Tactile display applications: a state of the art survey

Vasilios G. Chouvardas[1], Amalia N. Miliou[2], and Miltiadis K. Hatalis[3]

[1] Department of Informatics
Aristotle University of Thessaloniki
541 24 Thessaloniki, Greece
e-mail: vchou@csd.auth.gr
[2] amiliou@csd.auth.gr
[3] mkh@csd.auth.gr

Abstract. Tactation is the sensation perceived by the sense of touch. Kinesthetic information describes the relative positions and movements of body parts as well as muscular effort when touching and manipulating objects. Haptic perception involves both tactile perception through the skin and kinesthetic perception of the position and movement of the joints and muscles,through the skin of our fingers and the position of our fingers. A tactile display is a human-computer interface that utilizes tactile only signals to reproduce the tactile parameters of an object such as shape, surface texture, roughness and temperature. Tactile interfaces are used in virtual environments, and as a complement or substitution of the visual or auditory presentation of information. In this paper we present a review of the state of the art regarding the latest applications and software for tactile interfaces, in areas such as graphic display, medicine, military and engineering aiding the sensory impaired.

1 Introduction

A tactile display is a human-computer interface, that utilizes tactation to present information. Tactile displays can reproduce as truly as possible the tactile parameters of an object, such as shape, surface texture, roughness, and temperature. Tactile displays have been proposed as an interface, in Virtual Environment (VE) applications and as a complement or substitution of the visual presentation of information through the tactile channel for people with vision or hearing impairments [1], [2]. In addition, tactile displays can be utilized in other applications such as providing touch feedback for virtual reality and teleoperation [3], [4], and tactile communication in mobile environments [5]. It seems also interesting to develop cooperation between alternative modalities in order to compensate for the lack of vision. This approach, which is called cooperative multimodality, is useful for developing adaptable interfaces which exploit several alternative modalities according to the specificities of users in order to, for instance introduce redundancy [6]. Tactile displays are a closely related but clearly different from haptics as they utilize only 2D information and present it through tactation, while haptics concern 2D elevation maps or 3D surfaces and volumes and involve the notion of force feedback.

In order to better describe the applications and software for tactile displays, it is imperative to understand the skin physiology and the energy forms used for tactile communication.

Tactile perception can be induced, by directly stimulating the human skin, which is sensitive to pressure (positive or negative), vibration, temperature, electric voltage and current. The skin includes pain receptors, heat flow receptors (for sensing temperature) and mechanoreceptive units. The *mechanoreceptors* are embedded in the upper layers and when activated, they transmit signals to the brain, through nerves. The mechanoreceptors can be classified 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. The skin also includes thermal sensors. *Thermoreceptors* are sensitive to thermal flux and not temperature. Experiments [7] have shown that it is possible to discriminate between two contact points, based on the thermal flux on fingers.

The Pacinian corpuscles, located deep in the dermis, are responsible for the detection of most high frequency vibrational stimuli [8]. They are the fastest-adapting of the class of fast-acting receptors. The frequency range is $50Hz$ to $600Hz$ with optimal sensitivity around $400Hz$. Meissner corpuscles detect low frequency signals, such as stroking and fluttering. Pressure and texture are detected by Merkel Disk receptors and Ruffini endings are responsible for the detection of skin stretch.

It is reported that it is possible to discriminate between two points located at least $0.5mm$ apart [9], [10].

The devices implemented so far, exploit the modalities of the skin's sensors. The systems designs can be classified into the following major categories, based on the modality used:

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

Furthermore the mechanical or electrical stimulation of the receptors classifies the devices into three categories. Pressure (exerted by pin devices) [11], [12], [13], vibration [8], [14], [15], [16], [17], [18], surface acoustic wave [19], electrorheological [20] and magnetorheological [21] 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 [22], [23]. A third class uses focused ultrasound in order to activate receptors directly or through ultrasound radiation pressure [24]. 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.

Movement and energy comes from solenoids, voice coils, piezoelectric crystals, RC servo-motors, Shape Memory Alloys, pneumatic systems, RF antenas, electric field and magnetic field.

Earlier systems were fabricated using conventional methods, but nowadays microelectronics and micromachining are employed to fabricate high-density tactile stimulators, exploiting the potential of cost reduction and miniaturization. These new fabrication techniques are expected to ease the emergence of new cost effective systems that will support applications over a wider area.

There is a growing family of applications for tactile displays both hardware and software. Software applications are predominantly designed for the Windows environment. However the lack of standardized hardware has resulted in software that strongly depends on the implementation used, is embedded in the hardware or assists the hardware. Currently there no such thing as a "universal" application that communicates with the hardware through a "driver". Some indicative recent application areas include:

A. Text and Graphics.
B. Medical applications.
C. Entertainment and Educational applications.
D. Military applications.
E. Engineering applications-assisting the blind and visually impaired.
F. Virtual environment applications.
G. Tactile displays embedded in consumer electronics and wearable devices.

2 Text and Graphics

Tactile devices allow the user to read the computer screen and obtain text-based information using refreshable Braille displays [13], [25], Braille readers [26] and/or tactile mice [27], [28], [29] in direct-manipulation systems. A refreshable Braille display (RBD) is an electro-mechanical device displays Braille characters in a sequential way by raising and lowering pins through holes in a flat surface, in response to an electronic signal, while the same concept has been introduced on a rotating-wheel based refreshable Braille display. These applications in conjunction with screen readers and other software, made it possible for Braille readers to enjoy much of the flexibility navigation of electronic texts. On some models the position of the cursor is represented by vibrating the dots, and some models have a switch associated with each cell to move the cursor to that cell directly.

Tactile mice are designed to allow blind and visually impaired to navigate through a computer screen providing tactile feedback to the user's fingertips and also to recognize graphic shapes, text, maps, pictures, and art though touch. In *"SmartTouch"* [23], visual images captured by a sensor are translated into tactile information and displayed through electrical stimulation (at the fingertip). As the system facilitates the recognition of printed materials through the tactile sense, it could be applied as a Braille display for the visually impaired.

HyperBraille [30] 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 [31] that presents hypermedia information in Braille. Furthermore, projects like GUIB (Graphical User Interface for the Blind) [32] or Mercator [33] aim towards accessing GUI through a non-visual interface supporting special sounds and tactile output devices. Additionally, a tool has been developed, called HOMER [34], which facilitates the development of dual user interfaces (visual and non-visual). The *HOMER* system currently supports communication with visual and non-visual lexical technologies at run-time.

3 Medical applications

Tactile sensing is an important source of information and allows the surgeon to feel structures embedded in tissue. Important vessels and ducts are usually shrouded in connective tissue; their presence must be felt rather than seen to avoid damage. Tumors within the liver or colon must be removed without exposure that would allow the spread of cancerous cells. Teletaction allows sensing and display of tactile information to the surgeon. In teletaction, a tactile sensor array can be used to sense contact properties remotely. To provide local shape information, an array of force generators can create a pressure distribution on a fingertip, synthesizing an approximation to a true contact [35]. A comparatively large number of devices have already been developed and some are commercially available for medical applications. A remote palpation system was developed, that will convey tactile information from inside a patient's body to the surgeon's fingertips during minimally invasive procedures [36]. This system will contain tactile sensors that measure pressure distribution on the instruments as tissue is manipulated. The signal from the sensors will then be sampled by a dedicated computer system, which will apply appropriate signal processing algorithms. Finally, the tactile information will be conveyed to the surgeon through tactile display devices that recreate the remote pressure distribution on the surgeon's fingertips. Creation of remote palpation technology will increase safety and reliability in present minimal invasive procedures and bring the advantages of these techniques to other, more complex procedures, which are not possible today.

4 Entertainment and Educational applications

Adding a tactile interface to computer animation will permit end-users to interact physically with game environments, i.e. feel the recoil from a weapon, encounter turbulence in the flight simulation or walk into a physical wall. Several software applications have been developed for entertainment providing sensory enhancement. Tactile stimulators (Tactors) can be used to simulate sensations from electrical shock and bee stings to bullet impacts, as part of a 3-D movie or gaming experience. Some indicative applications include: (i) the *"TIM"* (Tactile Interactive Multimedia) project [37], [38], that makes use of tactile boards and moves detectors as part of a flexible multimodal game interface, designed for blind and visually impaired children. The main objective of the project is to offer to visually impaired children, of various levels of psychomotor development, the possibility to play computer games in an autonomous way, without the aid of a sighted person. There are three types of games compatible with the devices and approach used: construction games, school preparation and socio-emotional games. The approach taken by TIM is to adapt existing games and educational software by providing a description of the software in a specially developed scripting language. The script for the game is interpreted by the TIM games platform, which facilitates access to the game through a flexible multimodal user interface. This interface can be tailored to the needs of different children and can incorporate a wide range of input and output devices. This means that user interfaces should become transparent and display information in the more appropriate way for each user. Following this approach needs for reformulation of data, redundancy in the data storage formats and storage of information using a well structured model that allows the change of structure in the display, (ii) the *VTPlayer software*, which is specially developed for blind and visually impaired children and can be played with the *VTPlayer*, a specially developed mouse-like game console. VTPlayer has the same functionality as a regular mouse, but with additional tactile displays. With the tactile displays one can feel with two fingertips on two fields with 4x4 dynamic Braille pins the images, animations and characters of the software. The VTPlayer software library includes: tactile geographical maps (TactileMaps), cognitive games (VTDoom, Duck shooting, etc), tactile tools, and a range of learn & play software applications [27], (iii) an application program for the delivery of music notation to blind people [39]. Graphical music notation can present a large quantity of information which is perceived by the reader in a near parallel fashion. The system, called Weasel, uses PVC tactile overlays on an Intellikeys touchpad in conjunction with speech output and audio output. Results obtained from the close observation of users working with the system have been used along with existing psychological knowledge on interaction with raised lines, tactile symbols and textures, to create a set of fundamental design principles for tactile interaction.

5 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 without diverting the user's attention away from the operational task at hand [40], [41], [42], [43], [44], [45]. There are currently four main applications for which tactile displays are considered to have great potential for military applications: orientation, navigation, communication and training and simulation [42], [46].

Orientation: Spatial disorientation is a tri-service aviation problem that costs Departments of Defence around the world a vast amount of money annually in lost aircrafts and it is directly attributed to the pilot's loss of spatial orientation and awareness. Spatial orientation is the ability of an individual to correctly know where they are oriented in space, normally in relation to the direction down. For example, a ground direction cues applied to the torso, via the Tactile Situation Awareness System (TSAS) [47], developed by the US Naval Aerospace Medical Research Laboratory (NAMRL) enables pilots to maintain spatial orientation and perform aerobatic manoeuvres without external cues (blindfolded) or internal instrument displays. The same device can improve the ability of personnel to detect and determine relative position and motion of targets. Extreme disorientation can also occur under water and in conditions of microgravity, which would be encountered by divers and astronauts respectively. The TLS positioned the 20 electro-mechanical tactors on the torso of the body as an array that consisted of four columns of five tactors located 90 degrees apart on the front, left, back, and right of the test pilot. The test pilot in the rear seat was shrouded to block any outside visual cues and all flight instruments in the rear cockpit were removed. The system was embedded in a T-34 jet aircraft, a UH-60 helicopter and the T-22 JSF. The objective was to show: 1. that a significant amount of orientation and awareness information can be intuitively provided continuously by the under-utilized sense of touch, 2. the use of the TSAS display, with no visual cues, can help the pilot to effectively maintain control of the aircraft or the helicopter in normal, acrobatic flight conditions and in complex rotary wing environment.Engineering Acoustics, Inc has developed *tactors* capable of being fitted inside a wetsuit and working underwater, and has demonstrated the effectiveness of tactile displays for underwater operations [42]. The intent of the testing was to evaluate the feasibility of using tactor technology for steering indicators in an underwater environment. This test compared the ability of EOD Divers to navigate underwater with visual displays only, and with tactile cues only. The data showed that the divers cross-track navigation error was less using the tactile-only system. Positive user feedback also indicated that it reduced visual navigation workload and allowed the divers to concentrate more on locating mines. This demonstration also revealed a number of improvements that would be required before an operational system could be fielded (e.g. the system exceeded magnetic signature thresholds for the EOD mission). In addition, NASA has conducted research into the use of tactile displays in microgravity using parabolic flights and further study into this environment is being carried out on the International Space Station by researchers from TNO Human Factors Research Institute (NL) [48].

Navigation: Navigation through space is a task that must be performed in many different environments and tactile devices can provide directional cues for this purpose. Tactile cues could, for example, inform a pilot of the bearing of a missile that is locked onto an aircraft or the direction of an emergency rendezvous location. The tactile navigation displays are designed to give information of course errors and course correction instructions. Waypoint navigation using tactile cues has been demonstrated in a variety of environments. These include divers operating underwater at NAMRL, high-speed boats at QinetiQ [49], automobiles at TNO, and aircraft at NAMRL and at TNO. However, we expect that not only astronauts and pilots can benefit from this development. A simpler variant (e.g. a belt around the torso) could be very useful as a navigation display for the visually handicapped, for drivers who need to keep their eyes on the road, and for fire fighters who operate in smoke, dust or darkness.

Qinetic also developed a new underwater navigation and search system which is set to play a significant role in mines counter measures (MCM) operations, particularly those conducted in shallow littoral waters. Incorporating a high frequency, forward looking sonar search capability with highly accurate navigation technologies, a data recording facility and user-friendly display, the D*iver Reconnaissance System* addresses a number of issues that currently hamper the effectiveness of divers in MCM operations. Traditional diver rope search techniques are man intensive, time consuming and difficult to conduct, particularly in tide. The QinetiQ DRS is based on a handheld swimboard concept and incorporates a fully functioning microprocessor which can receive various sensor data and log and display mission information. The diver has full control over the system functions by means of underwater mouse controls fitted into the handles. The primary search sensor is a forward-looking, electronic-scanning, high-frequency sonar. Typically the sonar can detect a $-25dB$ target at a range of $30m$. The sonar can be configured for obstacle avoidance or target location. The sonar has been successfully tested by QinetiQ and Royal Navy dive teams for its ability to detect calibrated spheres and realistic mine shapes. The navigation system uses long-baseline active acoustic transmissions. This requires between 2 and 4 acoustic transponders to be positioned on the seabed in known positions to calculate an absolute position fix. Transponder position may be determined by GPS to obtain absolute positioning or by acoustic ranging to provide relative positioning. The diver is able to navigate in a pre-determined search area to an accuracy of approximately $0.5m$.

Communication: Communication of information other than orientation or navigation information can take place on a very simple or very complex level. It is generally considered that for a display to be highly intuitive it should only convey very simple information. The vibrating alert on a mobile phone communicates simply that someone wishes to speak with the telephone's user. However, with this application the potential exists to provide more information, such as whether the call is of a business or personal nature, or if the telephone has received a txt message. Therefore, it is necessary to differentiate between different tactile cues. The tactile equivalent of audio ring tones might be different vibration rhythms. This technology will require the construction of intuitive "tactile melodies", or "tactile icons" [43], which can be immediately recognized with little cognitive processing required. The potential of tactile cues for communication are far-reaching and they are particularly suited to environments where sound and light cues are either unavailable or undesirable. The key to successful implementation of tactile displays lies in the ability to convey a strong vibrotactile sensation to the body with compact lightweight devices that can be comfortably incorporated in the user's workspace, or clothing, without impairing movement.

Training and Simulation: Virtual reality (VR) and motion-based simulation have become essential part of training the modern soldier. Computer generated graphics and sound can submerse the user in a very realistic environment, however the sense of feel is typically absent. In some VR environments, a user can actually move limbs though solid objects, and can only use visual cues to determine his proximity to objects, even if touching them. Tactile displays can add the sense of feel and provide a more realistic physical response in training situations.

6 Engineering applications- assisting the blind and visually impaired

Blind and visually impaired individuals rely heavily on touch feedback, whilst individuals who are both blind and deaf are totally dependent on their sense of touch. One example of how tactile technology can enhance the capabilities of the visually impaired is by improving autonomy of navigation. A tactile waypoint navigation system, developed by QinetiQ [49], has been used to assist in the setting of the first blind water speed record. The increasingly successful exploitation of tactile displays can be seen within the recently developed blind walking cane *Ultracane*, by Sound Foresight Ltd. [50] and the QinetiQ Vibroacoustics team, which uses sound to provide tactile feedback to the user from ultrasonic transponders in the cane, in order to help visually impaired people perceive their surroundings. Users can be informed of both the direction of, and distance to, objects in their vicinity. The use of the tactile display means that they receive this information both intuitively and discretely. Their starting point was submarines, which navigate using sound waves and bats that have been using sonar for millions of years to enable them to fly and catch prey in complete darkness. Using commercial off the shelf materials, that are readily amenable to large-scale industrial manufacturing processes, they managed to develop a low cost system.

At the university of Heidelberg in Germany a tactile vision and substitution system was developed [51], which can be positioned at any location on a two dimensional surface to explore the line structure of a virtual image. This virtual tactile display (VTD) receives data either from camera systems equipped with suitable image processing capabilities or from a computer. Graphic tactile displays enable viewing 2D images and 3D objects by the sense of touch on a reusable surface [51], while some experimental work has been done on conveying object surface texture [52], [53]. More specifically, an interactive tactile display system has been developed for the visually disabled to actively recognize 3D objects or environments [54]. The display presents visual patterns by tactile pins arranged in 2D format. Also, in [11] a system called *"MIMIZU"*, using a stylus pen and a body containing tactile display units is giving the opportunity to the visually impaired user to draw and erase tactile images. *"MIMIZU"* could be used to provide effective educational materials and enjoyable entertainment. Handy Tech Elektonik GmbH has developed *"GWP"* (Graphic Window Professional), a system for blind people to access graphics [55]. The graphics are converted into tactile pictures. *"GWP"* uses image-processing techniques to extract the most important information of the display. The tactile graphics vary dynamically in real-time according to the changes on the screen. The TACTile Image Creation System (*"TACTICS"*) is a prototype attempting the unsupervised conversion of pictorial information to tactile form [56], [57] based on applicable image processing techniques and principles of psychophysics. Moreover, considering that the most important characteristic of a picture is not its channel of perception but the method of arranging information in space, a tool has been developed at the university of Berlin to allow blind people to draw pictures and at the same time study their drawing process [58].

7 Virtual environment applications

Several applications in the area of tele-operation and tele-presence are on the market as ready to buy products or on laboratory as prototypes. Among the most promising are:

(a) *"CyberTouch"* [59], which provides a tactile feedback option for the CyberGlove. The tactile actuators are attached on each end of the finger and the palm of the hand to provide impulses and vibrations.
(b) *"TouchMaster"* [59], provides a tactile display to the tips of all four fingertips and the thumb using voice coil actuators.
(c) *"Tactool System"* [59], where the tactile display is attached to a cable assembly for mounting on fingertips.
(d) *"Surface Acoustic Wave Tactile display" (SAW)* [60]. Researchers proposed a tactile interface, which is excited by surface acoustic wave, which can continuously change the fineness of the surface's grain.

8 Tactile displays embedded in consumer electronics and wearable devices

Tactile interfaces can also be used as a channel for communication with miniature handheld [12], [18], [61], [62] or wearable devices [8], [63] providing more effective, comfortable and enjoyable interaction. Some of the uses will include navigation [17], [45] notification though touch, monitor the status of a process or use of gestures to interact with the device.

There are many reasons why users could benefit from the inclusion of tactation as a modality for communication and interaction within a given system. Visually dominated interfaces are commonplace yet may not always be the most efficient or intuitive method for performing a given task. In the most extreme scenario the graphical user interface simply excludes visually impaired users. However, there are also instances where a user needs to control and observe a process where the process itself is already providing visual feedback (e.g. slide projector, radio controlled equipment, stage lighting etc.). In these circumstances, the user is likely to benefit from some level of increased tactile feedback so that their visual attention can be maximized in terms of directly observing any changes being made. In certain other circumstances, using a car radio whilst driving for example, a strategic shift in balance from visual toward tactile interaction could prove to be safer [39].

Miniature handheld computing devices are part of our daily lives therefore the interface design of such devices is an exciting challenge especially when the sense of touch is employed. Advances in this area include: (i) a tactile apparatus, which is embedded in a Sony PDA touch screen enhancing its basic GUI elements with tactile feedback [12], [61] -different tactile sensations are associated with various GUI elements, (ii) the *"ComTouch"* that is a vibrotactile device sleeve that fits over the back of a mobile phone [18]. The devices are bi-directional and both users can send and receive signals simultaneously. Studies on these devices showed that users developed an encoding system similar to that of Morse code, as well as three original uses: emphasis, mimicry and turn-talking.

Furthermore, among the most promising wearable tactile display devices are: (i) the "*Kahru*" which would allow a hiker to enjoy unfamiliar territory without a guide or frequent stops to check a compass and topological maps. The embedded tactors would simply nudge the hiker in the right direction [44], (ii) the "*ActiveBelt*" which enables users to obtain multiple directional information with the tactile sense. Four applications of the concept have been proposed, i.e., (1) "*FeelNavi*" for human navigation systems, (2) "*FeelSense*" for location-aware information services, (3) "*FeelSeek*" for search of lost properties, and (4) "*FeelWave*" for entertainment [40]. Finally, several research groups are employing the tongue (one of the most sensitive parts of human body) in human-computer interaction to display information. One example of tongue electro-tactile device was presented as a kind of wearable equipment for alternative viewing of graphical images [64] while in another application, electro-tactile stimulation of the tongue is used to transform short conditional messages, presented by symbols or graphics, into electro-tactile patterns [65].

9 Conclusion

In this paper we have presented an overview of the state-of-the-art in tactile display applications and software. Tactile interactions provide important sensory modalities that are exploited in many types of practical applications. The classification was made based on the application area. The applications presented cover a wide area from medical and sensory impaired aids, to consumer and entertainment and to the military. Tactile display technology is a promising area for future products improving peoples' lifes, as well as specialized devices for industry and the military. Although a lot of R&D has been performed the past 50 years, there is no such thing as a killer application in the market due to the inherent difficulties in tactile display implementation. It is the writers' belief though that the addition of microelectronics and MEMS will bring out new systems that will use tactation as a new man-machine interface in every day life, as navigation aids, graphic displays and large area text/graphic panels for the visually impaired.

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