A Thermopneumatic Approach for Tactile Displays

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***Abstract*—This paper presents a new tactile display based on thermopneumatic actuators. Since the main drawback of these devices in the market is their cost, this proposal is intended to reduce the price because of the simplicity of the actuator and the potential low cost assembling. A small display with 4 x 4 taxels and 2.54mm of distance between centers has been built and results from a single actuator with proposed activation circuitry illustrate its performance in this first prototype. Specifically, rise and fall times of 2 and 11 seconds respectively are measured as well as maximum stroke and force above 1mm and 0.1N respectively. This results are good to implement a large tactile screen. Power consumption is high, but it could be lower if latching mechanisms are used to keep the taxel active without power supply. Finally, thermopneumatic actuators have been used in micropumps and microvalves in technologies for MEMS, thus very small and smart tactile devices could be fabricated to improve the resolution and performance.**

***Index Terms*—Blind people aids, Tactile graphic displays, Thermopneumatic actuator.**

I. Introduction

Tactile displays show the information by stimulating the sense of touch. They are required as reading tools for blind people and more recently in areas like virtual reality and telesurgery. Most devices in the market are based on piezoelectric cells. However, a Braille cell (eight points) costs around 35€, and a Braille display (one line of text) costs around 10000€. The display DMD 12060 from Metec implements an array of 159 x 59 miniature solenoids with a distance of 3mm between centers and a cost around 60000€ [1]. Obviously, the main drawback of these devices is its high cost, specially for large *displacement displays* [2] which are those explored with the fingers.

A common strategy to reduce the cost in the so called *force displays* [2] is by means of a pointer device, for instance a computer mouse, and a small tactile display on it. A finger (or a few fingers) rests on the display whose content is refreshed as the mouse is moved along the so interpreted virtual tactile image. The VirtTouch mouse is based on this idea and costs around 5000€. However, the information these devices transmit to the skin is quite limited. That is because much information is collected by dynamic mechanoreceptors in the skin while the fingers explore a surface, because of the slip or tangential forces [3][4]. Thus, there is still a great interest in new actuators that allow a more efficient implementation in terms of cost and performance.

There is a wide range of possibilities, but most work is done in electrical stimulation [5][6], SMA (shape memory alloy) actuators [7][8], pneumatic [9], based on ER (electrorheological) fluids and organic gels [10][11] or based on MEMS (Micro-Electro-Mechanical Systems) [12][13]. Electrical stimulation is an old idea but it has not got yet the desired results, although advances have recently achieved [6]. SMA wires change its length (around 5%) when heated by a current (around 2A) through them. Most problems to solve are small stroke, high power consumption, slow response, hysteresis and difficult assembling. Pneumatic devices are bulky unless they use microvalves to control the flow, for instance valves in MEMS technologies [12]. These devices are not yet mature enough although they could be a good choice in the future. The response of the ER fluids is fast (in the milliseconds range) but the resolution and stroke are poor. A pneumatic display based on these fluids has been proposed and seems to improve the performance of previous approaches [10]. Finally, an interesting proposal is reported in [14], where a vibrotactile display is presented that is based on electromagnet actuators with microcoils implemented in multi layer PCB (Printed Circuit Board) technology.

In summary, much work is carried out in the development of new actuators that could lower the cost and improve the performance of tactile displays. This paper presents another alternative. It exploits the idea behind thermopneumatic microvalves and micropumps to build a simple tactile display. Although there are still many problems to be solved, the preliminary results show the viability of the proposal and encourage us to face the improvement of the actuator and control circuitry as well as the construction of a large display.

II. Thermopneumatic Actuator

Thermomechanical actuators provide good performance in terms of displacement, force and work per cycle. Thermopneumatic micropumps and microvalves are based on sealed cavities that have a flexible side [16]. The cavities are filled with a low boiling point liquid (for instance methyl chloride) and a resistive heater is built inside. When the heater increases the temperature in the cavity, the pressure grows because of the gas resulting from the liquid-gas phase transition, and the flexible side of the cavity is displaced.

This idea is proposed by the authors to build tactile displays. Fig. 1 shows the actuator as built to get the results of this paper. It consists of a small cylinder made of brass with an end sealed with tin and the other with a flexible diaphragm. A signal diode has been chosen as heater due to its small size, although it can be replaced by a resistor or other semiconductor devices.

The Clapeyron's equation gives the following expression for a region close to the boiling point (P_B, T_B),

$$P = P_o \exp\left(-\frac{l_v}{RT}\right) \qquad (1)$$

where $P_o = P_B \exp\left(\frac{l_v}{RT_B}\right)$, P is the vapor pressure inside the cavity, T is its temperature and l_v and R are constants.

On the other hand, the displacement s of a circular diaphragm under a pressure P is,

$$s = 0.0151(1-\mu^2)\frac{Pa^4}{Eh^3} \qquad (2)$$

where a is the radio, μ is the Poisson coefficient, E is the Young modulus and h is the diaphragm thickness.

From (1) we conclude that the change of the pressure with the temperature is high near the boiling point, and it will be the same for the displacement in (2). Thus, we should work close to the boiling point to have the best performance. Liquids with low boiling points are required to save power in increasing the temperature up to the boiling point, although they should be higher than the ambient temperature to avoid undesired activations. In addition, the diaphragm should have small values of μ, E and h, i.e. it must be flexible.

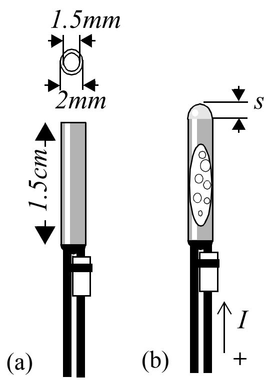


Fig. 1 Thermopneumatic actuator.

With regard to the actuator in this paper, its shape and size are shown in Fig. 1, the liquid inside is acetone, with boiling point at 56.2ºC, or methanol, with boiling point at 65ºC (phase transition in SMA devices is around 50ºC) and the diaphragm has been implemented with a 150µm thick latex membrane, although it is stretched and so the ending thickness is lower. Although these choices allow us to show a display with a resolution similar to other reported proposals and preliminary experimental results point to the feasibility of the approach, both the display and actuator are not optimized yet. Special care has to be taken to reduce leakage, which is large in this prototype because of the latex permeability and faults in the sealing mechanism. Specifically, flexible plastic diaphragms can replace the latex ones in future displays and microchannels in PCB technology [15] could provide a way to refill the cavities.

III. Tactile display

Fig. 2 shows a prototype of display with the proposed thermopneumatic actuator. It consists of an array of 4 x 4 actuators with a distance of 2.54 mm between centers and an active area around 1 cm^2. Fig. 2 (a) shows a draw with a side cut of the prototype as well as a photograph. The thermopneumatic actuators have been mounted in a standard circuit prototyping board. Drills have been made and individual electrical control as well as a sealing mechanism have been implemented. The display is showing a 'one' in Braille at the photograph in Fig. 2(b).

Other reported displays have 4 x 4 actuators with 0.7mm diameter and separated 2mm [6], or 6 x 6 actuators with 1.5mm diameter and 16mm x 16mm display area [17], while the ideal resolution (given by human skin features) is 1 actuator per square millimeter, thus this first prototype is close to other state-of-the-art proposals in terms of spacial resolution. The existence of micropumps based on the same thermopneumatic actuators will allow likely to build displays with ideal resolution based on this technology.

IV. Activation circuitry

The activation of the proposed actuator shares many problems with that of other actuators based on thermal principles, like SMA devices. With regard to the latter, they have hysteresis while it is not the case of the proposed actuator. However, there is also a trade-off between turn-on and turn-off times improvement. Let us use the simplified model in the Fig. 3 to illustrate the design problem.

In Fig. 3, P is the electrical power dissipated by the heater (a diode in our case), R is the thermal resistance and C is introduced to model the transient behavior. For this simple model the temperature evolution during turn-on in Fig. 3(a) is

$$T = T_a + PR(1 - e^{-t/RC}) \qquad (3)$$

and that for turn-off in Fig. 3(b) is

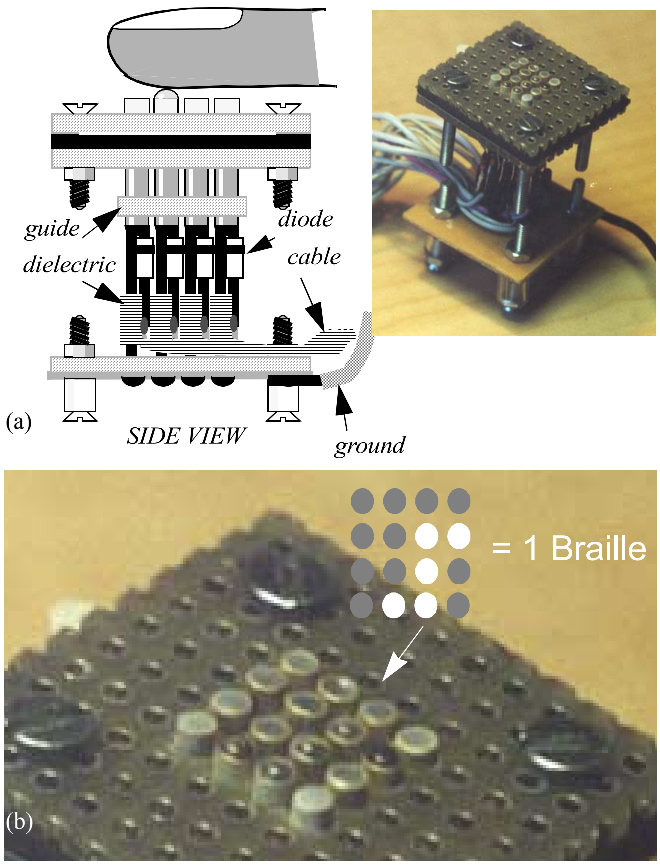


Fig. 2 Prototype of tactile display with thermopneumatic actuators.

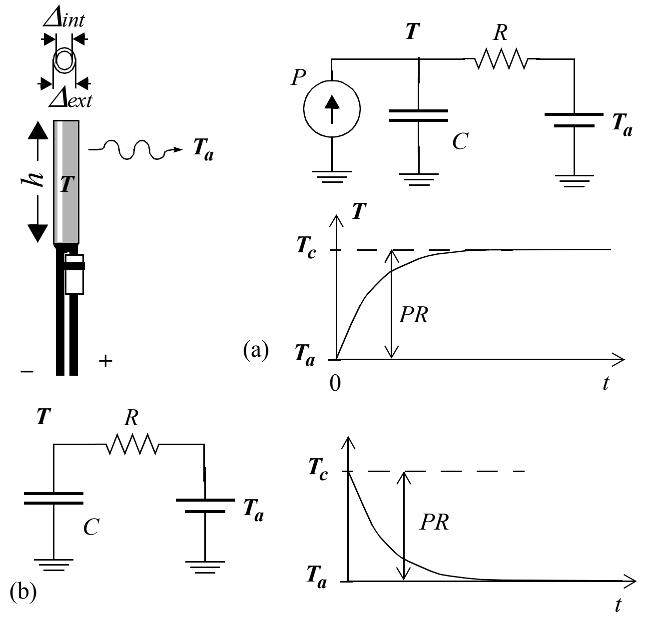


Fig. 3 Models and temperature evolution during turn-on (a) and turn-off (b)

$$T = T_a + PRe^{-t/RC} \tag{4}$$

hence both follow an exponential behavior with a time constant equal to RC. C is related to the actuator volume while R is related to the actuator surface and shape. In order to reduce turn-on and turn-off times a low value of R is desired. However, this means a higher power has to be dissipated by the heater to reach the target temperature T_c (note that PR is the temperature increment in Fig. 3). Hence, low values of R and high values of P are required for a fast response.

Force displays based on SMA actuators have to be refrigerated (R is reduced) with water to work at a frequency of 30Hz. This strategy has not been implemented in the prototype of this paper. It will not be likely necessary to build a large screen displacement display, where the frequency of operation is not essential and times of a few seconds can be tolerated. Nevertheless, a bi-level strategy has been implemented to increase the speed that consists in injecting a high power P_{exc} at the beginning of the activation to increase the temperature quickly, and a lower power P_{hold} once the actuator is active to reduce power consumption and avoid damage of the heater element.

Circuitry in Fig. 4 has been proposed to implement the bi-level strategy. The signal diode D4148 drives a current

$$I = \frac{V_{pol}}{R} = \frac{V_{DD}R_2}{R(R_1 + R_2)} \tag{5}$$

as long as the transistor Q_1 is cut off. This is achieved by generating a negative pulse of duration Δ at input. As soon as the pulse finishes and the input becomes high Q_1 saturates, V_{pol} is small and I is negligible. The rated pulse width Δ and the current I could be obtained from the diode data sheet. However, since a brass tube is soldered to the diode the thermal resistance has been modified and data in the data sheet referred to maximum power are not longer valid and deep work of thermal behavior modeling has to be done to obtain optimal performance.

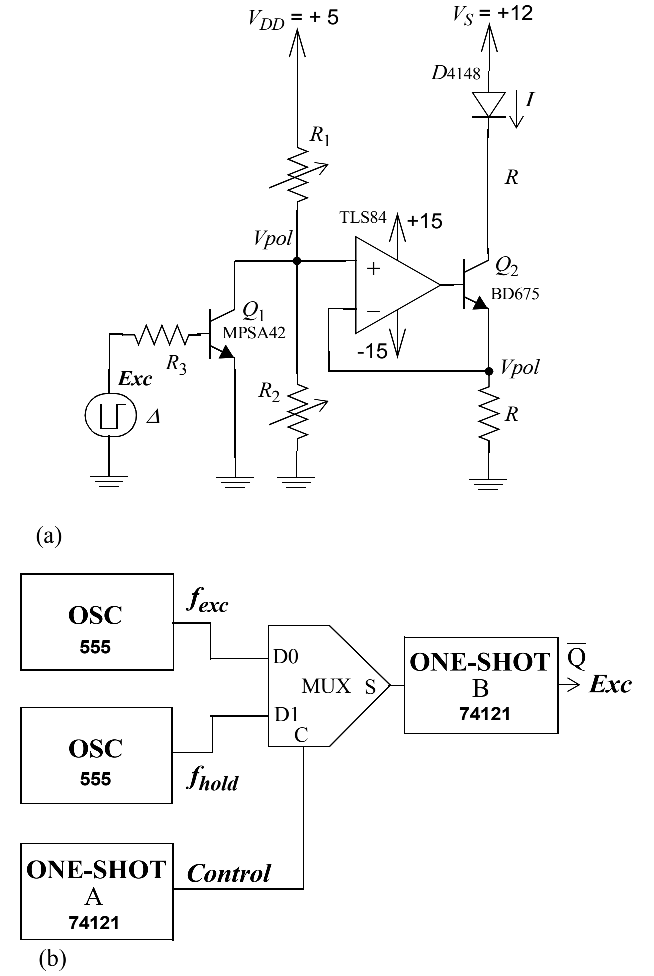
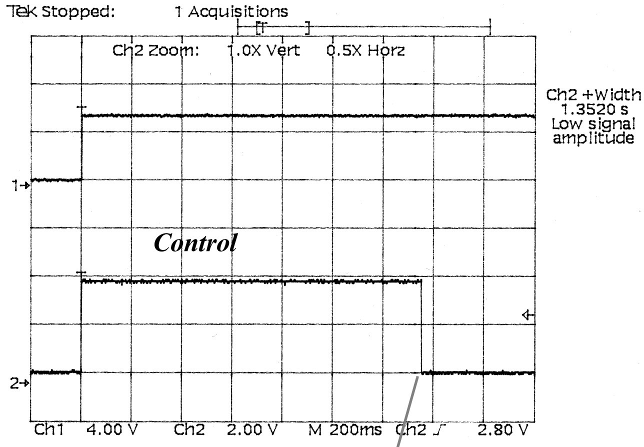


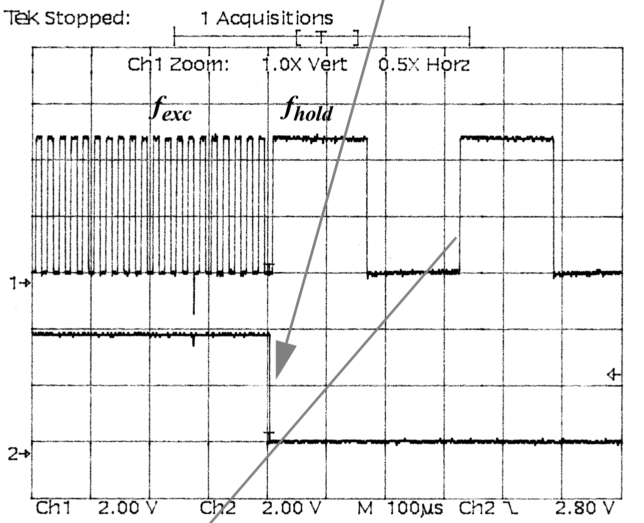
Fig. 4 Circuit to generate a current pulse (a) and circuitry to implement bi-level strategy (b).

A pulse train instead of a constant current is generated to feed the diode. This excitation has been found to increase quickly the temperature of power semiconductor devices. The pulse train is obtained by triggering a one-shot with an oscillator. The bi-level strategy is implemented by means of two oscillators, one to generate the high excitation frequency f_{exc} and the other to generate the holding frequency f_{hold}. A multiplexor (implemented with just 3 nand 74LS00 gates) put the proper output depending on the state of the control signal, which is generated with another one-shot. The result is a current pulse train in the diode with a frequency f_{exc} for a time controlled by the one-shot A, and a current pulse train of frequency f_{hold} after this period. The duration of every current pulse is controlled by the one-shot B (i.e. the duty cycle) and its amplitude by the resistors R_1 and R_2 (see Fig. 4(a) and eq. (5)).

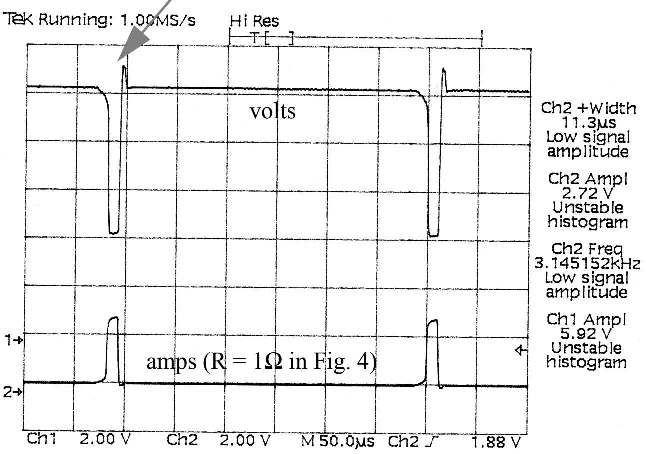
Fig. 5 Illustrates the above description with measurements of the control signals and excitation pulses in the preliminary results of this paper (see Fig. 4 for signal references). Fig. 5(a) shows the activation signal (top) and the control signal (bottom) that determines the excitation burst length while Fig. 5(b) shows the multiplexor output (top) and control signal (bottom). In addition, Fig. 5(c) shows the current pulse in the diode (bottom) and the voltage drop in it (top) respectively.



(a)



(b)



(c)

Fig. 5 Activation (top) and control signal (bottom) (a) Multiplexor output (top) and control signal (bottom) in the bi-level strategy (b), and current pulse (bottom) and voltage drop (top) in the diode (d).

V. RESULTS AND DISCUSSION

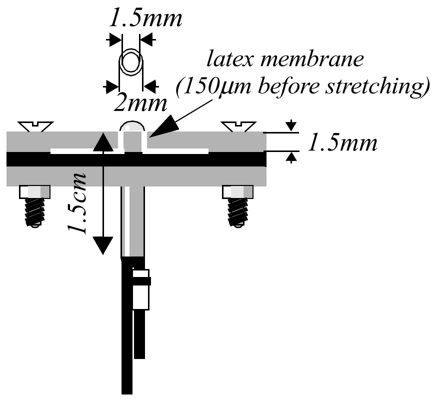


Fig. 6 Single thermopneumatic actuator.

This section presents some results from a single actuator. It was built with the same procedure described in the section III. Fig. 6 shows this actuator and some significant dimensions. Results in this section has been got with the activation circuitry in Fig. 4 and methanol as the liquid inside the cavity. Results in Fig. 2(b) were obtained with a simpler activation circuitry and acetone as liquid inside the cavity. We observed a larger leakage in the later case.

Fig. 7 illustrates the behavior of the actuator during its turn-on and turn-off. Rise and fall times are around 2 and 11 seconds respectively. The activation conditions are those in Fig. 5 with $f_{exc} = 50kHz$ and $f_{hold} = 3.1kHz$. The top curve in Fig. 7 has been obtained by using an LDVT as displacement sensor, which was calibrated with a micrometer and has a sensibility of 0.8 V/mm, while the bottom curve in Fig. 7 is the activation signal. There was not any weight added to the LVDT core, thus the actuator lifts 1.1grams. Power consumption is around 600mW (from data in Fig. 5(c)) in the holding phase and around 9watts in the excitation phase. This is a drawback of the proposal, and it is also common in thermomechanical actuators. The improvement of the device, the activation circuitry and the use of a locking mechanism to keep the taxel active without power consumption are strategies to overcome it.

Fig. 8 shows the force generation versus displacement graph. It was obtained in static conditions. A discrete number of weights were added to the LVDT core and the stroke was

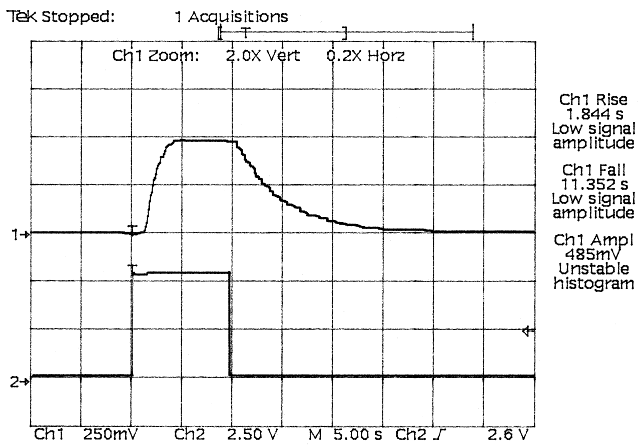


Fig. 7 Activation and deactivation response of the actuator.

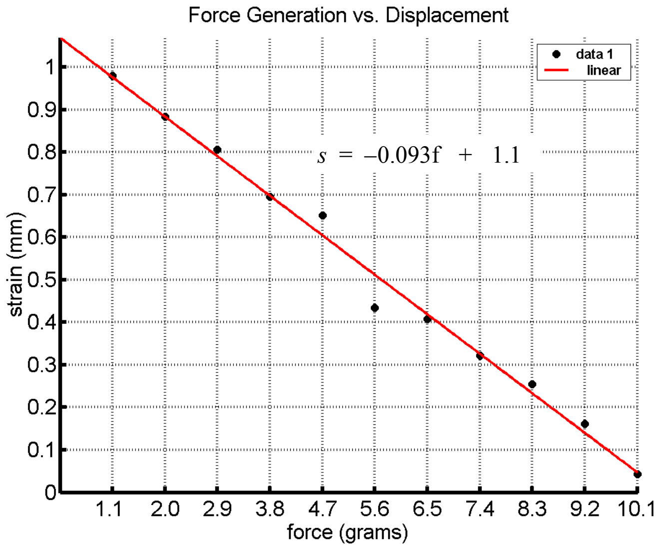


Fig. 8 Force generation versus displacement graph of the actuator.

measured with the LVDT after waiting for the signal to be stable. Significant results are the maximum force and stroke which are above 10grams (0.1N) and 1mm respectively. Note that the stroke in Fig. 7 (0.6mm) is not as large as that in Fig. 8 for the same weight. In fact, the mesa in the top curve of Fig. 7 has a small positive slope because the pressure still increases in the holding phase. A fine adjustment of the excitation burst length as well as f_{exc} and f_{hold} or a smarter control circuitry should result in a better agreement between the static and dynamic measurements of the stroke.

Comparison with other proposals is difficult at this stage of the research. The ideal tactile display should have a resolution of one actuator per square millimeter. The DMD-12060 has a distance of 3.08 mm between centers and a standard piezoelectric cell in a refreshable tactile display has 3.21mm and 2.45mm of x and y distance between centers respectively. The 3D display in [4] has a distance of 3mm between centers. With respect to the stroke or vertical displacement, the Braille cell in a refreshable display has a stroke of 0.7mm, and the skin is able to detect shapes as thin as 0.1mm high [4]. The force of the finger against a taxel during exploration could be up to 2.35N as reported in [4] and our actuator lifts more than 10 grams weight, hence a equivalent force of 0.1N. However, the skin can detect forces as small as 0.001N [18]. In addition, 0.1N force is enough if a latching mechanism is used, because the stiffness of the taxel is very high once it is latched. As regard to the dynamic response, refreshing times of 15s are reported for the display in [4]. Requirements of the pointer device based displays are much more restricted for the dynamic response, and strategies like cooling are used to reach the desired speed. That could be the case of a similar display made with the proposed actuator. With respect to a large tactile screen, although multiplexing can improve the performance, the power consumption could be of a few thousands of watts. Although it can be reduced by means of locking mechanisms as already said above.

It is important to highlight that the presented actuator is not obtained off-the-shelf, but it is actually a hand-made experimental device. Many variables affect the results, for instance the ambient temperature, the thickness of the latex membrane, how much it is stretched in the sealing process, the compliance of the sealing rubber, the size and shape of the tube, the material it is made of, the vapor to liquid ratio in the cavity, etc. Special care has to be taken to avoid air bubbles in the cavity because it results in a worse behavior of the device. As a consequence, the repeatability of the measurements we obtained was low, and the process to obtain them was a bit cumbersome. Much work has to be done still to improve the performance of the device, with respect to the technology and also the circuitry.

Nevertheless, the results in this section are intended to show that the thermopneumatic approach is able to provide good results in comparison with other implementations, specially in the case of a large tactile screen with a latching mechanism to lower the power consumption. The simplicity of the proposal could solve the main problem of these devices, which is the price. The implementation of the screen in a technology close to a conventional one and with minimum assembling cost is still an important step to demonstrate this price reduction. In this sense, work is done now to exploit the techniques reported in [15] to fabricate microfluidic devices in PCB technology.

This work has been supported by the Spanish Government under contract TIC-2003-09817-C02-02.

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