Tactile interfaces: a state-of-the-art survey

Mohamed Benali-Khoudja[1], Moustapha Hafez[1], Jean-Marc Alexandre[1], and Abderrahmane Kheddar[2]

1: CEA LIST SRSI
Route du Panorama, 92265 Fontenay-aux-Roses, France
mohamed.khoudja, moustapha.hafez, jean-marc.alexandre@cea.fr
http://www.cea.fr
2 : Laboratoire Systèmes Complexes - University of Evry, Fre2494 CNRS
40, rue du Pelvoux, 91020 Evry, France
kheddar@iup.univ-evry.fr

Abstract- **Virtual reality techniques allow one to interact with synthetic worlds, i.e. virtual environments. Tactile feedback means conveying parameters such as roughness, rigidity, and temperature. These information and many others are obtained thanks to the sense of touch. Tactile feedback is of prime importance in many applications.**

In this paper we examine the state-of-the-art in tactile interfaces design. Thorough reviews of the literature reveal a significant amount of publications concerning tactile human-machine interfaces, especially onwards the ~1990. This paper reports the progress in tactile interfaces technology in the following areas: teleoperation, telepresence, sensory substitution, 3D surface generation, Braille systems, laboratory prototypes, and games. Different parameters and specifications required to generate and feed back tactile sensation are summarized.

Keywords: Tactile Interface, Touch feedback, Teleoperation, TVSS, Haptic technology, Virtual Reality.

I. INTRODUCTION

One of the human being characteristics allowing him to be fully autonomous in his environment and to modify it is his ability to interact with the external world. This characteristic is common to almost all the living species. The collected/exchanged information, usually called "natural signals", are of different types such as mechanical, thermal, and chemical excitations. These natural signals are first detected by specific biological sensors, and then translated as biological internal signals.

The human haptic sense is composed by two sub-modalities[1]: the kinesthetic sense (force, motion) and the tactile sense (tact, touch). In this paper, only the tactile interfaces are presented. A tactile device is a man-machine interface that can reproduce as truly as possible the tactile parameters, such as the texture, roughness, temperature, and shape. Such systems find applications in (i) virtual environments (applications based on the virtual reality technology) and (ii) teleoperation applications. This paper aims to overview what have been achieved so far in this field and to summarize the different specifications that may help researchers and engineers in future tactile interfaces development's considerations.

From the technological point-of-view, tactile stimulation can be accomplished in different ways. The used technologies for virtual environment (VE) systems were inspired from matrix pin-printers technologies and Braille systems for blinds. Solutions based on mechanical needles actuated by electromagnetic technologies (solenoids, voice coils), piezoelectric crystals, shape memory alloys, pneumatic systems, and heat pump systems based on Peltier modules have been proposed. Other technologies, such as electrorheological fluids which change the viscosity and therefore the rigidity under the application of an electric field, are still under investigations. Technologies dedicated to medical applications such as electro-tactile and neuromuscular stimulators have not yet been used because of their invasive nature.

II. AN OVERVIEW OF TACTILE TECHNOLOGY

In this section, we present existing state-of-the-art tactile stimulators, their physical, spatial, and frequency characteristics. A classification in terms of application domains has been defined in order to present the different tactile interfaces. The different applications are listed below:

1. Teleoperation and telepresence;
2. Laboratory prototypes to study the different tactile parameters;
3. Sensory substitution;
4. 3D surface generation;
5. Braille systems;
6. Games.

[1] Tough this separation is far from being physiologically established.

ISR 2004, 35th International Symposium on Robotics, 23-26 March, Paris France.

II.1 Tactile interfaces for tele-operation and tele-presence

Dave Andaleon, from the Sandia National Laboratories, conducted work on tactile devices that interact with the fingertip for VE applications. The tactile interface consists in a pin-matrix of 2 × 3 electromagnetic actuators, mounted on a frame, and fixed on the finger of the user (Fig. 1). Each actuator operates in the range of frequency of 8–100Hz, is able to actuate with an indention of 762µm, and operates at a maximum pressure of 1.2N/cm² [1].

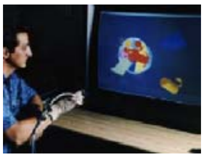
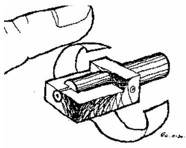




Fig. 1 Fig. 2 Fig. 3

Fig. 1. Sandia National Laboratories Tactile Interface**.**
Fig. 2. Prototype of slip to a degree of freedom.
Fig. 3. Touch Master of EXOS, Inc.

The EXOS researchers focused on the sensations feedback of slip and shearing [2]. The slippery feedback has been developed to reproduce the sensations of adherent loss and lateral stretching on the skin. The maximum speed is about 0.0254m/s and the normal force may reach 17.8N (Fig. 2).

Another interface developed by EXOS, is the TouchMaster (Fig. 3). It is a tactile interface that allows the stimulation of each of the four fingers and the thumb. The actuators are electromagnetic of voice coil type. These actuators give a “vibrotactile” feedback, which supply a fixed frequency of about 210-240Hz, at constant amplitude.

In the framework of collaboration between Ottawa University and the Canadian Space Agency, Petriu and McMath described a device of tactile sensors used on a slave robot [3]. The tactile stimulator consists of 8 × 8 electromagnetic vibration needles/heads on a surface of 6.5cm² (Fig. 4).

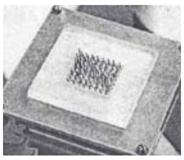


Fig. 4 Fig. 5 Fig. 6

Fig. 4. Tactile Interface for Teleoperation. **Fig. 5.** Tactile Interface operating in a vibration mode. **Fig. 6.** The Teletact (University of Salford).

In the Armstrong laboratory, Chris Hasser studied the perception characteristics on a tactile surface of 5 × 6 actuators, separated by 3mm in each direction. The actuators of this interface are based on shape memory alloy (SMA) wires, used to push and pull the tactile elements (contactors) [4]. This work results in a tactile interface (matrix) device known as HAP-TAC (Haptic Tactile), which has been used in the TacGraph[2] system, to allow feedback data drawings for blind persons. The closed loop behavior brings together the required performances for a maximum force value of 2N, with a resolution of 0.12N [5].

Using the same technology, the Harvard university researchers in the group of Robert Howe, developed tactile interfaces prototypes. Developed tactile devices allow, all together the shape feedback and/or the vibration feedback. The tactile interface (Fig. 5) uses pins driven by actuators of the SMA wire type. The pin diameter is about 1.7mm, the distance between two pins is 2.1mm, and the force delivered by each pin is 1.2N [6].

A tactile glove, that exhibits pressure and temperature feedback, called Teletact (Fig. 6), was developed by the Salford university researchers, from the electronic department. The interface is composed of a ceramic disk of PZT (lead zirconate titanate) with 10mm diameter and 1mm thickness.

The DataGlove (Fig. 7) developed by VPL is a data glove with 14 sensors that measure the finger bending (two sensors by finger). Zimmerman from IBM's Almaden Research Center, and his group, modified a DataGlove by associating piezoceramic actuators under each finger.



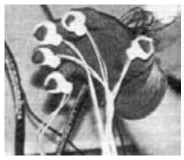


Fig. 7 Fig. 8 Fig.9

Fig. 7. Data Glove. **Fig. 8.** ARRL Interface. **Fig. 9.** Pneumatic actuators.

The ARRL (Fig. 8) haptic interface was developed by the Salford university group. It integrates three pneumatic actuators (inflating balloons), in order to reproduce simple tactile feedback, when the hand (or the user virtual cursor) enters in contact with a virtual object. These pins are controlled by a servo-valve, and can be replaced by actuators of the solenoid type [7].

[2] TagGraph: a tool that permits to build graphic tactile scenes.

The Toshiba Nuclear Engineering Laboratory researchers in Japan, integrated inflatable actuators in the form of a ring, on a VPL DataGlove [8][9]. The pneumatic actuator (Fig. 9) is located at the ring basis/center, and inflates the balloon that exhibits a pressure on the operator's fingertip. Its size is 8mm in diameter, and 12mm long (in the inflated state). The maximum resulted pressure is of $2Kg/cm^2$.

Begej, under a contract with the Johnson Space Center (NASA), developed a large scale tactile interface. This interface has 512 actuators i.e. tactile elements. The same company developed a glove that allows tactile feedback and force on the three fingers. It supplies the user with force feedback through an exoskeleton mechanism.

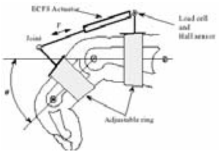
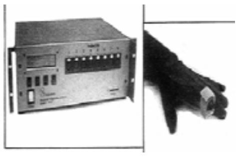



Fig. 10 Fig. 11

Fig. 10. Actuator assembled on the finger (MEMICA). **Fig. 11.** DTSS from CM, Inc.

Kenaley and Cutkosky were the first to propose the use of Electro Rheological Fluid (ERF) to provide tactile feedback on robotic fingers [10]. One of the first to propose the application of ERF in tactile device design was Monkman [11]. Taylor and his group at the University of Hull at RU proposed and tested experimentally a tactile interface of 5×5 actuators of the ERF type [12]. Furthermore, the MEMICA system (Fig. 10) developed by the Rutgers university researchers at the JPL (Jet Propulsion Lab), uses ERF based gloves for haptic feedback [13] [14].

The CM Inc. researchers proposed the DTSS system (Fig. 11), which was used for VE applications. When the system is used with some localization devices, it allows temperature feedback at the appropriate location in VE, felt by the user's fingertip. The actual product, the DTSS X/10 model, is intended to be a research tool. It is composed of a controller, and eight thermodes. The temperature variation interval lies between 10°C and 45°C with a resolution of 0.1°C.

In 1995, Virtual Technologies Inc, proposed the CyberTouch (Fig. 12) which provides tactile feedback in addition to the standard CyberGlove used in many applications. The tactile actuators are attached on the each end of the finger and the palm of the hand to provide impulses and vibrations [15].

Xtensory Inc, developed the Tactool system (Fig. 13) made of tactor (actuator) connected by a cable to the power supply. Spacing between the pins is of 3mm. Each actuator delivers a force of 30g and operates in vibration/oscillatory mode.



Fig. 12 Fig. 13 Fig. 14

Fig. 12. CyberTouch from Virtual Technologies, Inc. **Fig. 13.** The Tactool system from Xtensory, Inc. **Fig. 14.** Interface exploration of surface of Hashimoto.

Within the Hashimoto Laboratory at the Institute of Industrial Science, University of Tokyo, researchers were interested in the telenanomanipulation by using techniques of microscopes with tunnel effect (Scanning Tunneling Microscope STM) and Atomic Force Microscope AFM. This system can explore a surface at the nano-scale level, and the operator can feel roughness at this scale (Fig. 14).

II.2 INTERFACES TO STUDY THE TACTILE PARAMETERS

At the university of Nagoya Japan, Toshio Fukuda and his team [16] proposed a prototype of an electromagnetic actuator (Fig. 15), which satisfies the requirements of tactile feedback (density, temporal bandwidth, force, etc). The actuator is composed of a micro solenoid and a permanent magnet which is displaced within the solenoid.

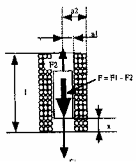


Fig. 15 Fig.16 Fig.17

Fig. 15. Electromagnetic Actuator. **Fig. 16.** Tactile interface of Karlsruhe. **Fig. 17.** Harvard tactile interface.

At the department of technology and engineering of the research center of Karlsruhe, Fisher's group developed a system of tactile feedback that can be interfaced to a flexible endoscope's forceps. The interface is composed of 3 × 24 needle actuators, providing a total of 72 actuators. The various needles are actuated using electromagnets operating at a maximum frequency of 600Hz (Fig. 16).

C R. Wagner et al. [17] proposed a tactile interface driven by RC servo-motors (Fig. 17). These motors have a large bandwidth, and a large vertical displacement at a relatively low cost and a simple construction. The active surface has a high density of active pins. The interface has

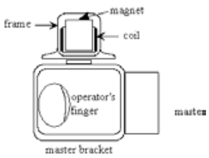
6 × 6 mechanical pins with 2mm spacing between the pins, and a resolution of 4 bits. For a vertical displacement of 2mm, the rise time is of 41ms.

P. Wellman and R.D. Howe studied the application of vibrotactile feedback to add a new dimension of realism to virtual environments (Fig. 18).

Based on the work of Brodey and Holmen [18], a new haptic transmission concept was developed by CompuTouch. The system is a simple design and is composed of a low cost two-axis motor. The maximum tilt angle is of +/- 10° (Fig. 19).

The Exeter interface was developed to simulate tactile sensations on the fingertip. The interface has been designed with 100 pins, fitting in 1cm² to cover the fingertip (Fig. 20). Each contactor is driven by a piezoelectric actuator. The 100 actuators can be addressed individually by software.

A stimulator with 400 tactile elements (Fig. 21) was developed to study the properties of spatial responses of neurons, located in cortex areas (the brain area, which receives and treats somatic senses) [19][20]. The researchers developed their device based on the physiological characteristics of man. A spacing between two actuators of 1mm, a frequency reaching 300Hz, and an amplitude of indentation up to 2mm.



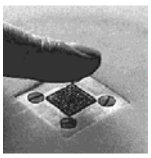



Fig. 18 Fig. 19 Fig. 20

Fig. 18. Voice Coil Interface. **Fig. 19.** The tactile button of CompuTouch. **Fig. 20.** The tactile matrix

Akamatsu et al. [21], worked on a comparison between tactile, sound and visual feedback, using an interface computer mouse (Fig. 22). They modified the standard mouse, so that it can give a tactile feedback at the end of the finger. Tactile information is provided through a unique aluminum pin (of 1 × 2mm). The pin is controlled by a solenoid.

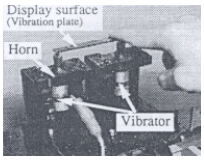


Fig. 21 Fig. 22 Fig. 23

Fig. 21. Tactile interface of JHU. **Fig. 22.** Tactile mouse. **Fig. 23.** Tactile interface with electromagnetic actuators

In Shinoda lab at the university of Tokyo, [22] researchers proposed a method to reproduce a tactile feeling that results when exploring a surface. The system is composed of four magnets attached on the skin in a linear configuration (Fig. 23), and controlled by four coils.

At the NTT Interdisciplinary Research Laboratories of Tokyo, T. Watanable and S. Fukui [23] developed a tactile device which is able to transform the roughness of a surface into a smooth tactile sensation (Fig. 24). This is achieved by vibrating the surface at ultrasonic frequencies of about 77kHz. The maximum amplitude of vibration is approximately 2µm.



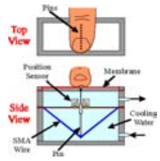



Fig. 24 Fig. 25 Fig. 26

Fig. 24. NTT Tactile Interface. **Fig. 25.** Programmable tactile surface (TiNi Alloy Company). **Fig. 26.** Design of SMA actuator.

In collaboration with the Center of the Human Systems of US Air Force, the company TiNi developed a tactile interface composed of a distribution of 5 × 6 pins, with a spacing of 1.5mm, a diameter of 1mm and a force of 6g, developed by each SMA wire actuator (Fig. 25). The time response is 100msec.

Johanson proposed a tactile interface driven by SMA wires with 5 × 6 pins and operating at 20Hz [24]. Another tactile interface proposed by Wellman et al. is composed of a line of 10 pins individually actuated [25][26]. SMA wires are used to control the pins (Fig. 26). The pin is raised when a current is applied to the SMA wire. Each pin move up to 3mm and produce more than 1N force.

The HAPTAC product of the Armstrong Laboratory (Fig. 27) uses tactile actuators of the SMA type in order to reproduce tactile feelings with.

Kontarinis and Howe [27] proposed a prototype of a tactile interface based on SMA wire actuators (Fig. 28). This device contains a 3 × 3 pin-actuators (with a final version of 10 × 10 pin-actuators to cover all the space of the fingertip) spaced by 2.2mm center to center. These pin-actuators could produce displacements of 3mm and a force of 1.2N per element. The time response in the two directions is 62ms for a displacement of 2.5mm.

Taylor et al. developed also a tactile interface based on SMA actuators [28]. Each actuator consists of a wire of 120mm length and 0.1mm in diameter. The amplification mechanism is the same presented in (Fig. 28). The interface consists of 8 modules and 8 actuators. The spacing is 2.54mm. A maximum deflection is reached during 500ms with amplitudes of 1.7mm.

Fig. 27

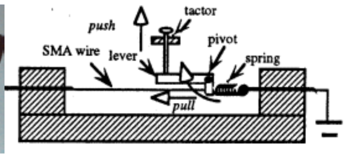


Fig. 28

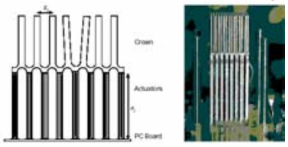


Fig. 29

Fig. 27. The HAPTAC system. **Fig. 28.** SMA Actuator (Harvard University). **Fig. 29.** McGill University Interface with Piezo-ceramic Actuators.

Fukuda et al. presented a matrix interface of 50 actuators in a 5 × 10 configuration with an aim of making texture feedback [29]. The interface T50-2 consists of 50 pins of 0.5mm diameter and spaced by 2mm. The active surface is 8 × 18mm² and the frequency at which the actuators operate is 250Hz.

Hayward et al. developed a tactile interface which carries out transversal or lateral deformations of the skin [30] [31] [32]. The technology used for actuation is the piezo-ceramic. The actuators are manufactured in ceramics PZT plates being composed of four layers of 0.25mm covered with electrodes (Fig. 29). They provide a displacement of ±5µm for an applied voltage of ±200V. The last version named STReSS 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 [33].

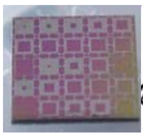


Fig. 30

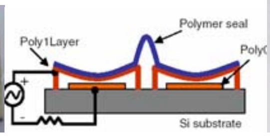


Fig. 31

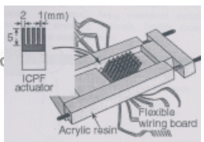


Fig. 32

Fig. 30. Chip MCNC MUMPS. **Fig. 31.** Micro-machined Actuator with Polysilicon Membrane. **Fig. 32.** Tactile interface based on EAP

At the Microelectromechanical Systems Laboratory of the University of Carnegie Mellon, researchers developed a tactile interface based on MEMS technologies. The Chip MCNC MUMPS contains 24 actuators of different sizes on a surface of 1cm² (Fig. 30). Dimensions of an actuator are roughly 2 × 2mm². To date, the project is made in the frame of collaboration between the MIT Touch Lab at RLE and Prof. Kaigham J. Gabriel at the MEMS Laboratory at Carnegie Mellon University (CMU). Initial work has focused on the development of a single stimulator or actuator that consists of two gas- or fluid-filled chambers as shown in (Fig. 31). The chambers are covered and sealed by a common membrane such that when the membrane covering the outer chamber is displaced by electrostatic force, the membrane covering the inner chamber is also displaced (a greater distance) by the movement of the fluid.

At the university of Kobe in Japan, Konyo and Tadokoro developed an interface using a composite polymeric known as IPMC or ICPF [35] (Fig. 32). The goal was to reproduce the feeling of touching a surface.

At the Hull University, United Kingdom, researchers developed a 5 × 5 tactile interface based on electro-rheological fluids (Fig. 33) for VE applications [36].

In [37], the authors describe a 4 × 5 actuator array of individual vibrating pixels for fingertip tactile communication. The array utilizes novel micro-clutch MEMS technology (Fig. 34). Individual pixels are turned ON and OFF by pairs of microscopic thermal actuators, when the main vibration is generated by a vibrating piezo-electric plate.

At the university of Tokyo, the team of Tachi [38], proposes a tactile interface 2D made up of 4 × 4 electrodes separated by a distance of 2.54mm. The working frequency is of 100Hz.

Fig. 33

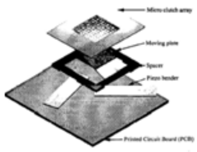


Fig. 34

Fig. 33. Interface based on ER fluid. **Fig.34.** Micro electrical Mechanical System.

Shuichi Ino of the University of Hokkaido in Japan carried out several research works on the tactile sense and the tactile interfaces based on pneumatic actuation. The pressure on each cylinder is controlled by a computer, using an electropneumatic regulator controlling the pressure, and producing feelings of shearing by means of a transverse displacement. The amplitude of displacement is of ±3mm. Moreover, they developed another interface that gives thermal feedback [39]. The temperature of the surface is measured by a thermocouple and a module with Peltier effect (Fig. 35). The temperature range covered lies between –10 and +60°C with a resolution of 0.1°C.

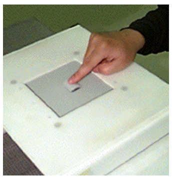
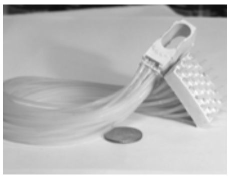
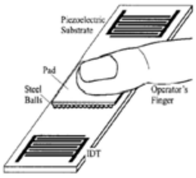




Fig. 35 Fig. 36 Fig. 37

Fig. 35. Device with returned temperature. **Fig. 36.** NIBH Interface **Fig. 37.** Teletaction.

Some haptic interfaces using force feedback, like the PHANToM, can reproduce a texture of a surface or sliding effect, and thus reproduce a tactile feedback. On the other hand, some tactile interfaces have limited force feedback. An example is the FEELit mouse produced by Immersion Corporation (San Jose, CA) [40]. Its workspace is of 2.5 × 1.9cm², and the maximum delivered force is 1N.



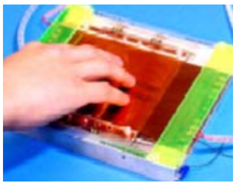


Fig. 38 Fig. 39

Fig. 38. Tactile Interface Based on SAW. **Fig. 39.** Thin Type Electrostatic Linear Actuator

Another interface developed by the team of Shinohara at NIBH in Japan is presented in (Fig. 36). The goal is to generate 3D shapes by rising and lowering pins using a ball fixed on a 2D translation stage [41].

Researchers at the University of Berkley [34] developed a prototype of 5 × 5 tactile interface actuated by pneumatic technology with 3 bits of resolution. The pneumatic prototype interface delivers up to 0.3N/actuator (Fig. 37).

Researchers proposed a tactile interface which is excited by a surface acoustic wave SAW [42]. A SAW is generated by an alternating voltage with an inter-digital transducer in a Li-Nb-O3 substrate of 17 × 63 × 1mm³ (Fig. 38). The wavelength of the SAW is 265µm with a frequency of 15MHz.

At Higuchi Lab from the University of Tokyo, researchers developed a new type of tactile display based on force feedback technique using electrostatic linear actuator. The device is shown in (Fig. 39). The main part is an electrostatic linear actuator that consists of a thin film slider and a stator. The user can obtain tactile sensation by moving the slider with his finger. The electrostatic linear actuator generates shearing force on the user's fingertip according to the slider position, and the user obtains some tactile feeling.

II.3 Tactile vision substitution systems (TVSS)

Unitech Research developed VideoTact which allow producing a tactile image through a 20 × 20 matrix of 400 actuators containing solenoids of 1mm of diameter. The Felix system developed by Norbert Wiener in the Fifties, at the Research Laboratory of Electronics at MIT, is an interface dedicated to the deaf persons [43].

At the University of Heidelberg in Germany, a very particular interest was related to the fusion of visual and tactile feedback [44]. The VTD interface is 230 × 300 mm² has a resolution of 2880 taxels, a working frequency of 50Hz, and is actuated by piezo technology (Fig. 40).

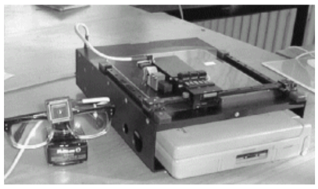



Fig. 40 Fig. 41

Fig. 40. VTD (University of Heidelberg). **Fig. 41.** TDU of Wisconsin University.

Paul Bach-y-Rita developed a tactile interface that communicates information on the tongue (TDU for Tongue Display Unit). Electrotactile stimuli are delivered on the tongue which comes in contact with a flexible configuration of electrodes (Fig. 41).

Optacon is composed of a small camera held in the hand with a network of photocells (6 columns × 24 lines), and a corresponding tactile interface, composed also of 6 × 24 pins (dimensions of the pin are 1.1 × 2.7cm²) [43]. A new version named Optacon II is presented in (Fig. 42).

The Tactaid products are instruments equipped with small batteries to assist a deaf person to distinguish between different noises, while enabling him to feel a vibratory configuration, which corresponds to a given noise [43].



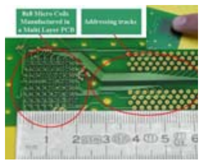


Fig. 42 Fig. 43 Fig. 44

Fig. 42. Optacon II. **Fig. 43.** Abtim interface. **Fig. 44.** VITAL interface.

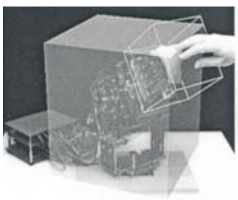
The German company Abtim developed in 2002 an interface that is made of two independent parts (a sensing device and a displaying device). The communication is achieved by wireless transmission. The tactile part presents a screen of 256 sticks on a grid of 4 × 4 cm² (Fig. 43). It transforms the visual information into tactile information. The weight of the tactile device is 800g and its dimensions are (14 × 20 × 3cm³).

At the CEA (the French Atomic Energy Center), a new vibrotactile interface based on electromagnet actuators has been developed (Fig. 44). A new multi layer approach was proposed to build a new low coast tactile interface that is adapted to an industry production [45]. The VITAL display has a maximum pin deflection of ±100μm with a resolution of 6 bits. The display can accurately operate at frequencies up to 800Hz, with a first resonance frequency at 270Hz. The maximum force delivered by each micro-actuator is about 13mN with a pin spacing is 2mm [46].

II.4 Tactile interfaces based on the generation of a 3D surface

The authors in [47] were interested in the concept of a universal surface for haptic feedback. The interface consists of 4 × 4 pins, on a square surface with a dimension of 20mm². Each pin has a stroke of 50mm. The different combinations of the pins' amplitudes produce different 3D surfaces that can be explored (Fig. 45).

Iwata et al. worked on FEELEX [48] (Fig. 46). FEELEX is composed of linear actuators which deform a plane surface of 3mm thickness. Each linear actuator is composed of a mechanism with a screw controlled by a DC motor. The screw converts a rotation into a linear displacement of the tactel. The smallest diameter of the motor which can control the screen is 4cm. Therefore, a matrix of 6 × 6 linear actuators can be placed under the screen.



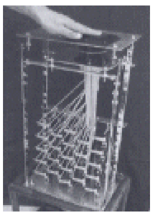


Fig. 45 Fig. 46 Fig. 47

Fig. 45. Tactile interface based on returned of form. **Fig. 46.** FEELEX Interface. **Fig. 47.** MATRIX (A Multipurpose Array of Tactile Rods for Interactive eXpression).

MATRIX Interface is a device which allows a real-time control of a deformable surface (Fig. 47) [49]. MATRIX is composed of 144 rods which move vertically forming a matrix of 12 × 12.

II.5 Braille interfaces for blinds persons

The RBD Braille interface generates Braille characters by raising and lowering pins, in response to an electronic signal. It consists of actuators containing piezoelectric crystals. The main drawback of the RBD (Fig. 48) is its high price. Another Braille device is the rotating-wheel based refreshable Braille display. It has been developed mainly to reduce the cost of the previous system (Fig. 49). The working principle of this device is to rotate the cells of Braille under the fingertip and the different characters are refreshed in this way. It is enough in this case to have three actuators for the whole device (currently developed by the National Institute of Standards and Technology).

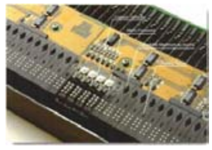


Fig. 48 Fig. 49 Fig. 50

Fig. 48. RBD Braille Interface. **Fig. 49.** Rotating Wheel. **Fig. 50.** DM80 Interface from BAUM

In the case of Braille interface DM80 from BAUM, the contents of the screen is read by means of 80 piezoelectric tactile elements fast and reliable (Fig. 50).

II.6 Tactile interfaces for games

PainStation is a game for two players and was developed by German designers at the Academy of media arts of Cologne.

Fig. 51. Pain Station

This interface produces pain sensations (thermal pains and mechanical pains) (Fig. 51).

III. Conclusion

In this paper, a state-of-the-art based on the various applications of tactile interfaces is presented. Another classification, based on various manufacturing and actuation technologies would have been possible. It is worth noting that:

1. The most used technology is electromagnetic actuation. This is due to the performances that these types of actuators offer. In the case of electric-motors, the interfaces are rather bulky and can not be portable.

2. The SMA wire technology is widely used in tactile interfaces. Mechanical amplification systems are used to increase strokes. The drawback of this actuation technology is the low bandwidth and the poor performances.

3. For commercial applications such us Braille systems, the actuation technology seem to trust on piezoelectricity. This is due to the high bandwidth and forces generated by such actuation technology.

4. Solutions such us: MEMS, ER fluid or Polymers, arouse the interest of some research groups. However they are not yet widely used.

5. None of the interfaces among those discussed in this paper deals with the fusion of all the physical parameters which are necessary to reproduce a texture (temperature, vibration, pressure).

A summary of the performances of various actuation technologies is presented in table 1:

	Frequency			Remarks
	<10	50	250	
Motors	×	×	o	Encumbering, potential large race
Electrostatic	×	×	×	Small forces
Piezoelectric	×	×	×	Large deformation requires amplification., cumbersome
SMA	×	o	o	Low frequencies, high forces
Electro Active Polymers	×	×	×	High voltage, high deformations
Electrorheologic	×	o	o	Variation of viscosity, high voltage
Pneumatic	×	×	o	Delocalised encumbering
Electrical	×	×	×	Invasive excitation

Tab. 1. Actuation technology characteristics

When the goal is to reproduce various tactile feelings, it is essential to design a tactile interface that satisfies some requirements. Among, the parameters to be taken into account are: a distance between two micro-actuators of 1mm, a bandwidth of 300Hz for each actuator and a threshold in pressure of 0.5MPa. It is of primary importance to couple this first type of actuators (mechanical) with a second thermal actuator. A temperature interval from 10°C to 45°C would be enough.

REFERENCES

1. T. Anderson, A. Breckenridge, G. Davidson, "FGB: A Graphical and Haptic User Interface For Creating Graphical, Haptic User Interfaces", Sandia National Laboratories, 1999.
2. E.Y. Chen, B.A. Marcus, "Exos Slip Display Research and Development", DSC- Vol. 55-1, Dynamic Systems and Control: Volume 1, ASME, 1994.
3. E.M. Petriu, W.S. McMath, "Tactile Operator Interface for Semi-Autonomous Robotic Applications", AIRAS, Artificial Intelligence, Robotics and Automation, Space, pp. 77-82, Toulouse France, September 1992.
4. C.J. Hasser, J.M. Wesenberger, "Preliminary Evaluation of a Shape-Memory Alloy Tactile Feedback Display" In DSC-Vol. 49, Advances in Robotics, Mecha-tronics, and Haptic Interfaces, pp. 73-80, 1993.
5. C.J. Hasser, M.W. Daniels, "Tactile Feedback with Adaptive Controller for a Force-Reflecting Haptic Display. Part 2: Improvements and Evaluation" In Proc. 15th Southern Biomedical Engineering Conference, Dayton, OH, March 29-31, 1996.
6. D.A. Kontarinis, R.D. Howe, "Tactile Display of Vibratory Information in Tele-operation and Virtual Environments", Presence.
7. R.J. Stone, "Haptic Feedback: A Potted History, From Telepresence to Virtual Reality" MUSE Virtual Presence, Chester House, UK.
8. E. Igarashi, K. Sato, M. Kimura, "Development of a Tactile Feedback Device Used a Pneumatic Balloon Actuator", Proc. Of the Second International Symposium on Measurement and Control in Robotics, ISMCR, Tsukuba Science City, Japan, 15-19 November, 1992.
9. K. Sato, E. Igarashi, M. Kimura, "Development of Non-Constrained Master Arm with Tactile Feedback Device", 7803-0078/91/0600-0334$01.00, IEEE, 1991.
10. G.L. Kenaley, M.R. Cutkosky, "Electrorheological Fluid-Based Robotic Fingers With Tactile Sensing", Proc. IEEE International Conference on Robotics and Automation, Scottsdale AR, pp. 132-136, 1989.
11. G.J. Monkman, "An Electrorheological Tactile Display", Presence, MIT Press, Vol. 1, No. 2, 1992.
12. P.M. Taylor, A. Hosseini-Sianaki, C.J. Varley, "An Electrorheological Fluid-Based Tactile Array for Virtual Environments", Proc. IEEE, International Conference on Robotics and Automation, Minneapolis, Minnesota, April 1996.
13. C. Pfeiffer, C. Mavroidis, Y. Bar-Cohen, B. Dolgin, "Electrorheological Fluid Based Force Feedback Device", Proc. SPIE Telemanipulator and Tlepresence Technologies, VI Conference, Boston, MA, Vol. 3840, pp. 88-99, September 19-22, 1999.
14. Y. Bar-Cohen, C. Mavroidis, M. Bouzit, B. Dolgin, D.L. Harm, G.E. Kopchok, R. White, "Virtual Reality Robotic Telesurgery Simulations using MEMICA Haptic System", Proc. SPIE 8th Annual International Symposium on Smart Structures and Materials, Newport CA, Paper No. 4329-47, 5-8 March 2001.
15. C. Youngblut, R.E. Johnston, S.H. Nash, R.A. Wienclaw, C.A. Will, "Review of Virtual Environment Interface Technology", Institute for Defense Analyses (IDA) 1801 N. Beauregard St. Alexandria, VA 22311-1772, IDA Paper P-3186, DISTRIBUTION CODE 2A, July 1996.
16. T. Fukuda, H. Morita, F. Arai, H. Ishihara, H. Matsuura, "Micro Resonator Using Electromagnetic Actuator for Tactile Display", International Symposium on Micromechatronics and Human Science, 0-7803-4171-6/97 $4.00, IEEE, 1997.
17. C.R. Wagner, S.J. Lederman, R.D. Howe, "A Tactile Shape Display Using RC Servomotors", To be presented at Tenth Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Orlando, 24-25 March, 2002.

18. W.M. Brodey, H.K. Holmen, "Generic Haptic Device Description", CompuTouch AS, Confidential Report, Version: 2.1/19-10-2000.
19. Zanvyl Krieger Mind-Brain Institute, "The 400 Pin Tactile Stimulator Array", 400 Pin TSA User's Guide, The Johns Hopkins University.
20. D.T.V. Pawluk, C.P. van Buskirk, J.H. Killebrew, S.S. Hsiao, K.O. Johnson, "Control and Pattern Specification for a High Density Tactile Display", Submitted to the Haptics Symposium, ASME IMECE, Anaheim, CA, 1998.
21. M. Akamatsu, I.S. MacKenzie, T. Hasbrouc, "A Comparison of Tactile, Auditory, and Visual Feedback in a Pointing Task Using a Mouse- Type Device", Ergonomics, 38, 316-827, 1995.
22. N. Asamura, N. Tomori, H. Shinoda, "A Tactile Feeling Display Based on Selective Stimulation to Skin Receptors", Proc. IEEE VRAIS, pp. 36-42, 1998.
23. T. Watanable, S. Fukui, "A Method for Controlling Tactile Sensation of Surface Roughness Using Ultrasonic Vibration", IEEE, International Conference on Robotics and Automation, 0-7803-1965-6/95 $4.00, 1995.
24. A.D. Johansson, "Shape Memory Alloy: Tactical Feedback Actuator", Technical Review AAMRL-TR-90-039, AD-A231 389, 1990.
25. W.J. Peine, P.S. Wellman, R.D. Howe, "Tomporal Bandwidth Requirements for Tactile Shape Displays", Proceedings of the IMECE Haptics Symposium, Dallas, TX, November 1997.
26. P.S. Wellman, W.J. Peine, R.D. Howe, "Mechanical Design and Control of a High Bandwidth Shape Memory Alloy Tactile Display", Proceedings of the International Symposium of Experimental Robotics, Barcelona, Spain, June 1997.
27. D.A. Kontarinis, R.D. Howe, "Tactile Display of Contact Shape in Dextrous Telemanipulation", To be presented at the Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, ASME Winter Annual Meeting, New Orleans, 28 Nov. 3 Dec., 1993.
28. P.M. Taylor, A. Moser, A. Creed, "A Sixty-Four Element Tactile Display Using Shape Memory Alloy Wires", 0141-9382/98/$19.00, Elsevier Science B.V., pp. 163-168, 1998.
29. Y. Ikei, M. Yamada, S. Fukuda, "A New Design of Haptic Texture Display-Texture Display2-and Its Preliminary Evaluation", Virtual Reality Conference, Yokohama Japan, 13-17 March, 2001.
30. V. Hayward, "Haptics : A Key to Fast Paced Interactivity", International Conference on Machine Automation, Osaka Japan, 25-27 September 2000.
31. V. Hayward, J.M. Cruz-Hernandez, "Tactile Display Device Using Distributed Lateral Skin Stretch", Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, IMECE, November 5-10, 2000.
32. V. Hayward, "Survey of Haptic Interface Research at McGill University", Proc. Workshop in Interactive Multimodal Telepresence Systems, TUM, Munich Germany, March 20-29, pp.91-98,2001.
33. J. Pasquero, V. Hayward "STReSS: A Practical Tactile Display System with One Millimeter Spatial Resolution and 700 Hz Refresh Rate", Eurohaptics, Dublin, Ireland, 2003.
34. M.B. Cohn, M. Lam, R.S. Fearing, "Tactile Display for Teleoperation", SPIE, Vol. 1833, Telemanipulator Technology, 1992.
35. M. Konyo, S. Todokoro, "Artificial Tactile Feel Display Using EAP Actuator", Worldwide ElectroActive Polymers, Artificial Muscles, Newsletter, Vol. 2, No. 1, July 2000.
36. P.M. Taylor, A. Hosseini-Sianaki, C.J. Varley, "Surface Feedback for Virtual Environment Systems Using Electrorhelological Fluids", International Journal of Modern Physics B, Vol. 10, No. 23 & 24, pp. 3011-3018, 1996.
37. E.T. Enikov, K.V. Lazarov, G.R. Gonzales, "Microelectrical Mechanical Systems Actuator Array for Tactile Communication", International Conference on Computers for Handicapped Persons, pp. 551-558, Austria, 2002.
38. H. Kajimoto, N. Kawakami, T. Maeda, S. Tachi, "Electrocutaneous Display as an Interface to a Virtual Tactile World", Virtual Reality Conference, Yokohama Japan, 13-17 March, 2001.
39. S. Ino, S. Shimizu, T. Odagawa, M. Sato, M. Takahashi, T. Izumi, T. Ifukube, "A Tactile Display for Presenting Quality of Materials by Changing the Tempera-ture of Skin Surfaces" In Proc. IEEE 2nd International Workshop on Robot and Human Communication, Tokyo, Japan, November 3-5, pp. 220-224, 1993.
40. G.C. Burdea, "Haptic Feedback for Virtual Reality", Rutgers University, CAIP Center, 96 Frelinghuysen Rd, Piscataway, NJ 08854, USA, 1999.
41. M. Shimojo, M. Shinohara, Y. Fukui, "Human Shape Recognition Performance for 3D Tactile Display", IEEE Transaction on Systems, Man and Cybernetics, Part A, Vol.29, No.6, pp.637-644, November 1999.
42. T. Nara, M. Takasaki, T. Maeda, T. Higuchi, S. Ando, S. Tachi, "Surface Acoustic Wave (SAW) Tactile Display Based on Properties of Mechanoreceptors", Virtual Reality Conference, Yokohama Japan, 13-17 March, 2001.
43. H.Z. Tan, A. Pentland, "Tactual Displays for Wearable Computing", MIT. Media Laboratory Perceptual Computing Section Technical Report No. 431, Appear in : Proc. of the International Symposium on Wearable Computers, 1997.
44. T. Maucher, M. Loose, K. Meier, J. Schemmel, "The Heidelberg Tactile Vision Substitution System", ISAC, 2000.
45. M. Benali Khoudja, M. Hafez, J.M. Alexandre, A. Kheddar, " Electromagnetically Driven High-Density Tactile Interface Based on a Multi-Layer Approach", Best Paper in International Symposium on Micromechatronics and Human Science, pp.147-152, Nagoya Japan, 2003.
46. M. Benali Khoudja, M. Hafez, J.M. Alexandre, A. Kheddar, V. Moreau, " VITAL: A New Low-Cost Vibro-TActiLe Display System", Submitted to ICRA, USA 2004.
47. K. Hirota, M. Hirose, "Surface Display: Concept and Implementation Approaches", ICAT/VRST, Int. Conf. on Artificial Reality and Tele-Existance, pp.185-192, Nov. 21-22, Chiba Japan, 1995.
48. H. Iwata, H. Yano, F. Nakaizumi, R. Kawamura, "Project FEELEX: Adding Haptic Surface to Graphics", IEEE, 0-8186-8192-6/97, 1997.
49. D. Overholt, E. Pasztor, A. Mazalek, "A Multipurpose Array of Tactile Rods for Interactive sXpression", Technical Application, SIGGRAPH, 2001.