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TACTILE DISPLAY DEVICE USING DISTRIBUTED LATERAL SKIN STRETCH

Vincent Hayward **Juan Manuel Cruz-Hernández**

Department of Electrical Engineering and Center for Intelligent Machines
McGill University
3480 University Street, Montréal, Qc, H3A 2A7, Canada
{hayward|manuel}@cim.mcgill.ca

ABSTRACT

In the past, tactile displays were of one of two kinds: they were either shape displays, or relied on distributed vibrotactile stimulation. A tactile display device is described in this paper which is distinguished by the fact that it relies exclusively 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. Some preliminary observations are reported with respect to the sensations that this kind of display can produce.

INTRODUCTION

Tactile displays are devices used to provide subjects with the sensation of touching objects directly with the skin. Previously reported tactile displays portray distributed tactile stimulation as a one of two possibilities [1]. One class of displays, termed “shape displays”, typically consists of devices having a dense array of skin contactors which can move orthogonally to the surface of the skin in an attempt to display the shape of objects via its spatially sampled approximation. There exist numerous examples of such displays, for recent designs see [2; 3; 4; 5].

In the interest of brevity, the distinction between “pressure displays” and shape displays is not made here. However, an important distinction with regard to the focus of this paper must be made between displays intended to cause no slip between the contactors and the skin and those intended for the opposite case.[1] Displays which are intended to be used without slip can be mounted on a carrier device [6; 2].

Another class of displays takes advantage of vibrotactile stimulation. With this technique, an array of tactilly active sites stimulates the skin using an array of contactors vibrating at a fixed frequency. This frequency is selected to maximize the loudness of the sensation (200–300 Hz). Tactile images are associated, not to the quasi-static depth of indentation, but the amplitude of the vibration [7].[2]

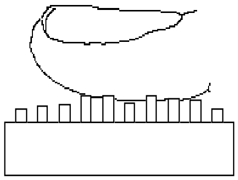

Figure 1. Typical Tactile Display. Shape displays control the rising movement of the contactors (resp. the force applied to). In a vibrotactile display, the contactors oscillate at a fixed frequency.

Devices intended to be used as general purpose tactile displays cause stimulation by independently and simultaneously activated skin contactors according to patterns that depend both on space and on time. Such patterns may be thought of as “tactile images”, but because of the rapid adaptation of the skin mechanoreceptors, the images should more accurately be described as “tactile movies”. It is also accepted that the separation between these contactors needs to be of the order of one millimeter so that the resulting percept fuse into one single continuous image. In addition, when contactors apply vibratory signals to the skin at a frequency, which may range from a few Hertz to a few kiloHertz, a perception is derived which may be described

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[1] Braille displays can be found in this later category.

[2] The Optacon device is a well known example [8].

as "buzzing" and which depends strongly on the waveform of the stimulating signal [9].

The purpose of this paper is to describe initial exploration in a third direction. It is known that the skin's mechanoreceptors responds to a wide variety of stimuli, again for brevity see [10]. Of particular interest is the ability of the skin to respond to lateral stretch (resp. lateral compression), both physiologically and mechanically [11]. In the next section, we will observe that stretch corresponds to sensations that differ from what might be expected. In order words, mechanical stretch does not correspond to a sensation of stretch.

An important consideration which motivates our approach is purely of technological nature. The practical realization of tactile displays based either on shape or vibrotactile sensations is a considerable technical challenge. Difficulties arise (1) from fabricating micro-scale actuators (millimeter scale) which can be packed in dense arrays, and provide for displacements commensurate to their form factors. They must also provide high levels of energy densities, which implies low levels of dissipation; (2) from the necessity to fabricate large quantities of such actuators preferably in an integrated manner; and (3) from operation in environmental conditions resulting from the contact with humans.

PRINCIPLE

Some of the sensations which can be caused by the device to be described later in this paper may be directly experienced by the reader.

An Inexpensive Prototype

A comb is held so that the line of fine pitched teeth contacts the index tip along its length, as in Figure 2.

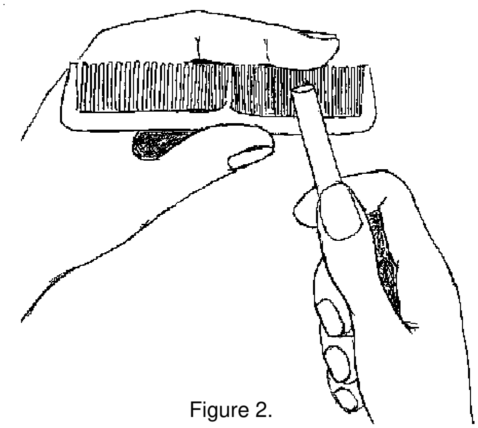

Figure 2.

At rest, the individual teeth cannot be distinguished apart and create the sensation of a continuous edge. Then, the teeth are gently stroked back and forth at mid length with a stick. The resulting sensation is that of an "embossing" running under the index finger. The motion of each individual tooth is minuscule, of the order of a few micrometers and yet the resulting sensation is very present. (It is also important to notice that the same experiment performed with the coarse pitched side of the comb is not nearly as convincing.) In a second step, the same comb is applied to the skin, but this time such that its teeth indent the skin when bent (achieved by touching the comb on its side and again running the stick). The resulting sensation is remarkably similar if not indistinguishable from the previous case. In both cases, the comb teeth indent the skin, and in both cases skin stretch changes are caused, however in the former case there are changes in the lateral direction only and very small ones in the orthogonal direction.

Observations

This demonstration suggest that humans are sensitive to very small displacements of the skin under lateral stretch. This is important because it indicates that loud sensations can be cause by displacements much smaller than the millimeter scale. In fact, we have found that movements of the order of $\pm 50\ \mu$m would probably be sufficient in terms of sensation intelligibility. This is an encouraging prospect given the aforementioned technical fabrication difficulties.

A second observation is that the details of the direction of the movements of individual contactors may be of little importance to some resulting sensations. In fact, in reference to the experiment above, more relevant factors include the diameter of the stick which is used to displace the teeth (which vary the space-time waveform of the global stimulus) and the surface finish of the stick which varies the high frequency components of the global waveform.

In is well known that for general purpose tactile stimulation the temporal resolution of the stimulus must be very fine. While it is difficult to speak of bandwidth since the entire transduction process of tactile sensation is highly nonlinear (as illustrated by the dramatic difference between tone-like stimulation and impulsive-like stimulation) it is concluded that a tactile display can benefit from several kHz of transduction bandwidth.

DESCRIPTION OF THE DEVICE

Initial studies were performed with a device which featured a single line of contactors. It is briefly described here to define terms. Then, the concept is extended to two dimensions, to yield a surface display.

Actuators

The actuator technology which fits best our needs is the piezoceramic actuator. It is mature, well understood, and relatively practical to implement. For the purpose at hand, its major limitation is a small strain. For both the line display and the surface display, we used actuators available from SensorTech Inc. derived from the standard process.[3] Several alternatives including stacked type actuators were examined. Eventually we settled on a sandwiched actuator operating in the d_{31} mode which means that strain is exploited in a direction orthogonal to the electric field applied. The actuators are manufactured in plates consisting of four 0.25 mm layers coated with electrodes. Once cut, the plates yield actuators with a $1 \times 1 \times 20$ mm form factor. The electrode arrangement makes it possible to apply voltage at both ends. They provide a displacement of $\pm 5\ \mu$m for an applied voltage of ± 200 V. Several engineering improvements are possible, however these are left to further developments.

Line Display

Consider a single part flexure element that we call a ‘crown’ to perform several functions.

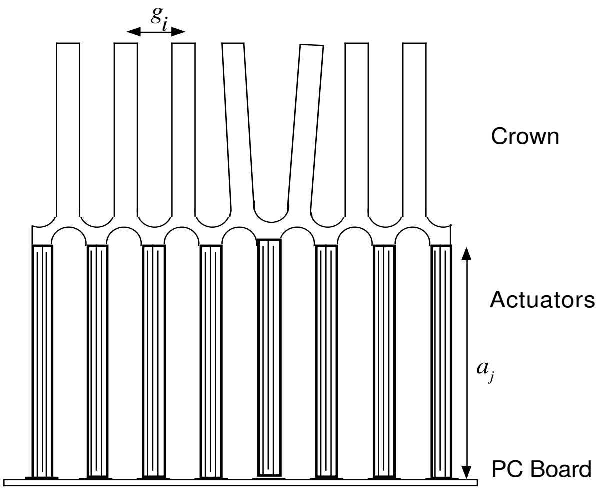

Figure 3. Contactors swing laterally when the actuators are activated: here, the fifth from the left is shown stretching.

Referring to Figure 3, a series of features provide for actuator bonding surfaces on the bottom side of the crown. Being metallic, the crown also form an electric circuit which grounds all the actuators and guarantees protection for the subject. The actuators are connected electrically to an array of pads etched on a conventional printed circuit board for individual addressing of the actuators. Mechanically, the actuators are grounded at the bottom, but are free to move at the top due to the flexural design of the crown. The skin contactors arise from the crown so as to respond to the differential displacement of two neighboring actuators by swinging laterally. Assuming a perfect hinge behavior of the flexural regions, a mechanical movement amplification of an order of magnitude can be expected for contactors 10 times taller than the pitch of the array.

Note that it is possible to relate the gap distances g_i to actuator lengths a_j, provided that two extra constraints are given since there are two fewer gaps than there are actuators. We have use the constraint of conservation of length $\sum g_i = \text{cst}$ for an infinite array (which is equivalent to considering dummy fixed half gaps at the boundaries).

Surface Display

The extension from a line display to a surface display is not completely straightforward. To gain some insight, consider Figure 4. The shapes at the top of the figure symbolize the entries of the deformation tensor for an element of skin. These deformations could in principle be specified independently at the cost of using more than one actuator per “stimulation site” (each square stands for an ‘element of skin’).

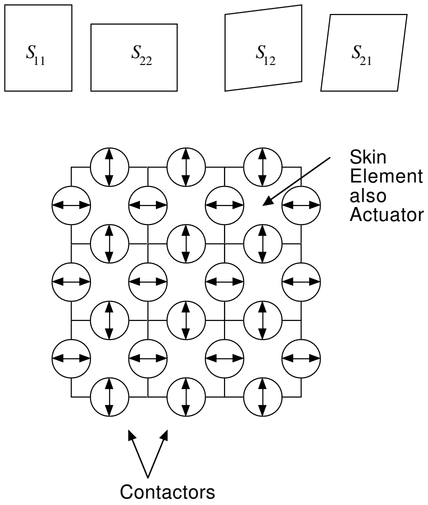

Figure 4. Relationship between each finite skin elements (squares) and contactors (circles). The arrows indicate their movements orientation.

A minimal requirement is to associate one actuator per skin finite element (for an infinite array). This yields the necessity to provide for twice as many contactors as there are actuators (and finite skin elements), as illustrated on Figure 4. Thus, to each actuator length change, there corresponds a skin element area change ($s_{11} = s_{22}; s_{21} = -s_{12} = 0$). The application of the constraint of conservation of area over an infinite array, yields a relationship between 2D strain patterns and the actuator lengths. Note that the vertical and horizontal alignments of actuators and contactors correspond to the case of line display case.

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[3] `http://www.sensortech.ca`

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PROTOTYPE

To date, three “64 actuator/112 contactor/36 gap” surface displays has been manufactured. Figure 5 shows a complete prototype. The actuators are addressed individually via 64 optical switches. For the time being they are driven row-by-row by a bank of eight voltage amplifiers (refresh rate 1 kHz).

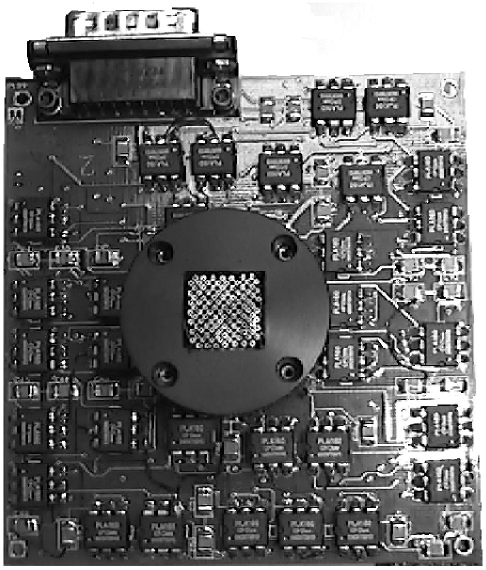

Figure 5. To give scale, the active area is 12×12 mm.

The counterpart of the crown in the line display is now a membrane. The top face (Figure 6) has an array of stumps to attach 112 skin contactors. An array of holes is needed to provide flexibility. In effect, a thin plate cannot deform according to arbitrary patterns without special provisions. The membrane is micromachined out of brass and its thickness in the present prototype is 200 μm.

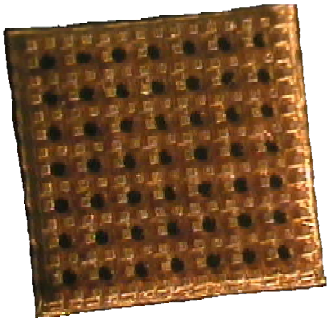

Figure 6. 12×12 mm membrane.

The bottom face of the membrane in shown Figure 7. It also has an array of features to allow for the actuators to bond firmly to it. A micrograph of a cut-away sacrificial test assembly is shown in Figure 8. Two four-layer actuators are seen bonded. The corresponding stump is seen on the other side. The features for inserting the actuators are designed to provide for a significant bonding area working in shear stress.

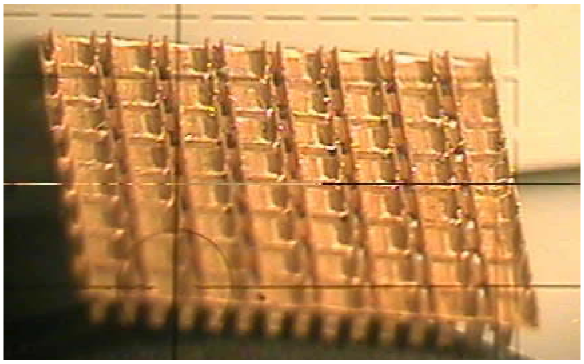

Figure 7. The geometry of the features to bond the actuators is better seen on Figure 8.

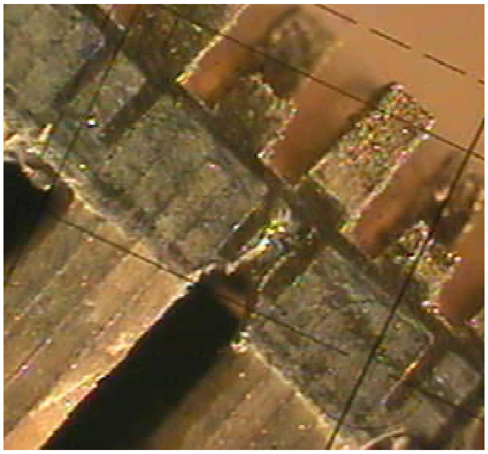

Figure 8. Two four-layer actuators (1 mm) are seen bonded to the bottom of the membrane. The corresponding 1 mm tall stump is seen at the top.

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A partial assembly is shown Figure 9, where the membrane is seen attached to the 64 actuators. Figure 10 shows the final assembly with 112 skin contactors made of Ø 0.7 mm aluminium alloy tubes, attached to the top face of the membrane.

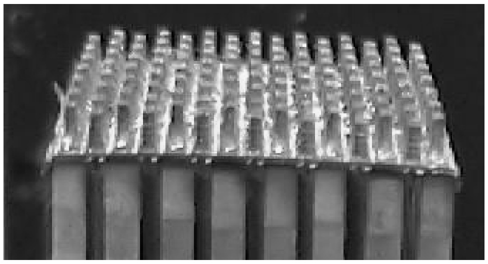

Figure 9.

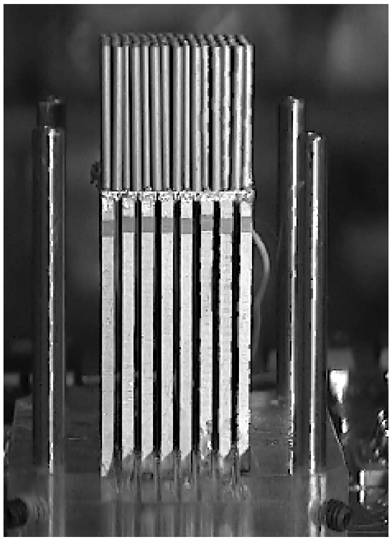

Figure 10.

Finally, Figure 11 shows the array of skin contactors tips. The assembly is encased in a protective cover.

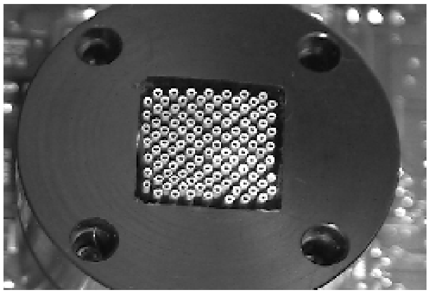

Figure 11.

PRELIMINARY PERCEPTUAL OBSERVATIONS

It was verified that the sensations caused by the “comb experiment” could in fact be reproduced by a single line display which was built in 1997 [12]. Later, a graphical interface was written to specify patterns of stimulation that could depend both on space (using a mouse input) and on time (using a variety of periodic and impulsive signals), both for the line display and the surface display.

A number of curious sensations could be experienced. For example, a stimulus in the form of a “traveling wave” pattern did not always elicit a sensation of motion as it would have been expected. They are sometimes experienced as “pulses”. Only under certain conditions one could experience what Sherrick called “good motion” [13]. The travelling speed seems to be a determining factor as well as the spatial extend of the travelling waveform. On the other hand, when the display is attached to a computer mouse and the interface programmed such that the stimulus becomes linked to the user’s movement, it is easy to have a feeling of “stationarity”. It is possible that these phenomena are related to what was later called time and space mutability on the skin [14].

Also, random temporal signals were applied to many gaps at once. The resulting sensations are difficult to describe and do not relate to everyday experience. One experiences a sensation of activity, but without signification, a tactile “can of worms”, so to speak.

Perhaps more importantly, it was possible to experience sensation specificity for a number of the characters of the stimuli. Two are particularly noteworthy. If a line of the display is activated to create a stress line that varies with time but not with space, then the spatial sharpness of the sensation seems to vary greatly with the rate of change. Alternatively, the sensation sharpness for a given rate depends noticeably on orientation, reaching a maximum in the longitudinal direction of the finger pad.

CONCLUSION AND FUTURE WORK

Our immediate objectives include a more systematic exploration of the kind of sensations this kind of displays can create, in the form of behavioral studies. It is hoped that a careful specification of the stimulation patterns will result in sensations of texture, although for a variety of reasons, we have not been able to obtain them to date. In the longer term, it is planned to carry out a variety of studies ranging from task-oriented user performance studies (such as locating features, discrimination), to determining the conditions under which specific populations of mechanoreceptors might be responding.

In the meantime, work is under way to develop metrology to characterize the existing prototypes more precisely. For example it appears that the device is capable of transducing signals to the skin from DC to several kHz, but how well this happens needs

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to be verified. A finite element model of the device is also under development to evaluate more systematically the factors which influence static performance [15].

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REFERENCES

1. Shimoga, K. B. 1993. A Survey of Perceptual Feedback Issues in Dexterous Telemanipulation: Part 2. Finger Touch Feedback, Proc. *IEEE Annual Virtual Reality International Symposium (VRAIS)*, pp. 271-279.
2. Caldwell G., Tasgarakis,, N., Giesler, C. An integrated shear feedback array for simulation of finger mechanoreceptors. Proc. *IEEE Int. Conf. on Robotics and Automation*. pp. 1287–292.
3. Wellman, P. S., Peine, W. J., Favalora, Howe, R. D. 1998. Mechanical design and control of a high bandwidth shape memory allow tactile display. In *Experimental Robotics V,* Casals, A., de Almeida, A. T. (eds.), Lecture Notes in Control and Information Science 232, pp. 35-45.
4. Pawluck, D. T. V., van Buskirk, C. P., Killebrew, J. H., Hsiao, S. S., Johnson, K. O. 1998. Control and Pattern Specification for a High Density Tactile Array. *7th Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. Proc. ASME Dyn. Systems and Control Division, DSC-Vol 6, pp. 97–102.
5. Hasser, C. J., Weisenberger, J. M. 1993. Preliminary Evaluation of shape memory alloy tactile feedback display. In *Advances in robotics, Mechatronics and Haptic interfaces*. Proc. ASME Dyn. Systems and Control Division, DSC-Vol 49.
6. Ramstein, C. Combining Haptic and Braille Technologies: Design Issues and Pilot Study. 1996. Proc. *ASSETS'96*, ACM, pp. 37–44, Vancouver, Canada,
7. Ikei Y. Yamada M., Fukuda, S. 1999. Tactile texture presentation by vibratory pin arrays based on surface height maps. *8th Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. Proc. ASME Dyn. Systems and Control Division, DSC-Vol 67, pp. 97–102.
8. Hislop, D. W, Zuber, B. L., Trimble, J. L. (1983). Characteristics of reading rate and manual scanning patterns of blind Optacon readers. *Human Factors*, 25(4), 379.
9. Rovan, B., Hayward, V. 2000. Typology of tactile sounds and their synthesis in gesture driven computer music performance. In *Trends in Gestural Control of Music*. Wanderley, M., Battier, M., (eds). Editions IRCAM: Paris, pp. 297–320.
10. Darian-Smith. I. 1984. The sense of touch: performance and peripheral neural processes. In *Handbook of Physiology. The Nervous System. Sensory Processes.* Bethesda, MD: A. Physiology Soc., Sect.1, Vol III, pp. 739-788.
11. Moy, G., Fearing, R. 1998. Effect of Shear Stress in Teletaction and Human Perception. *7th Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. Proc. ASME Dyn. Systems and Control Division, DSC-Vol 64, pp. 265–272.
12. Desmarais, C. 1997. *Skin Stretch Tactile Display*, Honours Thesis, Dept. of Mechanical Eng., McGill University.
13. Sherrick, C. E. 1964. Studies of apparent tactual movement. in *The Skin Senses*. (Details unknown, to be recovered).
14. Geldard, F. A. 1985. The mutability of time and space on the skin. *J. Acoust. Soc. Am.*, 77(1):233–237.
15. Teodori, E. 2000. McGill University. Dept. of Mech. Eng. Honours Thesis under preparation.