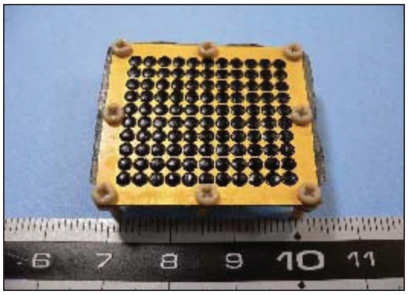

FIGURE 6 – Haptic switch using ion-conductive polymers.

Electroactive Polymer

Electroactive polymers (EAPs) changes shape when voltage is applied. They are generally divided into two principal types: dielectric EAPs and ionic EAPs.

In dielectric EAPs, electrostatic force between two electrodes actuates the polymers. This type of EAP requires high voltages (1–2 kV) to operate, except it consumes comparably low levels of electrical power. AMI Corporation developed the EAP artificial muscle (EPAM) using dielectric EAPs, which consist of a thin layer of dielectric polymer films between two conductive electrodes [Figure 5(a)] [14]. Using this technology, AMI Corporation also created X-Reflex, a haptic actuator, for mobile devices [Figure 5(b)] [14]. This actuator is attached to the back of the front panel of mobile devices and vertically moves a display panel about 150 μm.

Ionic EAPs are actuated by the movement of ions inside the polymer and can be operated at a low voltage. However, the ionic EAPs consume a large amount of power and need fluid to be actuated. Using ionic EAPs, EAMEX Corporation developed a thin haptic switch (Figure 6) [15]. The haptic switch, 0.3-mm thick, is constructed by using a bimorph structure of the electroconductive polymer. Koo et al. proposed a flexible tactile display device made up of soft EAP cells (Figure 7) [16]. Using such technologies, an EAP array was constructed to stimulate human skin without supplementary electromechanical conduction. This wearable tactile display covers the user's fingertip and transmits various tactile sensations to the user.

Shape-Memory Alloy

Shape-memory alloy (SMA) is a metal that has a shape-memory effect. An alloy has particular temperature T_p, and the shape-memory effect is observed when the body temperature becomes lower to below T_p. In this state, it can be easily deformed; however, the original shape can be recovered by heating the body above the temperature. This shape-memory effect has been broadly applied in various fields. The SMA changes its length according to its body temperature, and the SMA-actuating system can be developed by controlling the temperature. Mizukami and Sawada proposed vibration-generating actuator electrically driven by periodic signals. It consists of a muscle wire actuator using an SMA [17]. The muscle wire actuator was

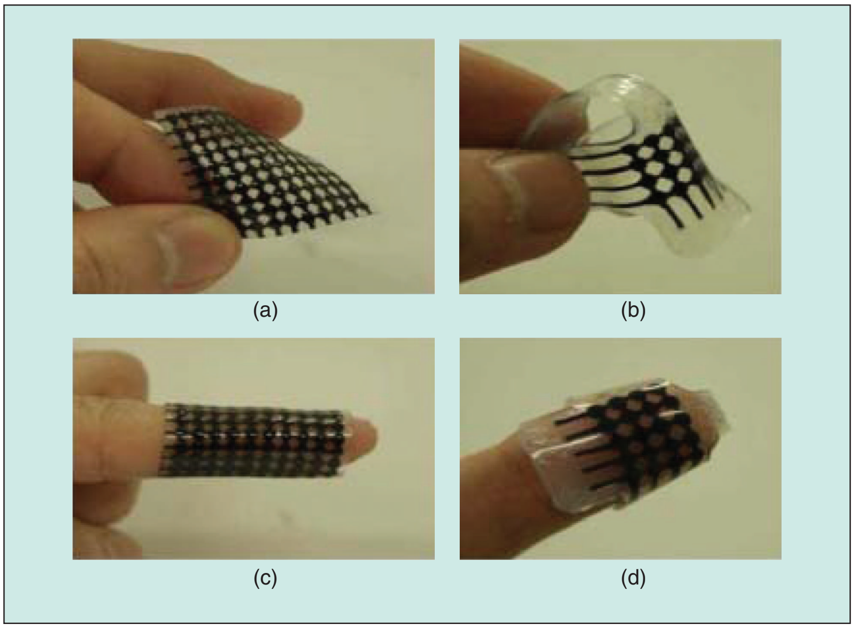

FIGURE 7 – Wearable tactile display using EAPs.

The EAP actuator can be easily molded into any shape, although having a comparably large strain rate.

well designed in the consideration of the size, the working frequency, and the power consumption.

Tactile Displays Using Tactile Actuators

Various tactile actuators, such as a VCM-type actuator, a piezoactuator, an EAP, and an SMA, were introduced. The various tactile displays have been researched using the tactile actuators. Yang et al. proposed a novel miniature pin-array tactile module (Figure 8) [18]. Each pin actuator of the tactile module consists of an elastic spring, a touch pin, a permanent magnet, and a solenoid. The feedback force in this actuator is generated by elastic and electromagnetic forces. To construct a tiny pin-array tactile module, the elastic springs of the actuators are separated into several layers, minimizing the contactor gap without decreasing the performance of the tactile module. Yamamoto et al. presented an electrostatic tactile display that consisted of a thin conductive film slider and stator electrodes [19]. When the electric current is applied into the stator electrodes, the electrostatic force between thin conductive film slider and the stator electrodes generates various tactile sensations. Nara et al. used surface acoustic waves (SAWs) to modulate surface friction [20]. The PZT material below the panel is used to generate SAWs, which control the coefficient of friction. By controlling the friction, various tactile patterns can be displayed. Konyo et al. proposed a ciliary device that uses soft high-polymer gel actuators to generate delicate haptic feedback [21]. Ionic conducting polymer gel film (ICPF) is used for actuating method. Using the ICPF, multiple tactile sensations, such as roughness, pressure, and friction sensations, are generated. Hafez and Khoudja suggested an electromagnet tactile display that consists of a flexible magnetic membrane and magnetic coils [22]. NdFeB permanent magnets are fixed on a flexible magnetic membrane. The flexible membrane is laser cut in the same monolithic steel sheet and positioned on the top of the coils. These microcoils are manufactured on a multilayer printed circuit. To provide more delicate tactile sensation to user, Velazquez et al. presented a pin-array tactile actuating system with an SMA coil and a permanent magnet [23]. In addition, a solenoid actuator has been used in many ways to develop the tactile display. The reason is that it creates enough force and stroke to stimulate human skin and generates a wide-enough frequency bandwidth to convey abundant tactile sensation. Moreover, a solenoid actuator can be easily redesigned for various structures and miniaturized. Therefore, many attempts have been made to develop the tactile displays with solenoid actuators [24]–[26].

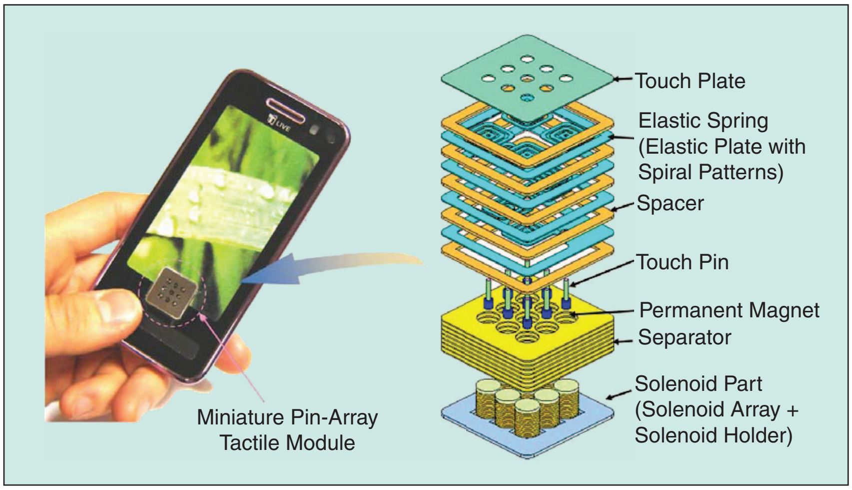

FIGURE 8 – Miniature pin-array tactile module.

Conclusions

This article presents the state of the art in tactile actuators and related applications. The tactile actuators and modules were classified according to actuating mechanisms or manufacturing processes.

First, we introduced a voice coil-type actuator using an elastic spring, a permanent magnet, and a solenoid coil. The voice coil-type actuator can generate a wide range of working frequencies with large strokes and forces. It also provides strong resistance to outer damage. For the aforementioned reasons, the voice coil-type actuator has been widely commercialized in mobile applications. Second, a piezoactuator (constructed using piezoceramic materials) was introduced. Although the piezoactuator is comparably thin and small, it can create strong vibrations across a wide range of working frequencies. However, the brittle characteristic of the piezoactuator limits the applications in mobile devices. Third, an EAP was presented. The EAP actuator can be easily molded into any shape, although having a comparably large strain rate. Hence, it has great potential to generate tactile sensation in mobile devices. Finally, an ultrasonic actuator composed of a PZT transducer and an inertial mass was discussed. A PZT transducer operating in ultrasonic range produces large inertial mass strokes. Through exploring tactile actuators and related applications in haptics technology, a great potential for new areas in mobile devices are prospected/expected.

Although much research has been done on constructing effective tactile displays, haptic feeling is still transmitted on a device separated from visual display. The ultimate goal of haptics is to convey haptic sensation over the visual display unit. Hence, the vibration motor is widely used, because vibration signal can be transmitted through the visual display unit. However, the vibration signal cannot be localized over the visual display. In the future, users will be provided with localized haptic information over the visual display. Thus, more immersive and realistic sensations will be conveyed to the users while interacting with their visual display.

The ultimate goal of haptics is to convey haptic sensation over the visual display unit.

Biographies

Dong-Soo Kwon (kwonds@kaist.ac.kr) received the B.S. degree in mechanical engineering from Seoul National University, Korea, in 1980, the M.S. degree in mechanical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Seoul, in 1982, and the Ph.D. degree in mechanical engineering from Georgia Institute of Technology, Atlanta, in 1991. From 1991 to 1995, he was a researcher at Oak Ridge National Laboratory. He is currently a professor of mechanical engineering and the director of Human-Robot Interaction Research Center at KAIST, Daejon, Korea. He is a Member of the IEEE, the Korean Society of Mechanical Engineers, and is involved with the Institute of Control Robotics and Systems. His research interests include human–robot/computer interaction, telerobotics, medical robots, and haptics.

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References

[1] J.-H. Ryu, D.-S. Kwon, and B. Hannaford, "Stable teleoperation with time domain passivity control," *IEEE Trans. Robot. Automat.*, vol. 20, no. 2, pp. 365–373, 2004.

[2] M. A. Srinivasan and C. Basdogan, "Haptics in virtual environments: Taxonomy, research status, and challenges," *Comput. Graph.*, vol. 21, no. 4, pp. 393–404, 1997.

[3] K. Salisbury, F. Conti, and F. Barbagli, "Haptic rendering: Introductory concepts," *IEEE Comput. Graph. Applicat.*, vol. 24, no. 2, pp. 24–32, 2004.

[4] D.-S. Kwon and S.-C. Kim, "Haptic interfaces for mobile devices: A survey of the state of the art," *Recent Pat. Comput. Sci.*, vol. 1, no. 2, pp. 84–92, 2008.

[5] S. D. Kweon, I. O. Park, Y. H. Son, J. Choi, and H. Y. Oh, Linear vibration motor using resonance frequency, inventors, U.S. Patent 7,358,633 B2, 2006.

[6] A. Chang, S. O'Modhrain, R. Jacob, E. Gunther, and H. Ishii, "ComTouch: Design of a vibrotactile communication device," in *Proc. ACM Designing Interactive Systems Conf.*, 2002, pp. 312–320.

[7] I. Oakley and S. O'Modhrain, "Tilt to scroll: Evaluating a motion based vibrotactile mobile interface," in *Proc. 1st Joint Eurohaptics Conf. and Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Pisa, Italy, Mar. 2005, pp. 40–49.

[8] (2006). Available: http://www.immersion.com/products/touchscreen-feedback/

[9] O. Yoshikawa and H. Ishibashi, Touch panel input device, inventors, U.S. Patent 7,215,329 B2, 2004.

[10] I. Poupyrev, S. Maruyama, and J. Rekimoto, "Ambient touch: Designing tactile interfaces for handheld devices," in *Proc. ACM Symp. User Interface Software and Technology (UIST'02)*, Paris, France, Oct. 2002.

[11] M. Wagner, A. Roosen, H. Oostra, R. Hoppener, and M. De Moya, "Novel low voltage piezoactuators for high displacements," *J. Electroceram.*, vol. 14, no. 3, pp. 231–238, 2005.

[12] (2005). Available: http://www.piezo-tech.com/product/ultrasonic.asp

[13] K.-U. Kyung and J.-Y. Lee, "Ubi-Pen: Windows graphical user interface interacting with haptic feedback stylus," in *Proc. Special Interest Group on Graphics and Interactive Techniques (SIGGRAPH'08)*, Los Angeles, CA, Aug. 2008.

[14] (2005). Available: http://www.artificialmuscle.com/products/reflex-products.php

[15] (2004). Available: http://www.eamex.co.jp/denshi_hp/english/touchPanel_e.htm

[16] I. M. Koo, K. M. Jung, J. C. Koo, J.-D. Nam, Y. K. Lee, and H. R. Choi, "Development of soft-actuator-based wearable tactile display," *IEEE Trans. Robot.*, vol. 24, no. 3, pp. 549–558, 2008.

[17] Y. Mizukami and H. Sawada, "Tactile information transmission by apparent movement phenomenon using shape-memory alloy device," in *Proc. Int. Conf. Disability, Virtual Reality and Associated Technologies*, Esbjerg, Denmark, 2006, pp. 133–140.

[18] T.-H. Yang, S.-Y. Kim, C. H. Kim, D.-S. Kwon, and W. J. Book, "Development of a miniature pin-array tactile module using elastic and electromagnetic force for mobile devices," in *Proc. 3rd Joint EuroHaptics Conf. and Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Salt Lake City, UT, Mar. 2009, pp. 13–17.

[19] A. Yamamoto, S. Nagasawa, H. Yamamoto, and T. Higuchi, "Electrostatic tactile display with thin film slider and its application to tactile telepresentation systems," *IEEE Trans. Visual Comput. Graph.*, vol. 12, no. 2, pp. 201–207, 2006.

[20] T. Nara, M. Takasaki, T. Maeda, T. Higuchi, S. Ando, and S. Tachi, "Surface acoustic wave tactile display," *IEEE Comput. Graph. Applicat.*, vol. 21, no. 6, pp. 56–63, 2001.

[21] M. Konyo, A. Yoshida, S. Tadokoro, and N. Saiwaki, "A tactile synthesis method using multiple frequency vibrations for representing virtual touch," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2005, pp. 107–111.

[22] M. Hafez and M. B. Khoudja, "Tactile interfaces: Technologies, applications and challenges," in *Proc. REM'05*, France, 2005, pp. 56–62.

[23] R. Velázquez, E. Pissaloux, M. Hafez, and J. Szewczyk1, "A low-cost highly-portable tactile display based on shape memory alloy micro-actuators," in *Proc. VECIMS Int. Conf. Virtual Environments, Human-Computer Interfaces, and Measurement Systems*, Giardini Naxos, Italy, 2005, pp. 256–262.

[24] S. F. Frisken-Gibson, P. Bach-Y-Rita, W. J. Tompkins, and J. G. Webster, "A 64-solenoid, four-level fingertip search display for the blind," *IEEE Trans. Biomed. Eng.*, vol. 34, no. 12, pp. 115–120, 1987.

[25] T. Fukuda, H. Morita, F. Arai, H. Ishihara, and H. Matsuura, "Micro resonator using electromagnetic actuator for tactile display," in *Proc. Int. Symp. Micromechatronics and Human Science*, Nagoya, Japan, Oct. 1997, pp. 178–184.

[26] M. B. Khoudja, M. Hafez, J. M. Alexandre, A. Kheddar, and V. Moreau, "VITAL: A new low-cost vibro-tactile display system," in *Proc. 2004 IEEE Int. Conf. Robotics & Automation*, New Orleans, LA, Apr. 2004, pp. 34–38.