Tactile Displays: a short overview and recent developments

Vasilios G. Chouvardas
Department of Informatics
Aristotle University of Thessaloniki
541 24 Thessaloniki, Greece
Email: vchou@csd.auth.gr
Tel.-Fax: +30-2310991922

Amalia N. Miliou
Department of Informatics
Aristotle University of Thessaloniki
541 24 Thessaloniki, Greece
Email: amiliou@csd.auth.gr
Tel.: +30-2310998407

Miltiadis K. Hatalis
Department of Informatics
Aristotle University of Thessaloniki
541 24 Thessaloniki, Greece
Email: mkh@csd.auth.gr
Tel.: +30-2310991916

***Abstract*— Tactation is the sensation perceived by the sense of touch. Tactation is based on the skin receptors. The skin nerves can be stimulated by mechanical, electrical or thermal stimuli. Apart from fibers for pain, skin has six more types of receptors. A review of the state of the art concerning the physiological and technological principles, considerations and characteristics, as well as latest implementations of micro-actuator based tactile graphic displays and the relative software interfaces structures and representations is presented. Fabrication technologies are reviewed in order to demonstrate the potential in tactile applications. Existing electronic Braille displays for accessibility are limited to text-based information. Graphic tactile displays enable for viewing images by the sense of touch on a reusable surface and substitution of the visual/auditory sense. Applications include education, engineering/artistic design, web surfing, and viewing of art and photographs. Tactile substitution can be used in augmenting accessibility for the blind or deaf in order to: (a) to enhance access to computer graphical user interfaces, (b) to enhance mobility in controlled environments. In general tactation based interfaces may allow communication of visual information to the brain in situations where the visual or hearing system is already overloaded such as race car drivers, airplane pilots, operating rooms, virtual reality and tele-presence.**

***Index Terms*— Tactation, tactile displays, tactile interface, tangible interface, MEMS.**

I. INTRODUCTION

Tactile interactions provide important sensory modalities that are prerequisites for many types of practical Virtual Environment (VE) applications. Tactile displays have been proposed as a human-computer interface, in virtual reality applications and as a complement or substitution of the visual presentation of information.

Several groups of researchers are investigating the development and use of tactile interfaces. Much of the basic psychophysical information needed to support a tactile interface in VEs is available, although further investigation is still needed.

Current research is exploring the human capability to detect different surface textures, colors, and complex patterns and utilize the findings in the development of practical devices. However even as research issues start to be resolved, practical problems in engineering and manufacturing versatile displays that can present tactile sensations to various hand and body areas remain to be tackled in order to arrive at new products with practical use.

This paper presents an overview of the state of the art in tactile display technology along with a number of indicative application areas.

In the first section the human tactual sensory system is examined in order to provide an understanding of how we, as humans, interface with the world around us.

The second section presents a classification of the implemented systems, which attempt to automatically convert the images from visual/audio to tactile. The specific techniques used in these systems are detailed along with their existing and potential applications.

The last section presents various software application areas along with their direct implementation to medicine, military, education and entertainment.

II. SKIN PHYSIOLOGY

The skin is the body's largest organ. It's functions include: 1) protecting the body against injury, heat and light radiation, 2) helping the penetration of chemical agents, 3) preventing the invasion of microbes and microorganisms, 4) regulating the body temperature, 5) eliminating harmful substances resulting from the metabolic activities, 6) secreting hormones and enzymes, 7) playing an immunological role, cooperating with langerhans cells and 8) acting as an external sensory organ having several kinds of sensors.

This last function of the skin is the one exploited in tactile interfaces. Unique from other senses the tactual sense is providing information to individuals and primarily to the visually and sensory impaired about such physical world qualities as temperature, perception of texture, position and motion.

In order to guide the design for better interfaces a thorough understanding of the several modalities of the skin's sensors and nerves and their response to external stimuli is essential.

The surface of the skin is made of a conglomeration of dead cells. Underneath the surface, there are very thin and distinct layers, which are called: the *Epidermis* which has a thickness that varies from $0.4mm$ to $1.6mm$, the *Dermis* which is 5 to 7 times thicker than the Epidermis, lying below the epidermis and is linked to it by the basement membrane

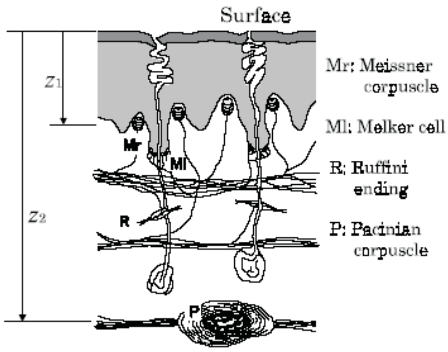


Fig. 1. Skin Anatomy [1].

TABLE I

HUMAN MECHANORECEPTORS AND CORRESPONDING SENSORY MODALITIES

Receptor	Sense modality
Meissner Corpuscle	Stroking, fluttering
Merkel Disk Receptor	Pressure, texture
Pacinian Corpuscle	Vibration
Ruffini Ending	Skin stretch
Hair follicle	Stroking, fluttering
Hair	Light stroking
Field	Skin Stretch

and the *Hypodermis* the skin's third and the last layer, which binds the skin with the muscle tissues. This layer is highly elastic and has fat cells acting as "shock absorbers", thereby supporting delicate structures such as blood vessels and nerves.

The skin characteristics vary along the many parts of the human body. However, the major part of the current research work is related to the glabrous skin (without hair), as most of the applications developed so far are applied either on the palm and finger or some other parts of the body like the abdomen or the arm.

The skin is sensitive to pressure (positive or negative), vibration, temperature, electric voltage and current.

In order to facilitate the sense of touch, the skin includes [2] 7 classes of Mechanoreceptors, 2 classes of Thermoreceptors, 4 classes of Nocioceptors, and 3 classes of Proprioceptors. Table I outlines seven mechanoreceptors and their respective sensory modalities. An analysis of each modality reveals different levels of appropriateness for the construction of a tactile display. Four kinds of mechanoreceptors rely in the skin tissue [1], [3], [4], [5], each at specific depths of the skin. On the palm, the shallowest (Meissner corpuscle) and the deepest (Pacini corpuscle) mechanoreceptors and , are located below the surface by about $0.7mm$ and $2mm$, respectively. Among the different classes of mechanoreceptors the most commonly exploited, in tactile display applications, are the Merkel cells for pressure sensation, the Meisner corpuscle for low frequency vibration and the deep Pacinian corpuscle for high-frequency vibration [6].

Heat and temperature are also important modalities for the sense of touch. Although it seems that the skin is sensitive to temperature, our receptors cannot measure the exact temperature of the surface but, they rather feel the thermal energy flow. Therefore, temperature is used to add quality characteristics to the tactual sense. Also it is known that skin temperature can significaly influence the sense of tactation [7], [8].

The parameters, for each receptor, that mostly affect the design of a tactile display are:

- spatial resolution and sensitivity of the sensors,
- temporal processing characteristics (adaptation, summation); these charactestics classify mechanoreceptive units into four categories; rapidly adapting I and II (RAI and RAII) and slowly adapting I and II (SAI and SAII), whose end organs are Meissner corpuscles, Pacinian corpuscles, Merkel cell neurite complexes, and Ruffini endings, respectively [9],
- spatial features of processing,
- delays in processing information $(0.4 - 120m/s)$.

III. HARDWARE IMPLEMENTATIONS

Exploiting the modalities of the skin's sensors, the systems implemented so far can be classified into the following major categories:

- pressure,
- vibration,
- electric field,
- temperature (or thermal flow).

Furthermore the mechanical or electrical stimulation of the receptors classifies the devices into two categories. Pressure, vibration, wave and electrorheological fluid based devices stimulate the mechanoreceptors using mechanical energy and exploit the modality of each mechanoreceptor. On the other hand a second class of devices has been proposed that directly activate nerves using electric field. The previous modalities are mainly used to present spatial information whereas thermal flow is used to add quality characteristics in the data presented, simulating color in vision. Some applications combine different modalities by selectively activating different receptors and creating a richer communication.

A. Mechanical energy devices

1) Pressure based devices: Pressure based tactile displays follow the scheme presented in Fig. 2. The tactile pattern is formed by an array of pins that can either be in one of two positions (up or down) or vibrate in the vertical direction in order to use both the pressure and vibration modalities of the skin. The array of pins can be used as a graphic display or a Braille display. In order to overcome the difficulties presented by the Braille paper usage, the earlier designs were using reconfigurable pressure tactile displays.

The pins are moved by actuators based on piezoelectricity [10], [11], [12], [13], electrically cotrolled pneumatic valves [14], electromagnetic forces [1], [3]. Piezoelectric Braille displays currently dominate the market, although they are quite

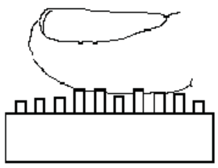


Fig. 2. Typical Tactile Display. Shape displays control the rising movement of the contactors. In a vibrotactile display, the contactors oscillate at a fixed frequency

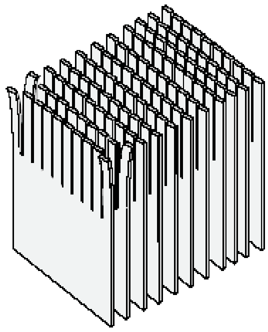


Fig. 3. The STReSS actuator [25].

expensive. They all use the same technology, a little piece of ceramic substrate that is shaped to the right dimensions.

2) Vibration based devices: A significant amount of research has been performed the past fifteen years regarding vibration based (also called *Vibrotactile*) interfaces [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [2], [25] [26], [27], [28], [29], [30], [31].

In [21] a tactile display device is described relying on lateral skin stretch stimulation. It is constructed from an array of 64 closely packed piezoelectric actuators connected to a membrane. The deformations of this membrane cause an array of 112 skin contactors to create programmable lateral stress fields in the skin of the finger pad. Using similar rationality a tactile display system (called the *STReSS* Fig. 3) was constructed [25], which can produce "tactile movies", that is, rapid sequences of tactile images refreshed at a rate of 700 Hz. The display uses an array of one hundred laterally moving skin contactors designed to create a time-varying programmable strain field at the skin surface. The density of the array is of one contactor per millimeter square, resulting in a device with high spatial and temporal resolution.

Ikei et. al [18], [19] presented the design of a haptic texture display consisting of fifty vibratory pins that evoke a virtual touch sensation of textured surfaces contacted to the users fingerpad. A pin drive mechanism was fabricated by adjusting a natural frequency to expand the displacement of a piezoelectric actuator, controlled by a system that enables amplitude changes in 200 steps. Sensation intensity was scaled and indicated by a power function of pin amplitude. The pins used vibrated at a frequency of $250Hz$, corresponding to the stimulation for Pacinian corpuscle.

ComTouch [23], is a device that augments remote voice communication with touch, by converting hand pressure into vibrational intensity in real-time and therefore enriching interpersonal communication by complementing voice with a tactile channel.

In [2] a vibrotactile display is integrated in the shoulder pad, researching the use of vibrotactile displays in wearable devices. Vibration is a suitable candidate for clothing insert based tactile displays as the scale of the impulse and geometry of a vibration device facilitate easy integration into small garment spaces. Furthermore in [29] a wearable interface called "*ActiveBelt*" is proposed, which enables users to obtain multiple directional information with vibratory activated tactile sense. Using Nitinol, a shape memory alloy (SMA), a small and flexible tactile display was constructed for the torso [30]. The design generates large stresses and strains and is able to fit in the thin space of a vest. In experimental tests conducted on the SMA, a pulse $1\ A$ in amplitude and $1\ s$ in duration produced an average displacement of $3.7mm$ and peak pressures about 20 times the touch threshold for the torso. These results are promising in using Nitinol as a basis for wearable devices.

A vibrotactile display, consisting of eight vibrating elements or tactors mounted in a driver's seat, was tested in a driving simulator [27]. The results of the tests ran on participants that drove with visual, tactile and multimodal navigation displays demonstrated that the tactile navigation display reduces the driver's workload, compared to the visual display, particularly in the high workload group. The fastest reaction was found with the multimodal display. It was concluded that a localized vibration or tap is an intuitive way to present direction information, and that employing the tactile channel may release other heavily loaded sensory channels, providing a major safety enhancement. The authors have also considered the use of a vibrotactile display in the cockpit [32].

Ref. [28] presents the use of vibrotactile cues in the torso, as a means of improving user performance on a spatial task. The vibrotactile stimuli were delivered using tactors placed at eight, evenly spaced compass points around the torso of the subject. The tactors were positioned individually for each subject, and held in place by pressure using a neoprene belt, forming a "*TactaBelt*". The tactors vibrated at a frequency of $142Hz$ at $3.0V$, and had a vibration quantity of $0.85G$. In a building-clearing exercise, directional vibrotactile cues were employed to alert subjects currently exposed in areas of the building that were not cleared yet. Comparing the results with and without the use of vibrotactile cues, subjects cleared more of the overall space when given the added vibrotactile stimulus. The average length of each exposure was also significantly less when vibrotactile cues were present.

3) Surface acoustic waves: In [33], [34] a tactile display based on Surface Acoustic Wave (SAW), which can continuously change the fineness of the surfaces grain, is presented. For their implementation they make use of the rapidly adapting characteristic of Meissner corpuscles and Pacinian corpuscles.

4) ElectroRheological and MagnetoRheological devices: *Electrorheological* (ER) tactile displays [35], [36] are a special class of mechanical devices that work with the aid of an ER fluid. An ER fluid is defined [37] as a suspension of a dielectric solid or polymeric particles (the dispersed phase) in an insulating base oil (the continuous phase), which under normal conditions behaves as a Newtonian fluid. On the application of an electric field the fluid has the ability to transform from a liquid to a plastic state in milliseconds, the fluid viscosity being proportional to the field strength. When a tactel (TACTual ELement) is activated the fluid layer above its surface stiffens and the passing probe experiences a significant horizontal and vertical force Fig. 4. A widely accepted description of the ER effect states that the dielectric solid particles in the fluid become polarized and form micro-structures (chains or clusters) under the presence of an electric field. The unique features of ER fluids have led to various applications in clutch systems, shock absorption, noise isolation and vibration control. Even some medical applications in biomedicine have been investigated. The majority of these applications use the fluids in shear mode, whereas the ER fluid in the tactile array is subjected to both shear and squeeze.

Similar to ER fluids, *Magnetorheological* (MR) fluids [38] are suspensions of micron sized ferromagnetic particles dispersed in different proportions of a variety of non-ferromagnetic fluids. MR fluids exhibit rapid, reversible and significant changes in their rheological (mechanical) properties while subjected to an external magnetic field. As with ER fluids, the MR fluids are also in liquid state without external stimuli. While MR fluids are subject to a magnetic field, they behave as solid gels, typically becoming similar in consistency with dried-up toothpaste. Recent MR fluids are becoming increasingly important in applications concerning active control of vibrations or switching/control of torque/force.

B. Electro-tactile stimulating devices

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 [15], [**?**], [39], [6], thus generating sensations of pressure or vibration without the use of any mechanical actuator.

In [?] and [6] the authors proposed an augmented reality system of cutaneous sensation, the SmartTouch. In the prototype system, a mounted optical sensor converts visual information from a contact object into tactile information, and electrical stimulation is employed as a means to present tactile information. The stainless steel electrodes, each $1.0mm$ in diameter, are arranged as a 4×4 matrix in the form of a Braille display. The longitudinal and transversal interval of the electrodes is $2.5mm$ and $2.0mm$ respectively. Using short anodic and cathodic pulses they have managed to selectively stimulate the Merkel cells (pressure sensation) and the Meissner corpuscles (vibratory sensation) respectively.

In [39] the design of a polyimide-based flexible oral tactile display with an array of 7×7 tactual actuators (*tactors*) is proposed, for the presentation of electrotactile patterns onto the roof of the mouth. The device is micro-fabricated on a rigid substrate using thin-film and electroplating processes. Dome-shaped tactors are electroplated through round openings $300\mu m$ in diameter in the flexible polyimide base for more uniform current distribution and better contact with the skin. The overall dimensions of the tactor array are $18.5 \times 18.5mm^2$, with a center-to-center spacing of $2.54mm$ between adjacent tactors. Each tactor is $200\mu m$ in height and $700\mu m$ in diameter. The flexible oral tactile display has been tested in human subject experiments and found to deliver comfortable electro-tactile stimulation with relatively low stimulation intensities.

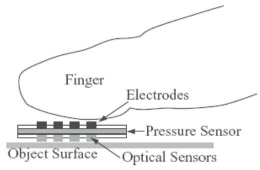


Fig. 5. Cross-section of prototype SmartTouch [?].

IV. Application Software

There is a growing family of software applications, predominantly designed for the Windows environment. Some indicative recent application areas include:

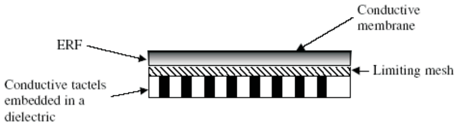
- Text and Graphics
- Medical applications
- Entertainment and Educational applications
- Military applications
- Tactile displays embedded in consumer electronics and wearable devices

A. Text and Graphics

Tactile devices allow the user to read the computer screen and obtain text-based information using refreshable Braille displays [14], [40], Braille readers [13] and/or tactile mice [41], [42], [**?**] in direct-manipulation systems. HyperBraille [43] provides access to the web adopting the GUI (Graphical User Interface) concept of the pull-down menus and customize it on a Braille display. Another example of a www -based system is the ACCESS project [44] that presents hypermedia information in Braille. Graphic tactile displays enable viewing 2D images and 3D objects by the sense of touch on a reusable surface [45], [46], [12] while some experimental work has been done on conveying object surface texture [47], [18]. Furthermore, projects like GUIB (Graphical User Interface for the Blind) [48] or Mercator [49] aim towards accessing GUI through a non-visual interface supporting special sounds and tactile output devices.

B. Medical applications

A remote palpation system will convey tactile information from inside a patient's body to the surgeon's fingertips during minimally invasive procedures [50]. These instruments will contain tactile sensors that measure pressure distribution on the instruments as tissue is manipulated. Creation of remote



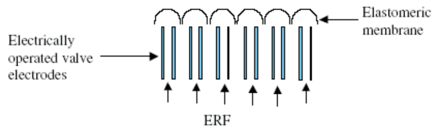


Fig. 4. ERF in squeeze mode (left) and ERF in flow mode (right) [**?**].

palpation technology will increase safety and reliability in present minimal invasive procedures. Furthermore, tactile displays may be used for "smart" surgery, i.e. when the "smart" scalpel contacts a vital region such as an artery, the sensor detects surface information and the display produces repulsive force to protect the region [6].

C. Entertainment and Educational applications

Several software applications have been developed for amusement and educational purposes. Most of the programs are realizing the function of drawing /erasing tactile images [12], cognitive games, tactile tools, and a range of learn & play software applications [41]. Additionally, an application program for the delivery of music notation to blind people has been developed [51].

D. Military applications

Tactile displays have shown to provide improved situation awareness to operators of high performance weapon platforms, and to improve their ability to spatially track targets and sources of information. Tactile displays can reduce perceived workload by its easy-to-interpret, intuitive nature, and can convey information (strong vibrotactile sensation) without diverting the user's attention away from the operational task at hand [52], [53], [29], [54], [55], [32].

Tactile displays are used specifically in:

- Military aviation for spatial orientation as well as threat and target information.
- Underwater operations for guidance and communication cues.
- Training and simulation adding the sense of feel and providing a more realistic physical response in training situations.
- Land forces for guidance, navigation and communication cues.
- Space exploration for continuous orientation information.

E. Tactile displays embedded in consumer electronics and wearable devices

Tactile interfaces can be also used as a channel for communicating with miniature handheld [10], [23], [11], [2], [31] or wearable devices [54], [2], [30] providing more effective, comfortable and enjoyable interaction. Some of the uses will include navigation [29], [55], [27], notification though touch, monitoring the status of a process or using gestures to interact with the device.

REFERENCES

[1] N. Asamura, N. Tomori, and H. Shinoda, "A tactile feeling display based on selective stimulation to skin receptors," in *Proc. IEEE Virtual Reality Annual International Symposium '98*, 1998, pp. 36–42.

[2] A. Toney, L. Dunne, B. H. Thomas, and S. P. Ashdown, "A shoulder pad insert vibrotactile display," in *Proceedings of the Seventh IEEE International Symposium on Wearable Computers (ISWC03)*, 2003, pp. 35 – 44.

[3] N. Asamura, N. Yokoyama, and H. Shinoda, "A method of selective stimulation to epidermal skin receptors for realistic touch feedback," in *Proceedings IEEE Virtual Reality Conference*, 3 1999, pp. 274–181.

[4] Geiger, *Handbook of Physiology*, 1984, ch. Section 1: The Nervous System.

[5] T. Maeno, K. Kobayashi, and N. Yamazaki, "Relationship between the structure of human finger tissue and the location of tactile receptors," *Bulletin of JSME International*, vol. 41, no. 1, pp. 94–100, 1998.

[6] H. Kajimoto, N. Kawakami, S. Tachi, and M. Inami, "Smarttouch: Electric skin to touch the untouchable," *IEEE Computer Graphics and Applications*, vol. 24, Issue 1, pp. 36 – 43, 2004. [Online]. Available: http://ieeexplore/ieee.org/iel5/38/28489/01273449.pdf?isnumber=28489&arnumber=1273449

[7] K. A. Provins and R. Morton, "Tactile discrimination and skin temperature," *Journal of Applied Physiology*, vol. 15, pp. 155–160, 1960.

[8] G. A. GESCHEIDER, J. M. THORPE, J. G. S., and J. BOLANOWSKI, "The effects of skin temperature on the detection and discrimination of tactile stimulation," *Somatosensory & Motor Research*, vol. 14, no. 3, pp. 181 – 188, July 1 1997.

[9] R. Johansson, "Tactile sensory coding in the glabrous skin of the human hand," *Trends in Neurosciences*, vol. 6, no. 1, pp. 27 – 32, 1983.

[10] I. Poupyrev, S. Maruyama, and J. Rekimoto, "Ambient touch: designing tactile interfaces for handheld devices," in *UIST '02: Proceedings of the 15th annual ACM symposium on User interface software and technology*. New York, NY, USA: ACM Press, 2002, pp. 51–60.

[11] I. Poupyrev and S. Maruyama, "Tactile interfaces for small touch screens," in *Proceedings of the 16th annual ACM symposium on User interface software and technology*. ACM Press, 2003, pp. 217–220.

[12] M. Kobayashi and T. Watanabe, "A tactile display system equipped with a pointing device — MIMIZU," *Lecture Notes in Computer Science*, vol. 2398, pp. 527–??, 2002. [Online]. Available: http://link.springer-ny.com/link/service/series/0558/bibs/2398/23980527.htm;http://link.springer-ny.com/link/service/series/0558/papers/2398/23980527.pdf

[13] C. Ramstein, "Combining haptic and braille technologies: design issues and pilot study," in *Proceedings of the second annual ACM conference on Assistive technologies*. ACM Press, 1996, pp. 37–44.

[14] L. Yobas, D. M. Durand, G. G. Skebe, F. J. Lisy, and M. A. Huff, "A novel integrable microvalve for refreshable braille display system," *JOURNAL OF MICROELECTROMECHANICAL SYSTEMS*, vol. 12, no. 3, pp. 252 – 263, June 2003.

[15] K. Kaczmarek, J. Webster, P. Bach-y-Rita, and W. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems," *IEEE Transactions on Biomedical Engineering*, vol. 38, Issue 1, pp. 1 – 16, 1991. [Online]. Available: http://ieeexplore.ieee.org/iel1/10/2420/00068204.pdf?tp=&arnumber=68204&isnumber=2420

[16] S. F. Wiker, G. Vanderheiden, S. Lee, and S. Arndt, "Development of tactile mice for blind access to computers: Importance of stimulation locus, object size, and vibrotactile display resolution," in *Proceedings of the Human Factors Society 35th Annual Meeting*, ser. General Sessions: Human Factors Issues in Medicine, vol. 1, 1991, pp. 708–712.

[17] D. A. Kontarinis and R. D. Howe, "Tactile display of vibratory information in teleoperation and virtual environments," Oct. 23

1996. [Online]. Available: http://hrl.harvard.edu/~howe/publications/HighFreqDisp.ps

[18] Y. Ikei, K. Wakamatsu, and S. Fukuda, "Vibratory tactile display of image-based textures," *IEEE Computer Graphics and Applications*, vol. 17, no. 6, pp. 53–61, Nov./Dec. 1997. [Online]. Available: http://computer.org/cga/cg1997/g6053abs.htm

[19] Y. IKEI, K. W. TSU, and S. FUKUDA, "Texture presentation by vibratory tactile display," in *Proceedings of the 1997 Virtual Reality Annual International Symposium (VRAIS '97)*, 1997.

[20] M. Kawakami, M. Mamiya, T. Nishiki, Y. Tsuji, A. Okamoto, and T. Fujita, "A new concept touch-sensitive display enabling vibro-tactile feedback," in *Proceedings of the HCI'98 Conference on People and Computers XIII*, ser. Innovative User Interfaces: Multimedia and Multimodal User Interfaces, Wearable Computers and Virtual Reality, 1998, pp. 303–312.

[21] V. Hayward and J. M. Cruz-Hernández, "Tactile display device using distributed lateral skin stretch," in *Proceedings of the 8th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME IMECE*, vol. DSC-69-2, 2000, pp. 1309–1314. [Online]. Available: http://citeseer.ist.psu.edu/380716.html

[22] S. F. Yasushi Ikei, Mariko Yamada, "A new design of haptic texture display/texture display2 and its preliminary evaluation," in *Proceedings of the Virtual Reality 2001 Conference (VR?01)*, 2001.

[23] A. Chang, S. O'Modhrain, R. Jacob, E. Gunther, and H. Ishii, "Comtouch: design of a vibrotactile communication device," in *DIS '02: Proceedings of the conference on Designing interactive systems*. New York, NY, USA: ACM Press, 2002, pp. 312–320.

[24] J. B. F. van Erp, "Guidelines for the use of vibro-tactile displays in human computer," in *EUROHAPTICS 2002*, 2002.

[25] J. Pasquero and V. Hayward, "Stress: A practical tactile display system with one millimeter spatial resolution and 700 hz refresh rate," in *Proceedigns of EUROHAPTICS*, 2003.

[26] J. Cohen, M. Niwa, R. W. Lindeman, H. Noma, Y. Yanagida, and K. Hosaka, "A closed-loop tactor frequency control system for vibrotactile feedback," in *CHI '05 : extended abstracts on Human factors in computing systems*. ACM Press, 2005, pp. 1296–1299.

[27] J. B. V. Erp and H. A. V. Veen, "Vibrotactile in-vehicle navigation system," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 7, no. 4-5, pp. 247–256, July-September 2004.

[28] R. W. Lindeman, J. L. Sibert, E. Mendez-Mendez, S. Patil, and D. Phifer, "Effectiveness of directional vibrotactile cuing on a building-clearing task," in *CHI '05: Proceeding of the SIGCHI conference on Human factors in computing systems*. New York, NY, USA: ACM Press, 2005, pp. 271–280.

[29] K. Tsukada and M. Yasumura, "Activebelt: Belt-type wearable tactile display for directional navigation," in *Lecture Notes in Computer Science*. Springer-Verlag GmbH, Oct 2004, vol. 3205, pp. 384 – 399.

[30] M. Nakamura and L. Jones, "An actuator for the tactile vest - a torso-based haptic device," in *Proceedings Haptic Interfaces for Virtual 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS 2003)*, March 22-23 2003, pp. 333 – 339.

[31] A. Nashel and S. Razzaque, "Tactile virtual buttons for mobile devices," in *CHI '03 extended abstracts on Human factors in computing systems*. ACM Press, 2003, pp. 854–855.

[32] H. A. H. C. van Veen and J. B. F. van Erp, "Tactile information presentation in the cockpit," *Lecture Notes in Computer Science*, vol. 2058, p. 174, 2001.

[33] T. Nara, M. Takasaki, T. Maeda, T. Higuchi, S. Ando, and S. Tachi, "Surface acoustic wave tactile display," *IEEE Computer Graphics and Applications*, vol. 21, no. 6, pp. 56–63, Nov./Dec. 2001. [Online]. Available: http://dlib.computer.org/cg/books/cg2001/g6056abs.htm;http://dlib.computer.org/cg/books/cg2001/pdf/g6056.pdf

[34] M. Takasaki, T. Nara, S. Tachi, and T. Higuchi, "A tactile display using surface acoustic wave," in *Proceedings 9th IEEE International Workshop on Robot and Human Interactive Communication (RO-MAN 2000)*, 2000, pp. 364–367.

[35] D. Klein, H. Freimuth, G. Monkman, S. Egersd?rfer, A. Meier, H. Bose, M. Baumann, H. Ermert, and O. Bruhns, "Electrorheological tactel elements," *Mechatronics*, 2005.

[36] G. J. Monkman, "An electrorheological tactile display," *Presence*, vol. 1, no. 2, pp. 219–228, 1992.

[37] P. M. Taylor, D. M. Pollet, A. Hosseini-Sianaki, and C. J. Varley, "Advances in an electrorheological fluid based tactile array," *Displays*, vol. 18, no. 3, pp. 135–141, 15 May 1998.

[38] Y. Liu, R. Davidson, P. Taylor, J. Ngu, and J. Zarraga, "Single cell magnetorheological fluid based tactile display," *Displays*, vol. 26, no. 1, pp. 29–35, January 2005.

[39] H. Tang and D. J. Beebe, "Design and microfabrication of a flexible oral electrotactile display," *JOURNAL OF MICROELECTROMECHANICAL SYSTEMS,*, vol. 12, no. 1, pp. 29–36, 2003.

[40] J. Roberts, O. Slattery, and D. Kardos, "Rotating-wheel braille display for continuous refreshable braille," in *Society for Information Display conference in Long Beach, California, May 18; 2000 SID International Symposium Digest of Technical Papers*, vol. XXXI, May 2000, pp. 1130–1133.

[41] "Virtouch imaging applications." [Online]. Available: http://www.virtouch2.com

[42] R. G. Hughes and A. R. Forrest, "Perceptualisation using a tactile mouse," in *VIS '96: Proceedings of the 7th conference on Visualization '96*. Los Alamitos, CA, USA: IEEE Computer Society Press, 1996, pp. 181–ff.

[43] T. Kieninger, "The "growing up" of hyperbraille an office workspace for blind people," in *UIST '96: Proceedings of the 9th annual ACM symposium on User interface software and technology*. New York, NY, USA: ACM Press, 1996, pp. 67–73.

[44] H. Petrie, S. Morley, P. McNally, P. Graziana, and P. Emiliani, "Access to hyper-media systems for blind people," Sensort Disabilities Research Unit, 1996.

[45] T. Maucher, K. Meier, and J. Schemmel, "The heidelberg tactile vision substitution system," in *Proceeding of the Sixth International Conference on Tactile Aids, Hearing Aids and Cochlear Implants*, 2000.

[46] Y. Kawai and F. Tomita, "Interactive tactile display system: a support system for the visually disabled to recognize 3d objects," in *Proceedings of the second annual ACM conference on Assistive technologies*. ACM Press, 1996, pp. 45–50. [Online]. Available: http://www.acm.org/pubs/articles/proceedings/assets/228347/p45-kawai/p45-kawai.pdf

[47] Y. Ikei, K. Wakamatsu, and S. Fukuda, "Texture display for tactile sensation," in *Proceedings of the Seventh International Conference on Human-Computer Interaction*, ser. Virtual Reality, vol. 2, 1997, pp. 961–964.

[48] H. Petrie, S. Morley, and G. Weber, "Tactile-based direct manipulation in guis for blind users," in *CHI '95: Conference companion on Human factors in computing systems*. New York, NY, USA: ACM Press, 1995, pp. 428–429.

[49] W. K. Edwards and E. D. Mynatt, "An architecture for transforming graphical interfaces," in *UIST '94: Proceedings of the 7th annual ACM symposium on User interface software and technology*. New York, NY, USA: ACM Press, 1994, pp. 39–47.

[50] R. D. Howe and Y. Matsuoka, "Robotics for surgery," *Annual Review of Biomedical Engineering*, 1999.

[51] B. P. Challis and A. D. N. Edwards, "Design principles for tactile interaction," in *Proceedings of the First International Workshop on Haptic Human-Computer Interaction*. London, UK: Springer-Verlag, 2001, pp. 17–24.

[52] "Engineering acoustics inc." [Online]. Available: http://www.eainfo.com

[53] S. Brewster and L. M. Brown, "Tactons: Structured tactile messages for non-visual information display," in *Proceedings of the 5th Australasian User Interface Conference (AUIC2004), Dunedin*, ser. Conferences in Research and Practice in Information Technology, A. Cockburn, Ed., vol. 28. Dunedin, New Zealand: ACS, 2004, pp. 15–23, fifth Australasian User Interface Conference (AUIC2004). [Online]. Available: http://crpit.com/confpapers/CRPITV28Brewster.pdf

[54] F. Gemperle, N. Ota, and D. Siewiorek, "Design of a wearable tactile display," in *Fifth International Symposium on Wearable Computers*, 2001, pp. 5–12.

[55] E. Rukzio, A. Schmidt, and A. Krüger, "The rotating compass: a novel interaction technique for mobile navigation," in *CHI '05: CHI '05 extended abstracts on Human factors in computing systems*. New York, NY, USA: ACM Press, 2005, pp. 1761–1764.