Design, realization and validation of a piezoelectric flexible haptic interface

Romain Le Magueresse, Fabrice Casset, Frédéric Giraud, Munique Kazar Mendes, Sébastien Brulais, Laure Peris y Saborit, Anis Kaci, Mikael Colin

DEVELOPMENT, REALIZATION AND VALIDATION OF A PIEZOELECTRIC FLEXIBLE HAPTIC INTERFACE

Romain Le Magueresse [1,2], Fabrice Casset[1], Frédéric Giraud[2], Munique Kazar Mendes[1], Sébastien Brulais[1], Laure Peris Y Saborit[1], Anis Kaci[2] and Mikael Colin[1]
[1]Univ. Grenoble Alpes, CEA, Leti, F-38000 Grenoble, France and
[2]Univ. Lille, Arts et Métiers Institute of Technology, Centrale Lille, Junia, ULR 2697 - L2EP, F-59000 Lille, France

ABSTRACT

This paper reports the development, realization and experimental validation of the first flexible haptic interface using friction modulation principle. This conformable haptic interface is composed of nine rigid haptic pixels formed with PZT ceramics bonded to square glass plates integrated on a KAPTON polyimide film. The design is optimized analyzing the flexural waves at the surface. An innovative hybrid process in cleanroom enables to obtain haptic resonators vibrating at ultrasonic frequencies, and creating displacements of 4 µm peak-to-peak for an actuation signal of 20 V peak-to-peak. Thanks to a dedicated actuation electronics based on an FPGA board, a haptic effect by friction modulation allowing to create virtual texture is obtained on this flexible haptic interface.

KEYWORDS

Haptic, Flexible Haptic, Piezoelectric, Friction Reduction

INTRODUCTION

To improve the interactions with human's machine interfaces, haptic technologies are studied for several years [1]. Researchers have introduced different vibration control techniques in haptic surfaces, such as inverse filtering [2], time reversal [3], stimuli confinement [4], friction modulation [5], or phononic crystals [6], enabling a large variety of tactile sensations such as vibrations, pulsations and textures. In particular, friction modulation, or ultrasonic lubrication, exploits the airgap created between skin and a vibrating surface as well as the intermittent contact that results from the vibration, allowing a large range of sensations including the creation of virtual textures.

Nowadays the trend is to develop new interactive conformable surfaces such as foldable and rollable displays. In this way, researchers have developed some flexible haptic solutions [7]. These devices have demonstrated their capability to produce vibrotactile stimulations [8], [9] but cannot use friction modulation to allow the creation of textures.

Considering this, recent studies [10], [11] show the possibility for the development of a new kind of flexible haptic interface based on a hybrid solution. The principle is to create local vibrating plates at ultrasonic frequency actuated by piezoelectric actuators and to embed them in a polymer matrix. This solution combines the characteristics of rigid haptic devices based on ultrasonic lubrication with the flexibility of a polymer to obtain a conformable surface.

The paper first presents the development of the nine-pixel surface. The realization is then explained and validated electromechanically.

DEVELOPMENT

Background

Previous works have allowed us to introduce and validate the concept of haptic pixel [10]. This one is composed of three main elements: a square glass plate of surface 1 cm² and thickness 500 µm, a PZT actuator of diameter 5 mm and thickness 150 µm and a polymer film (Figure 1). This haptic pixel, when activated at its resonance, creates a flexural wave in the polymer and allows to obtain texture sensations thanks to the technique of ultrasonic lubrication. When the finger is in active touch condition, i.e. in movement on the polymer surface it is possible to feel virtual texture thanks to the friction reduction between the finger and the haptic pixel. For this purpose, the actuation signal at the pixel resonance is modulated at a frequency lower than 1000 Hz [12].

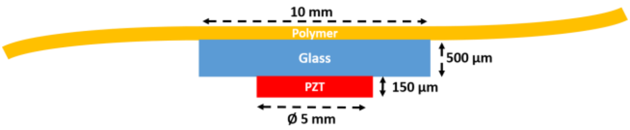

Figure 1: Validated concept of the haptic pixel [11].

Two polymer films were selected: PEEK and KAPTON for realizations where the fabrication had been manual (realizations without equipment of cleanroom, welding of wires, etc.). Here we are only interested in realizations with 75-µm thick KAPTON with a manufacturing obtained in cleanroom for a surface of nine pixels.

Design of the surface

As mentioned in the previous works, a flexural wave on the surface is created by each haptic pixel actuated at its resonant frequency. The wavelength depends on the actuation frequency ω, the density ρ, the bending rigidity D and the thickness h of the KAPTON film (Eq. 1).

$$\lambda = 2\pi \left(\frac{D}{\rho h \omega^2}\right)^{\frac{1}{4}} \qquad (1)$$

It is in this situation around 3 mm that allows to consider a haptic feeling on the polymer for the ultrasonic lubrication. Indeed, the spatial acuity under the fingertip is about 2 mm [13].

When several haptic pixels are activated, the waves interfere with each other. It is thus possible to size the distance L between two pixels to maximize the transverse displacements by creating a constructive interference. This distance depends on the wavelength λ and an integer n, which corresponds to the number of vibration nodes along the polymer similar to a vibrating rope here (Eq. 2).

$$L = \frac{\lambda}{2}\left(n + \frac{1}{2}\right) \quad (2)$$

A distance of 10 mm is chosen for the realization. This distance allows, when the pixels are actuated in phase at their resonance, to have a constructive interference similar to a stationary wave with six nodes of vibrations.

The pixels are then multiplied to obtain a surface of nine haptic resonators. A COMSOL model of this surface is realized to highlight its vibratory behavior. We can observe in Figure 2 the standing wave created between two pixels with the six nodes of vibrations and the wavelength of 3 mm. Furthermore, the interference zones of the flexural waves allows to delimit specific zones of haptic feeling. In fact, by choosing the pixels activated, we also choose a specific area on the surface. Thus, elementary forms can be realized on the surface. Figure 2 shows, for example, the drawing of a "+" shape from the actuation in phase at their resonance frequency of five haptic pixels.

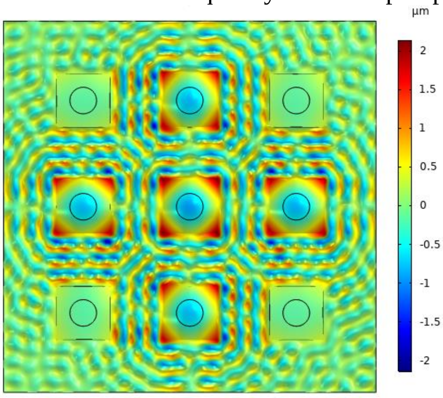

Figure 2 : « + » shape obtained from COMSOL model.

The amplitude of displacements estimated with the model for a voltage applied to the PZT of 20 V peak-to-peak is 4 µm peak-to-peak. These displacements allow us to consider an important haptic feeling on the active zone representing the "+" shape.

REALIZATION

Process

The haptic interface is realized with an innovative process composed by two main parts (Figure 3).

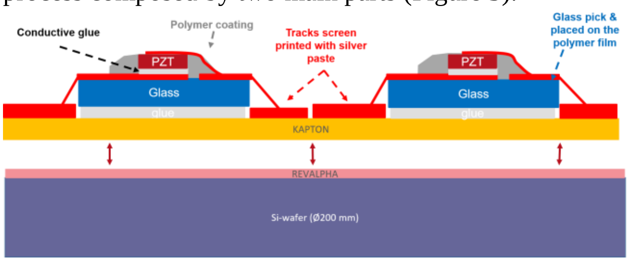

Figure 3: Schematic cross section of the interface fabrication process.

Firstly, the rigid vibrating plates are fabricated on a 500 µm-thick glass wafer in the cleanroom. The bottom electrode deposition was realized by screen-printed silver ink (ELEPASTE NP1 from TAIYIO INK) followed by annealing. A second screen-printing also followed by an annealing process is performed to deposit the conductive adhesive (H20E) used to bond the PZT ceramics (PI 255). The ø 5mm x 200µm ceramics are placed using a pick & place tool (DATACON 2200 Evo advanced). A polymer layer (Namics G8345-146) is then deposited all around the ceramics in order to electrically isolate the lower electrode from the future upper electrode. To obtain the desired thickness of 150 µm as designed the ceramics are thinned by a grinding technique. After manufacturing, the thickness is 145 µm, i.e. a 3.3% shift, as shown in the SEM cross-section of Figure 4.a). The top electrode is realized by the deposition of 500 nm of gold by evaporation through a shadow mask. Thus, we obtain on the wafer the instrumented glass plates with their actuators. To conclude the first part of the fabrication, a water jet cutting is carried out to obtain the 10 mm size individual squares as presented in Figure 4.b).

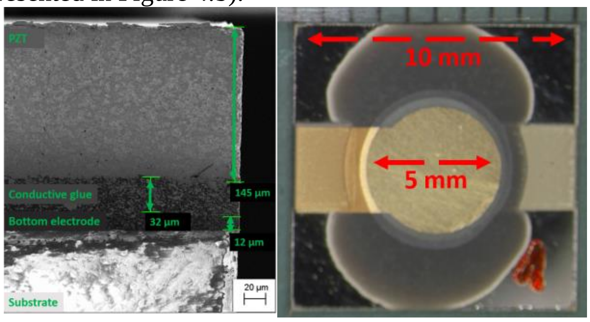

Figure 4: a) SEM cross section and b) top view of the haptic pixel.

In the second part, the haptic pixels are integrated on the KAPTON flexible substrate. For this purpose, a REVALPHA thermal release film is laminated on an 8-inch silicon wafer followed by the lamination of a 75 µm-thick KAPTON film. In this way, it is possible to carry out conventional manufacturing steps in a cleanroom on the flexible substrate. The electronic tracks are then screen-printed on the surface. The pixels made on glass wafer are bonded with epoxy (E505) by a pick and place technique. The electrical contacts are made with a silver ink between the tracks on the polymer and the electrodes on the pixels. Then the silicon wafer is heated to 170°C, which allows the REVALPHA film to disintegrate and the surface to be released as shown in Figure 5. We obtain four haptic interfaces per wafer: two interfaces with a distance of 10 mm between pixels, as expected, and two other interfaces.

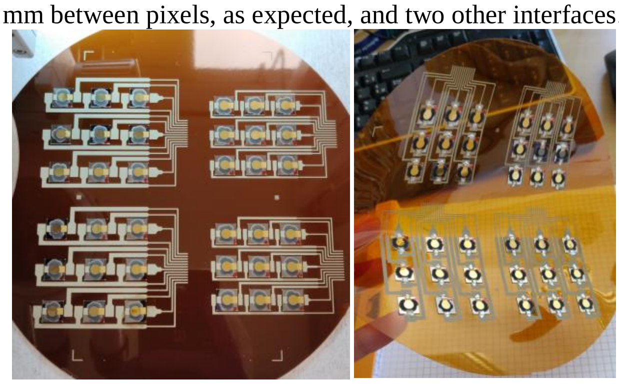

Figure 5: 4 haptic interfaces before and after the release of the REVALPHA from the silicon wafer.

Finally the instrumented KAPTON film is cut to obtain the four surfaces and a flexible connector is assembled to each surface to recover the connections of the electronic tracks. Figure 6 shows the finalized technology fixed on a cylindrical plastic support of radius 3 cm.

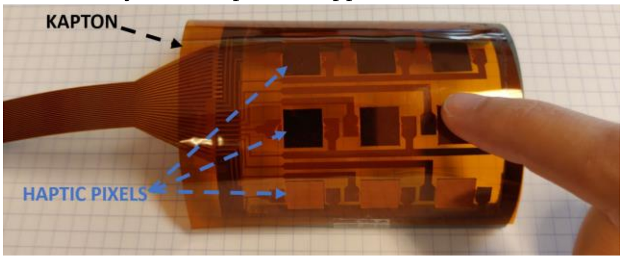

Figure 6: New flexible nine-pixel haptic interface.

Electronic

The actuation electronics is realized from a field-programmable gate array (FPGA) board and an amplification stage manufactured on a printed circuit. The FPGA produces the digital drive signals [0; +3.3V]. Then two field-effect transistors, mounted in push pull configuration and driven by a mosfet driver (IR2183), form the amplification stage as presented in Figure 7 for one PZT actuator. Thus, the signal generated by the FPGA board is elevated from to 3.3 to 48 V.

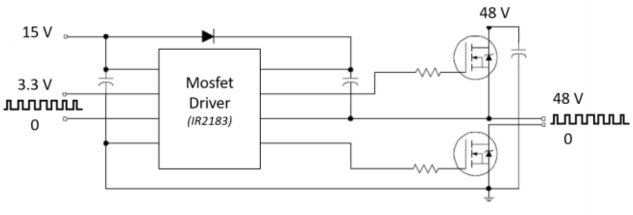

Figure 7: Amplification stage for one haptic pixel.

In this way, a pulse-width modulation (PWM) is produced on nine different channels to drive the nine piezoelectric actuators of the interface. The PWM allows to have an actuation signal at the resonance frequency of the pixels modulated at 250 Hz by an amplitude modulation for haptic feeling. A Python script enables to modify the voltage and the phase of the signal sent to each piezoelectric actuator. Thus, the pixels to be actuated are chosen in order to have a reconfigurable flexible haptic surface.

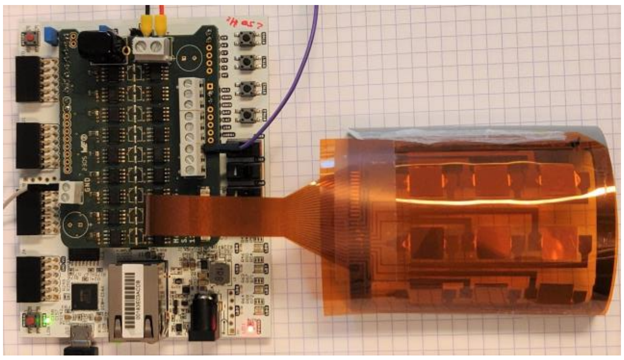

Figure 8: Actuation electronics with the interface on a cylindrical support.

EXPERIMENTAL VALIDATION

The haptic interface is validated by impedancemeter and vibration measurements.

Impedancemeter measurement

The electrical impedance of each haptic pixel is measured with an impedance analyzer (Agilent 4294A). This impedance is based on a Butterworth Van Dyke model with the equivalent circuit formed by the glass plate, the PZT ceramic and the KAPTON film and compared to that obtained with the model developed on COMSOL as presented in Figure 9.

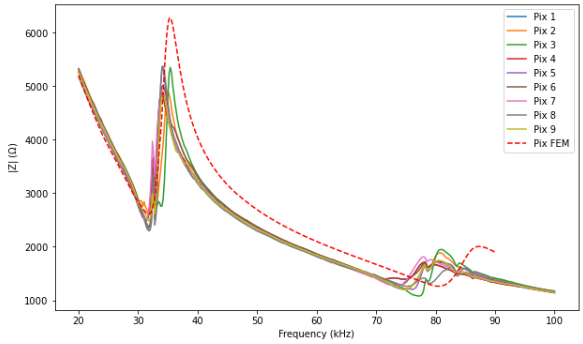

Figure 9: Impedance measurements for the nine pixels of the surface compared with the FEM.

The first vibration mode is well consistent with the simulation: 31.8 kHz with COMSOL against 31.7 kHz on average with a standard deviation of 0.2 kHz for the fabricated pixels. In addition, the impedance value varies only slightly between pixels around the resonance. The resonant behavior of the pixels is therefore similar. The pixels can therefore be considered as uniform. This confirms the interest of operating all the PZT actuators at the same frequency with the electronics realized.

Vibration measurement

Laser vibrometer measurements are performed to validate the displacement amplitude. A Polytec OFV-5000 modular vibrometer base with a sensor head OFV-505 and a programmable two-axis table are used. An example of a measurement is shown in Figure 10. Five haptic pixels are actuated with a voltage of 20 Vpp with the same phase at 31.7 kHz. The objective is to reproduce a "+" shape on the surface as presented in Figure 2 with the COMSOL model.

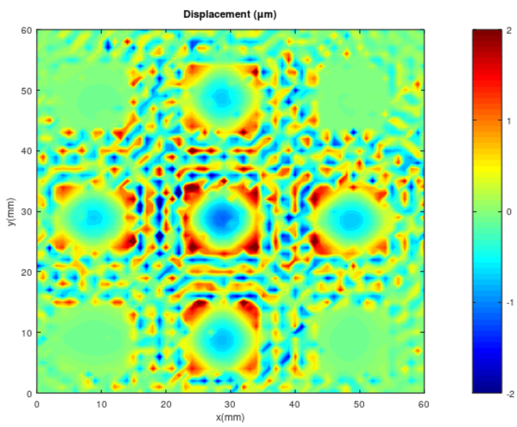

Figure 10: Laser vibrometer displacements measured for a "+" shape obtained with five actuated pixels.

The desired "+" shape is clearly visible in Figure 10. The displacements obtained are 4 µm peak-to-peak and consistent with the COMSOL model. These displacements are well above the limit often set in haptics of 1 µm for the feeling. Thus, the sensation will be very marked. It will be so possible to feel this shape of “+” when the user will touch in active condition the surface. The friction modulation technique will enable to feel texture on this shape.

CONCLUSION

This paper presents the development, realization and validation of a new flexible haptic interface using friction modulation. This conformable haptic interface is composed of nine rigid haptic pixels formed with PZT ceramics bonded to square glass plates embedded in a KAPTON film. The design was optimized by analyzing the flexural waves on the film surface. An innovative hybrid cleanroom process, based on two main phases, allows to obtain haptic pixels vibrating at ultrasonic frequencies, around 32 kHz, and to create displacements of 4 µm peak-to-peak for an actuation signal of 20 V peak-to-peak. Dedicated electronics using a FPGA board allows to drive the actuators and to obtain a haptic sensation by friction modulation.

Further work will be carried out to evaluate this new solution with the help of use cases.

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CONTACT

*R. Le Magueresse, tel: +33-438-780775; romain.lemagueresse@cea.fr