VITAL: an electromagnetic integrated tactile display

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Manuscript received, 2006; revised, 2006.
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Abstract

VITAL is an acronym for VIbro-TActiLe display concepts and devices. The new tactile displays presented are based on an integrated electromagnetic actuator arranged in a (8×8) pin matrix. A multilayer approach with a simple assembly procedure enables the development of a new generation of competitively priced tactile matrices with potentially high micro-actuator density. The independent amplitude and frequency control of each pin facilitates displaying various haptic patterns; hence, the displays can be used as haptic communication media. VITAL aims to satisfy both market and haptic research requirements. This paper uses a haptic communication scenario to detail the research and technological development of the first prototype (VITAL1) and its validating experiment results. Extensions of the VITAL display technology through two additional variants and other applications’ perspectives are also discussed.

Index Terms

Tactile displays, vibrotactile, haptics, multi-layer electromagnetic design, haptic communication.

I. INTRODUCTION

Emerging applications such as multi-modal media communication, e-commerce, virtual reality, and telepresence highlight the major importance of human sensory capabilities other than visual ones. Although vision enables understanding the essential parts of our surroundings, the second most important modality in any physical manipulation is indubitably the haptic sense.

The human haptic sense is composed of two sub-modalities: the kinesthetic sense (force, motion) and the tactile sense (tact, touch). A tactile display device aims at reproducing high-fidelity haptic patterns that are either communicative haptic language symbols, or basic surface features information acquired from an indirect (eventually remote) touch of real or virtual surface materials. Therefore, designing various forms of haptic display interfaces is an important challenge for assessing the previously cited applications.

The difficulty of haptic display design comes from the very fact that haptic perception is induced from a direct physical interaction through contact and taction. This is different from vision or sound, where information sampling does not alter its physical support. Haptic interaction and subsequent perception make use of a complex, yet not totally understood, exchange phenomena of different natural physical signals. Thus, it is difficult to establish precise technical requirements and to combine perceptual illusions and tricks to overcome inevitable technological limitations.

This work focuses on haptic stimulation in the tactile modality (excluding thermal and chemical exchanges). It deals with the design of a tactile display concept named VITAL. The first section of the paper presents a short description of state-of-the-art tactile display technology. A comparative evaluation of the different actuation principles motivated our choice of an electromagnetic-based solution. We are targeting a design that can evolve toward high-resolution displays, while taking into account miniaturization and integration issues. Therefore, an

1However, it is difficult to assess for this separation from the physiological or the perceptual point-of-views.
optimization study for the elementary electromagnetic actuator is presented. The second section of this work covers the hardware architecture and realization of the first prototype, VITAL1. It also explains the multilayer integration technique, the power supply, the electronics, and the control board design. The subsequent section is dedicated to the experiment validation of VITAL1. This scenario addresses haptic communication and consists of displaying directional information using geometrical haptic patterns (figure 1). The obtained results are promising and open the horizon for further investigations and improvements. Therefore, the last section deals with the presentation of two other prototypes to demonstrate the extension of the technology to other designs and possibly to other applications.

II. Tactile Feedback Requirements

Tactile displays are mechatronic devices that can be interfaced with hosting systems (e.g. communication media, hand phones, and car appliances) or software applications (e.g. e-commerce, telepresence, and virtual reality). The most usual design for tactile displays borrows from Braille or pin-printer technologies: a matrix of pins arranged by lines and columns. One may call each pin a tactile pixel or simply a taxel by analogy to pixels in visual screens. Each taxel is addressed independently in terms of desired indentation or force amplitude with a given frequency (the equivalent of pixel color). As for vision screens, it is quite challenging to integrate a high-resolution micro-actuator, each 2mm or less. Moreover, these micro-actuators should deliver forces of several tens of milliNewtons, operate at a frequency ranging from a few to several hundreds of Hertz, and indent the fingertip with amplitudes of at least several microns (see [1]), comparable to intensity range, pixel resolution, and scanning frequency.
A. A short review of tactile feedback displays

Different research groups have developed tactile display prototypes, most of which were designed to study the human touch sensory modality. Most of these were made in laboratories, and almost no actual system meets the requirements for mass production. Regardless of the application, the trade-off between display bandwidth and actuator density is a matter of technological barriers, and no satisfactory solution has yet emerged.

The choice of the actuation technology depends on: the application, the shaping requirements, the desired feedback sensation, and the total cost. Previously developed tactile displays are using electric motors e.g. [2], voice coils with conventional solenoids and permanent magnets e.g. [3], wires made of shape memory alloys e.g. [4] combined with mechanical amplification levers for each pin. Other technologies were investigated such as piezoelectric ceramics e.g. [5][6][7], electro-rheological fluids which change the apparent viscosity and therefore the rigidity under the application of an electric field e.g. [8][9], electro-active polymers e.g. [10][11][12]. Technologies dedicated to medical applications such as electro-tactile and neuromuscular stimulator have not yet been extensively used because of their invasive nature; exceptions of tactile displays through direct skin electro-stimulation can be found in [13][14]. A thorough review is presented in [15], and a recent tactile displays state-of-the-art is presented by the authors in [16].

B. Motivation for electromagnetic-based technology

In most previously developed tactile displays, the complexity of the assembling process increases with the number of taxels. A simple and inexpensive assembly process is therefore a key issue for the successful design and distribution of the technology. This paper addresses this difficult issue, since the complexity of the proposed VITAL concept is independent of taxel density.

[Image: Split view of the proposed concept device revealing the multilayer design.]

The VITAL design for tactile displays is based on a multilayer approach (figure 2), allowing the development of a new generation of tactile matrices having high-density micro-actuators. Each taxel is operated through a dedicated electromagnetic micro-actuator in which coils excite a flexible magnetic membrane ( [17]). The technology to
manufacture the micro-coils is based on a multilayer PCB, and the flexible membranes are laser-cut in a monolithic layer.

Next we will present the details of the concept and realization of such a tactile display. First, we will discuss how a single actuator is optimized, given preliminary parameters. The first prototype, VITAL1, is discussed and was thoroughly used throughout the study. Also, we will present two other prototypes, VITAL2 and VITAL3, in order to demonstrate the electromagnetic taxel technology potential in other possible designs. The choice of electromagnetic actuators was the result of our preliminary investigations, revealing that this technology was not totally exploited and fully investigated in tactile displays. We contend that electromagnetic technology offers flexibility in designing efficient and affordable tactile displays.

C. Optimizing a pin-element actuator

In order to integrate the micro-actuator into a single matrix tactile display, it is important to optimize it in terms of force, bandwidth, displacement, and power dissipation in the coils. An analytical model integrating these parameters and facilitating optimization computation of the micro-actuators has been developed. Based on electromagnetic theory and the laws of magnetostatics, and given the magnetic vector potential \( \vec{A} \), we adapted from [18] an analytical model that determines the force between a given coil and a given magnet. This model also optimizes the geometrical parameters of the actuator, so that the highest force and the lowest power dissipation are obtained within a given working volume of the actuator. We recall some basics that might be useful for non-specialized readers.

![Parallel wire segments.](image)

The \( x \)-component of the magnetic vector potential \( A_x \) in a wire segment of length \( l_1 \) in the \( x \)-direction (figure 3), having a flowing current \( i_1 \) and an origin located in the middle is given by:

\[
A_x = \int_{-\frac{l_1}{2}}^{\frac{l_1}{2}} \frac{\mu_0}{4\pi} \frac{i_1}{\sqrt{(x_1-x)^2 + y^2 + z^2}} \, dx_1
\]

(1)

The magnetic field \( \vec{B} \) created by this current is derived from:

\[
\vec{B} = \vec{\nabla} \times \vec{A} = \text{curl}\vec{A}
\]

(2)

In the case of a straight wire positioned along the \( x \)-axis, the \( x \)-component of the magnetic field \( \vec{B} \) is zero \( (B_x = 0) \), and the two other components are given by the following equations.

\[
B_y = \frac{\partial A_x}{\partial z}, \quad B_z = -\frac{\partial A_x}{\partial y}
\]

(3)
For two parallel wire segments (figure 3) (one wire having a length of \(l_1\) with a current \(i_1\) and the other wire having a length of \(l_2\) with a current \(i_2\)), an attractive or repelling force exists between them. An attractive force is created if the two currents flow in the same direction. The \(y\) and \(z\) components of the force acting on wire 2, due to the current flowing in wire 1, can be determined from the general equation of Lorentz’s force:

\[
\vec{F} = \oint i \cdot \vec{dl} \wedge \vec{B}
\]

(4)

where \(\vec{dl}\) is an element along the length of the conductor. \(F_y\) and \(F_z\) are expressed as follows:

\[
F_y = \int_{-\frac{l_2}{2}}^{\frac{l_2}{2}} i_2 B_y dx \quad \text{and} \quad F_z = \int_{-\frac{l_2}{2}}^{\frac{l_2}{2}} i_2 B_z dx
\]

(5)

These formulas can be applied to calculate the resulting force between a magnet and a coil. In fact, based on Faraday’s Law, it is possible to represent a permanent magnet by a coil, which has one single layer of a conducting material with a certain number of turns. The vertical axis of the coil corresponds to the magnetization direction of the permanent magnet. Therefore, the following relation applies:

\[
N \times i = H_c h_{mag}
\]

(6)

where \(N\) is the number of turns, \(i\) is the current flowing in the coil, \(H_c\) is the coercivity of the magnet, and \(h_{mag}\) is the height along the magnetization axis. This equation is valid when the BH-curve is a straight line in the second quadrant. In contrast, when the material exhibits nonlinear behavior, the right-hand term of equation 6 should be divided by the relative recoil permeability \(\mu_r\). The two components of the force between each single wire and all the other parallel wires in both the \(x\) and \(y\) directions are calculated from equation 5. In the case of full symmetry (i.e. the two coils are coaxial), the forces acting in the \(y\) direction between two parallel wires cancel. The sum of forces along the \(z\)-axis \(F_{act}\) gives the force generated by the actuator.

\[
F_{act} = \sum F_z
\]

(7)

Figure 4 indicates that for a specific magnet/coil distance we can reach a maximum force amplitude of 19.4mN. This maximum force corresponds to a magnet-coil distance of 2.6mm obtained when 40% of the magnet remains inside the coil.

An experiment was set up for validation. This setup was composed of a magnet, a coil, and a force sensor (figure 5). Two translation stages were used. The first stage moved the coil with respect to the magnet and fixed it at different positions along the \(z\)-axis. The other stage was an XY 2dof table and was used to center the magnet within the coil.

For each \(z\)-position, an electrical current of 5A was applied to the coil, and the force was measured by the force sensor. We finally obtained the curves plotted in figure 6; the simulated and experiment plots matched, since the same shape and the same maximum value of the force at the same magnet-coil distance were obtained with the analytical model. For each point, the error was less than 5%, which is acceptable.
Fig. 4. Simulated results of the force as a function of the distance. At the left side, the curve represents the force as a function of the distance $D_z$. The force is for a $5 \times 5 \times 5$mm micro-actuator using a Nd-Fe-B magnet 2mm in diameter and 4mm in height. The coil, constituting the given micro-actuator, is machined in a monolithic layer of copper by wire electrical discharge machining; the $N \times I = 35$. On the right side, the interactive simulation of the magnet motion is presented.

Fig. 5. Experiment setup to measure the force variation versus magnet-coil distance.

Various fabrication technologies can be used to manufacture the coils, including conventional winding technologies, deposition technologies (photolithography), and printed circuit board (PCB) technologies based on a multilayer fabrication procedure. The choice of one technology over another is based on the cost and the dimensions of the
actuator. For example, if the actuator is on the macro scale, a traditional winding technology is appropriate. If the goal is to integrate a high number of coil turns within a minimum surface (less than $1\text{mm}^2$), the techniques using deposition seem to be more appropriate. Finally, if the goal is simultaneously to integrate the maximum coil turns on a small surface and to make it in several layers, then PCB technology is well-suited. In each case, the imposed limits enable one to set geometrical parameters in the design of the actuator. Often, it appears that the lower limit is defined by the fabrication technology and the upper limit is defined by the application. The tool proposed in this work allows defining the best configuration between these two limits, by varying the geometrical parameters selected by the user. This optimization is based on a criterion that seems to apply in the majority of applications: maximize the force/dissipated energy ratio.

Fig. 6. Force measurements compared to the analytical simulated model (dimensions of the actuator are at top-right).

Fig. 7. Snapshot of the optimization interface: The upper curves illustrate the magnet height and width (or diameter) and the coil height. The two 3D curves illustrate the force as a function of the coil and magnet heights, and the force/dissipation energy ratio as a function of the same parameters.
To perform the optimization study, it was necessary to define both the basic geometry and the physical parameters. This process was completed, thanks to the optimization software tool we developed and thoroughly discussed in [19]. Once this step was performed, it was possible to define another configuration (representing the geometry limited by the fabrication technology or the application) and the variable geometrical parameters. It was also possible to define the variation range of each variable parameter. Finally, the optimization process was run by using the same interface (figure 7).

III. HARDWARE ARCHITECTURE

This section presents technical details on the building of the VITAL1 tactile display, based on the previously presented concepts and tools [20]. Two other prototypes are also described in a separate section, in order to demonstrate the extensibility of the proposed technology to other variants of tactile display designs.

Fig. 8. VITAL1: The first 8×8 vibrotactile display (left) and its integrated laser-cut flexible membrane (right).

A. A multi-layer integration approach

The first prototype consists of a 8×8 electromagnetic tactile display based on conventional solenoids. The spacing between a pair of pins is 5 mm; the pin diameter is 2 mm. A Nd-Fe-B permanent magnet 2 mm in diameter and 4 mm in height is fixed on a flexible magnetic membrane. This flexible membrane is laser-cut in the same monolithic steel sheet and positioned on the top of the coils (figure 8). The role of this membrane is twofold.

1) The laser cutting generates small pastilles that remain attached to the flexible membrane at some points but are allowed to have relatively independent displacements. These pastilles have the same diameter as the pins, and are necessary to maintain and guide the magnets (i.e. the tactile element pins or taxels).

2) It is also considered as a spatial filter and thus is designed to be flexible. Many researchers have conducted studies in an effort to define the thickness of such a filter [1]. We took into account their results, in addition to our constraint of having a magnetic membrane (this reduces the choice of material and allowable thickness while preserving flexibility).

The curve plotted in figure 9 depicts the variation of the static actuator force versus the applied current. The maximum static force delivered by each micro-actuator was determined to be 13 milliNewtons. The coils are 7.5mm
in height, 3.8mm in external diameter, and 2.6mm in internal diameter. In this case, the maximum applied current must not exceed 0.5A. With such parameters, the tactile display has a maximum pin deflection of \( \pm 100\mu \text{m} \). The display can accurately operate at frequencies up to 800Hz, with a first resonance frequency of 270Hz. The power \( P \) dissipated in the coil, which is mainly due to the Joule effect, is defined by:

\[
P = R \times I^2
\]

where \( R = \rho \times l/s \) is resistance, \( I \) is current, \( \rho \) is the resistivity, \( l \) is the length of the coil and \( s \) its cross section.

The maximum power dissipated in each coil for \( R = 1.6\Omega \) and \( I = 0.5\text{A} \) was \( P = 400\text{mW} \). In practical conditions the current was about 0.2A which corresponds to a dissipation power of nearly 64mW.

**B. The electronic architecture**

Since \( N \) is constant for a given actuator configuration, desired force and indentation amplitudes to be delivered by each micro-actuator are controlled through the current in each coil. In this case, the nominal current in each coil is a bi-directional \([0, 1]\)A.

Due to the large number of micro-actuators forming the tactile display, a dedicated electronic architecture has been realized. At first we implemented a compact amplifier capable of driving such values of current; we then built the appropriate architecture to embed them in a size-limited power board. A control board using a Digital Signal Processor (DSP) to address and calculate the wave profiles of the signal to be applied to each coil\(^3\) was also built. This DSP board was connected to the (graphical) user interface through a Universal Serial Bus (USB) or an RS232 link. The general diagram of the electronic hardware architecture is presented in figure 10.

A Pulse-Width Modulation (PWM) power driver voltage-to-current amplifier was used as the basic element to build the power board. The boards were designed to be generic and reconfigurable. Currently, four similar power boards, each supporting 32 PWM power drivers, are available. The electronic architecture is common to all previously

\(^2\)This current could be as high as \( \pm 1.5\text{A} \) for smaller coils.

\(^3\)Each coil is separately addressable and any waveform can be produced for each taxel.
cited VITAL concepts. The power boards can be stacked. For instance, by using a stack of four power boards we can independently drive up to 128 micro-actuators; using two power boards (as is the case for VITAL1), we can drive 64 \((8 \times 8)\) micro-actuators. Finally, four multi-channel (eight-bit octal) Digital-to-Analog Converters (DACs) were used for each power board to generate the current setpoint for each micro-actuator. The development of the control board was essentially based on TMS320F2810, a DSP from Texas Instruments. A USB interface and an RS232 serial interface were integrated on the control board. The communication between the control board and the software interface was made either through the RS232 standard interface or through the USB interface. As a final stage, once a satisfactory design was reached, the electronics were replaced by an Application-Specific Integrated Circuit (ASIC).

It is either possible to compute the micro-actuators’ input signals using the computer or the DSP. The computer solution is well suited for interactive applications. For example, to display an interactive virtual reality surface touch exploration, one can compute the appropriate signals using the computer (e.g. using advanced GPU techniques). If one considers communicating haptic patterns from outside sensors (e.g. camera images), signal processing of the mapping for each tactile interface actuator can be taken into account by the DSP.

When the overall components of the system were ready, VITAL1 was validated by experiments in order to assess the VITAL concepts and to investigate potential problems.

IV. EXPERIMENT RESULTS: COMMUNICATING DIRECTION THROUGH HAPTIC PATTERNS SCENARIO

Due to the VITAL1 characteristics as well as the project funding organization\(^4\), the validating scenario was chosen to address haptic communication media. VITAL1 was used to display haptic patterns, the interpretation of which was supposed to show directional information. Two sets of experiments were conducted: (i) displaying moving directional patterns, and (ii) displaying static geometrical shapes.

\(^4\)http://www.enabledweb.org/
A. Experimental scenarios

Ten blindfolded subjects (seven males and three females) with an average age of 25 years participated in the experiments. The total time to perform both experiments was 30 minutes [21].

Fig. 11. Direction stimulus patterns: full small arrow (left), empty large arrow (center), an empty small arrow having similar shape (not illustrated), and line (right).

The first experiment dealt with directional haptic pattern interpretation. It subsequently demonstrated the capability of the interface to display and communicate direction information. Four patterns were used in the four directions: South (S), North (N), East (E), and West (W). Two sets of 18 successive directions were displayed: [S S N E W W S E N N W E S W N S E E]. This sequence took into account most of the possible transition cases. The considered patterns were a full small arrow, an empty large arrow, an empty small arrow, and a line (figure 11). The subjects were asked to determine the direction of the displayed pattern.

Fig. 12. Shape stimulus patterns (medium size). The upper line represents the full shapes, and the second line, empty or wire shapes. From left to right: square, line, circle, and triangle.

The second experiment dealt with shape perception (for more details on the approach used in this experiment, please refer to [22]). Four patterns were considered: a square, a line, a circle, and a triangle. Each pattern had three different dimensions, small, medium, and large. For each case, the pattern was either full or empty, except for the line, the shape of which did not change (figure 12). The procedure was similar to that of the first experiments: a sequence of 18 successive shapes was randomly displayed. The subjects were asked to identify the shape. No precision on the size was requested, although the subjects often correctly detected size.
For both sets of experiments, subjects could choose the exploration mode and time freely in order to determine the average time required by the subject to answer. The working frequency of each taxel (micro-actuator) was 33 Hz, and the pin deflection was 100µm. These values were retained after preliminary trials with the VITAL1 interface. This step is common and necessary in psychophysics and human factors experiments (i.e. when parameters need to be tuned).

B. Procedure

For both experiments, the subjects were seated and were free to use either the right or the left hand. The tester immediately recorded the answers given by the subjects. In the direction experiments, the subjects received no training or extra time at the beginning of the experiment. The subjects were asked to specify in which direction the pattern had moved on the active surface. The subjects had previously been informed about the four existing directions and were not asked to pay attention to the shape of the moving pattern, since we wanted to determine if a particular form improved the recognition of directions.

For the shape experiments, the subjects were allowed some time to become familiar with the different shapes. The subjects were asked to specify the shape of the pattern displayed. The stationary shapes were displayed on an active surface (i.e. their location did not change). The subjects were previously informed about the four shapes and the three sizes for each shape. The subjects were asked to determine only the shape of the displayed item, not the size. Finally, the subjects were asked some additional questions, which will be discussed in the next section.

C. Results

For the direction-identification experiments, the exploration mode was intuitively passive because the forms were displayed in a propagation motion. For example, in addition to orienting the form according to the displayed direction information, the form also shifted dynamically from left to right to display the east direction, or from bottom to up to display the north direction. The subjects preferred to keep their hands stationary on the VITAL1. All of them used at least two fingers to achieve these experiments. (The display was not restricted to one finger; thus, two or more fingers could be used).

The results for the different directions using different shapes are reported in figure 13. The average percentage of error when a line was displayed to identify the four directions was less than 22%. When arrows (empty, full, large, and small) were displayed, the performances were the best for the small empty arrow, followed by the empty large arrow; they were worst for the full arrow. In the case of the large arrow, the subjects confused the horizontal displacement of the pattern with its displacement along the diagonal. The shape might have confused the subjects in their interpretation of the direction from a moving tactile pattern. Only two subjects were able to identify the form as a line or an arrow; the others had no idea as to what shape was being displayed by the interface.

It is noteworthy that identification of the north and south directions was more accurate than that of the east and west directions. When the pattern was moved toward the north or south, the displacement occurred in the direction of the fingers. However, for west and east directions, the displacement of the pattern occurred in the
lateral direction of the fingertips. In this case, discontinuity between the fingers might explain this result. Finally, the average direction-discrimination time was 4.5 minutes.

In the second set of experiments, the exploration mode was active; in contrast, the displayed form was static (i.e. the displayed shape was not shifted on the active surface). The subjects preferred to explore actively the surface of the VITAL1 interface.

At the beginning of these tests, the subjects were informed that four shapes would be displayed and that the shapes would be centered within the VITAL1’s display “screen.” They were told that the triangle would be oriented toward the top direction (figure 14) and that the line would always be horizontal. Even if each shape was displayed in three different sizes (small, medium, and large), subjects were asked only to define the shape, not its size.

The results of these tests are reported in figure 15. The mean error percentage for wire-frame shapes (all sizes) was less than 43%. It increased up to 68% for solid-filled shapes, with the exception of that obtained for the line, which was less than 17%. The highest percentage of error was due to confusion between circles and squares. The number of micro-actuators (64) versus the large active surface (in this version of VITAL1) seemed to be insufficient.
to distinguish easily between two shapes (square and circle) with close dimensions. For the same reason, the small shapes were more difficult to identify than the large shapes; the best performances were obtained when large shapes were displayed. Finally, the average shape-identification time was six minutes.

Tactile perception and identification of geometrical shapes and directions displayed on the VITAL1 interface was 78% for direction, 57% for wire shapes, and 32% for filled shapes, regardless of size. The perception of edges, lines, and contours was better than the perception of the full shape using vibro-tactile interface. At the end of the experiments, the subjects were asked the following questions.

1) Do you think that you have made a lot of mistakes? All the subjects said yes.
2) Was it easy to feel directions? All the subjects found that they were guided by the evolution of the vibration (independent of the shape information).
3) What was the easiest shape to recognize? For all subjects, the line was the easiest to identify.
4) Do you still feel the vibration now (when the experiment was over)? Some of the subjects said yes. None of the subjects felt anything after a certain period of time using VITAL1. (A break time of 20sec between two identifications was allowed.)

We concluded that the VITAL concept is viable and the VITAL1 display can be used as a haptic media interface for displaying moving shapes but not static ones. Other experiments that go beyond the scope of the paper have been conducted to study this technology for display of emotions; the results are thoroughly reported in [23].

The VITAL concept is a promising technology for tactile display interfaces. Nevertheless, the experiments conducted suggest that the resolution is of prime importance, and much effort is necessary to improve this parameter. By design, the VITAL concept allows such an extension. After these encouraging results, two other prototypes were devised.
In order to decrease spacing between the pins while increasing the indentation amplitude, a second version of VITAL has been realized. However, reducing spacing implies increasing magnetic interference.

The proposed alternative design is rather classical and has been devised only for technological purposes. In this version, the position of the magnet and the coil can be alternated all along the transmission cylinder, allowing reduction of magnetic interference. This design also avoids problems related to the material choice of the cover membrane in VITAL1; the magnetic flexible membrane has been replaced by simple pins sliding in a guiding element (figure 16). In this version, the spacing between the actuators is 3 mm. The micro-coils are conventional coils. The height of each coil is 10 mm, the internal diameter is 1.8 mm, and the external diameter is 2.7 mm. NdFeB magnets are also used in this version. Each magnet is 1.5 mm in diameter and 2 mm in height, and each is placed inside a cylindrical guide. Each pin is connected to the magnet or to a transmission cylinder (i.e. the magnet is placed alternatively on the top or the bottom of the interface in order to lower magnetic field interaction between the pins), but it can also be placed in the middle. The overall dimensions of the device are 30 × 30 × 20 mm$^3$. We emphasize that this prototype is not really an improved version of VITAL1; it is simply another design that might be suitable for applications where the height of the display is not a crucial constraint. It has not been used in our applications, since another prototype was devised just after its development.

Other haptic applications (e.g. virtual reality and telepresence) would have different requirements. Electromagnetic force is proportional to the product $N \times I$ (where $N$ is the number of turns of the coil and $I$ is the applied current). Thus, an electromagnetic actuator element could reach higher forces by lowering the current (or keeping it constant) while increasing the number of turns. Since high currents would lead to rather complicated electronics and might be of some danger for the operator, we devised a system with the possibility of increasing the number of turns while keeping a reduced space and satisfying tactile display requirements in terms of force, indentation, and bandwidth. The new design is based on a multilayer approach in which the complexity of the assembling process is independent of the number of taxels. The multilayer design is based on linear electromagnetic actuators with micro-coils, which are manufactured on the same printed circuit (figure 17). The PCB coil layer is separated from the mobile flexible magnet structure by an insulating layer. The separating layer offers the necessary volume in which the micro-actuators operate. Another layer contains both the coils and the addressing tracks.
Two VITAL3 prototypes have been devised based on multilayer PCB technology (figure 18). The displays are also $8 \times 8$ taxels of flat coils with 5mm interspaces. The PCB is composed of eight layers of nine copper turns per taxel; hence, there are 72 coil turns per taxel. The copper tracks composing the PCB coils have a section of $35 \times 120 \mu m^2$, allowing an alternating current of 0.3A amplitude in a typical application. The main advantage of using multilayer PCB technology is to build new tactile interfaces that are well adapted for mass production. To reach this objective, special attention was given to the design stage. The VITAL3 active surface effectively integrates the coils, micro-magnets, flexible membrane, and addressing tracks.

A simple assembling process is presented in the figure 18. Three main layers integrating the coils and addressing tracks, the magnets, and the flexible micro-membranes are stacked. Using this approach considerably reduces the time to assemble the VITAL3 active surface. The size of the first prototype is $126 \times 76 \times 17.8mm^3$, including the active surface and the connectors’ volumes. Using a conventional mouse tracking system, the display could be transformed into a vibrotactile mouse. The size of the VITAL3 mouse is $126 \times 76 \times 32.8mm^3$, which is 15mm
larger than the previous one. This prototype is made to be moved easily; therefore, the flat cable has been replaced by a round one.

Fig. 19. Technical performances obtained from the VITAL3: Force response measurement. Each actuator can deliver up to 8milliNewtonsw force output (left). The measured bandwidth is 320Hz and exhibits a resonant peak at 230Hz (right).

Figure 19 illustrates the measured performance and force characteristics of the tactile display. A heat-sink has been added on the back of VITAL3 (using the same PCB) to dissipate the thermal energy by convection. The compactness of the obtained display makes it a good candidate for applications in which size is an important issue.

Fig. 20. A more integrated prototype realization of the VITAL3.

A third prototype has been designed in order to build a more integrated device that could be embedded in a cell phone, for instance. A new multilayer PCB has been built with 24 layers and a 3.5mm actuator in between spacing (figure 20). It is also an $8 \times 8$ flat coil matrix manufactured in a 24-layer PCB Each layer contains 4.5 turns; hence,
each coil is composed of 108 turns. An alternating current can be applied with a maximum amplitude of 0.3A.
The same assembly process has been used (figure 20). The VITAL3 compact prototype is mainly composed of a
multilayer PCB, a monolithic layer holding the micromagnets, and an outer structure that allows assembling all the
components together. The size of the outer structure is $121 \times 62 \times 17\text{mm}^3$. The active surface size is $28 \times 28 \times 5\text{mm}^3$.
Such dimensions enable the system to be embedded in cell phones and other portable devices.

The last version of VITAL3 was designed with higher resolution to facilitate interfacing with Virtual Reality
and telepresence applications. The technology is being transferred to the industry through the HAPTION start-up.\(^5\).
Therefore, we now face problems that focus on computer haptics (i.e. how textures can be appropriately transformed
into vibration combined with a kinesthetic stage [24]) to render HiFi surface exploration using a bare finger or
hand ([25][26]).

VI. Conclusion

VITAL is a new vibrotactile concept for tactile display based on an electromagnetic actuator. A multilayer
approach is taken to build integrated vibrotactile interfaces. The electronic architecture and the overall design will
ensure the system is competitively priced, especially when mass produced. Using a home-developed optimization
tool, it is possible to optimize the elementary linear electromagnetic actuator for any configuration or design. It
is also possible to compute the optimal configuration that gives the highest force/dissipated energy ratio, and to
determine the influence of each geometrical parameter on the performance of the actuator. Following the encouraging
experiment results acquired from the VITAL1 prototype, the concept has been validated, and several other prototypes
have been devised.

The two sets of experiments that have been carried out with the VITAL1 (i.e. shape and direction identifications)
confirm that it is possible to communicate directional information and hence indicate potential utilization in haptic
communication media. However, VITAL1 requires a higher resolution to be able to display shapes and fine surface
roughness and textures. Consequently, future research challenges in improving the VITAL3 consist of: enhancing
the resolution, interfacing the VITAL3 hardware with our ongoing developments in computer haptics, and designing
integration within a flexible support (i.e. a flexible tactile display membrane that can be on top of a shape and force
display).

REFERENCES

Virtual Environments & Teleoperator Systems, 2002.

\(^5\)http://www.haption.com/