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Romain Le Magueresse, Frédéric Giraud, Fabrice Casset, Anis Kaci, Brigitte Desloges, et al.. Preliminary design of a flexible haptic surface. Hasti Seifi; A. M. L. Kappers; et al. Haptics: Science, Technology, Applications. EuroHaptics 2022., 13235, Springer, pp.207-215, 2022, Lecture Notes in Computer Science, 978-3-031-06249-0. 10.1007/978-3-031-06249-0_24 . cea-03713105

HAL Id: cea-03713105

<https://cea.hal.science/cea-03713105>

Submitted on 4 Jul 2022

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Preliminary Design of a Flexible Haptic Surface

Romain Le Magueresse^{1,2}, Frédéric Giraud²[0000–0002–5688–711], Fabrice Casset¹, Anis Kaci², Brigitte Desloges¹, and Mikael Colin¹

¹ CEA, LETI, MINATEC Campus, F-38054 Grenoble, France and Univ. Grenoble Alpes, F-38000 Grenoble, France

² Univ. Lille, Arts et Metiers Institute of Technology, Centrale Lille, Junia, ULR 2697 - L2EP, F-59000 Lille, France
romain.lemagueresse@cea.fr

Abstract. This paper presents the preliminary development of a flexible haptic surface in order to produce texture rendering on a large conformable area. For this purpose, Haptic Pixels vibrating at ultrasonic frequencies are actuated by piezoelectric elements and implanted on a flexible matrix. The design leads to square glass plates of $10 \times 10 \text{ mm}^2$ with a thickness of $500 \mu\text{m}$, actuated by PZT ceramics with a thickness of $200 \mu\text{m}$ and a radius of 2.5 mm bonded on a $100 \mu\text{m}$ thick PEEK film. Electromechanical characterizations validate the design. The PEEK film between two pixels is exploited to separate them, to obtain the flexibility of the surface and to create an area of friction reduction with a stationary wave. Haptic evaluations are carried out to confirm the performances of the approach on a Haptic Pixel.

Keywords: Haptic · Flexible haptic · Friction reduction

1 Introduction

A Haptic Surface displays to a user’s fingertip a tactile stimulation during active touch [1]. Researchers have proposed several actuation solutions to create the interaction forces, taking advantage of wave propagation into the Haptic Surface. For that purpose, they use localized vibrations thanks to inverse filtering [12], time reversal [8], stimuli confinement [6] or friction modulation [7] techniques. To be efficient, these solutions require specific properties from the surface to be actuated, and their principle have been demonstrated with flat and rigid material, with a simple geometry.

However, the trend in user interfaces is a demand toward ”smart-surfaces” [5] that incorporate several functionalities into a wide variety of material and shapes. Moreover, the emergence of new flexible technologies such as flexible phones, rollable screens or wearable devices push us to think about conformable haptic devices. A current solution for that goal is to bury an array of actuators in a polymer substrate, as in [14] with electromagnetic actuators, with Shape Memory Alloy actuators [3] which need a pneumatic circuit or with Dielectric Polymer Actuators [15]. In [11], the authors use a gel, that can change its stiffness with a temperature increased produced by an electrical current. These devices have

demonstrated their capability to produce vibrotactile stimulation, but they cannot be used to create programmable texture rendering by friction modulation, because elastic waves doesn't propagate in the soft substrate. In [2], electroadhesion is used to create friction modulation, but it requires the substrate to be in metal.

This paper presents the preliminary design of a flexible haptic device that can produce texture rendering over a large bendable surface. The principle is to create vibrating plates at ultrasonic frequency, actuated by piezoelectric actuators (named *Haptic Pixels* in the remaining of the paper), and to embed them onto a flexible substrate. This solution combine the characteristics of rigid haptics devices with the flexibility of a polymer to obtain a solution with friction modulation, as depicted Fig. 1 when used as a wristband. This interface can be developed for any tactile application where the surface must be conformable or foldable. Haptic Pixels could be controlled independently to allow localized effect and multiple finger interaction or their actions could be combined to create areas on the polymer for friction modulation.

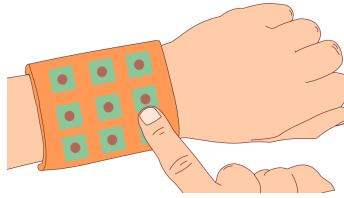


Fig. 1: Application of the proposed design to a Haptic Wristband. Each Haptic Pixel produce friction modulation while the whole device is bendable and conformable to the user's body.

The paper is organized as follows: the design and the evaluation of an elementary Haptic Pixel are first presented. Then, two pixels are combined together in a matrix in order to create an area of friction modulation and an overview of the complete surface is shown; an electromechanical characterization validates the design. Finally, a tribological and psychophysical studies are presented to confirm the results for an elementary Haptic Pixel.

2 Design of the device

2.1 Design of the haptic pixel

A Haptic Pixel is built with a rigid glass plate, actuated by a piezoelectric actuator and covered by a polymer film.

The first step is the design of the glass plate with the PZT actuator. The size of the glass plate should be as small as possible to make the device more bendable. However, it should be large enough to allow friction reduction by ultrasonic lubrication; we have considered that the pixel could not be smaller than the fingerpulp. Indeed the spatial resolution is about a few mms [9], thus the finger cannot detect the amplitude variations at the surface if the pixel is

too small. As a result, we set in our case a width of 10 mm with a square shape and a thickness of 500 μm . A piezoelectric disk actuator is added to the center of the glass plate. Simulations are carried out in order to determine the vibration mode of the plate and the size of the actuator. The values found are a radius of 2.5 mm, which corresponds approximately to the central antinode of vibration of this mode, and a thickness of 200 μm which maximise the displacement for this frequency. On Fig. 2, the pixel is detailed with the CAD drawing, the vibration mode in FEM and its realization. For the fabrication, a PZT ceramic (PI 255, 5 mm diameter and 0.2 mm thick) is bonded to the pixel with Vitralit 6128VT UV adhesive. Then two wires are welded on the ceramic, which have a wrap-around electrode. The first vibration mode is measured after realization at 28.6 kHz. This measurement, in good agreement with simulations, validates the design.

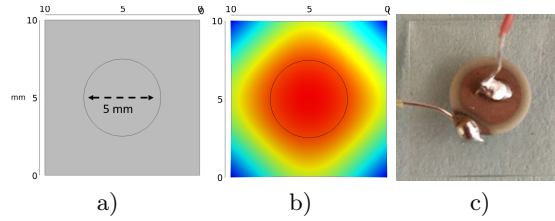


Fig. 2: a) Pixel CAD Drawing; b) 1st vibration mode in FEM; c) Realization

The polymer that is placed on the plate influences its resonant behaviour. To evaluate this change, new simulations are carried out with several types of polymer films, presented in table 1, used for flexible electronic circuits. For each film the same propagation behavior is observed as presented Fig. 3.a). Furthermore, the simulations results show a significant influence of the polymer on the resonant frequency and amplitude. The polymer decreases the resonant frequency and damps the vibration. The KAPTON and the PEEK film have the lowest vibration amplitude reduction; so they seem the most efficient for a haptic used. These results are confirmed by an experimental study presented in table 1. For that purpose, $80 \times 80 \text{ mm}^2$ polymer sheets of several types and thickness were bonded on plates with an epoxy glue (EPOTEK OG116-31).

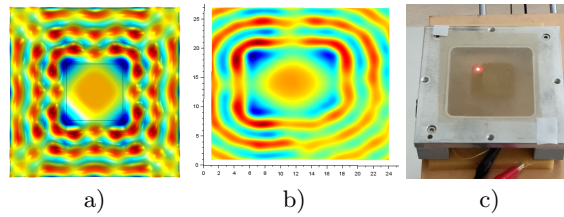


Fig. 3: Displacement field with a PEEK layer bonded on a Haptic Pixel: a) Simulation results; b) Measurements; c) Realization

Among all the tested material, the PEEK (polyetheretherketone) film has the lowest vibration amplitude reduction compared with the uncovered plate, with the same voltage (0.4 μm at the center of the Haptic Pixel for 40 Vpp). Therefore,

the PEEK film is used in this work. Finally, the cartography of the elementary Haptic Pixel is carried out, with a Polytec OFV-5000 modular vibrometer base with a sensor head OFV-505, and a resolution of 1 mm, as presented on Fig. 3b), which is close to the simulation. In particular, the propagation of the wave in the polymer sheet is observed, and exploited in the next section to create the flexible haptic surface.

Table 1: Realization and their characteristics

	Frequency (kHz)	Maximal displacement (μm)
No polymer	28.6	1.2
PC - 175 μm	25.7	0.2
PET - 100 μm	26.8	0.2
PEEK - 100 μm	25.8	0.4
KAPTON - 75 μm	25.9	0.3

2.2 Design of the surface

The flexible haptic surface is built by spreading ultrasonic plates over a 100 μm thick sheet of PEEK polymer. The further apart the plates, the more flexible the surface. But, in order to create a friction reduction between two plates, we take advantage of the wave propagation in the polymer sheet. Indeed, the simulation and experimental results of the figure 3 show a stationary bending wave with a wavelength of 3.5 mm around the square plate.

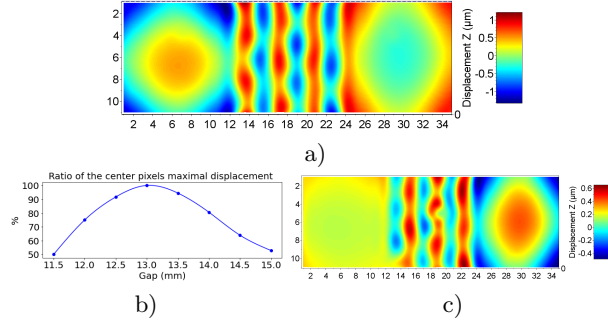


Fig. 4: The 2 Haptic Pixels prototype: a) Measured vibration field when the 2 pixels are energized for a distance of 13 mm; b) Simulated vibration amplitude at the center of the 2 pixels as a function of the distance between them; c) Measured vibration field when right pixel is energized.

To precisely set the distance between two plates, a study with 2 pixels is carried out. By simulation, we obtain the vibration amplitude at the center of the two pixels as a function of the distance; the results are depicted on Fig. 4b). As it can be seen, there is an optimal distance between the two plates, estimated at 13 mm, that allows a maximum vibration amplitude at a given voltage on the two pixels. This distance corresponds to an integer number of wavelength of the standing wave that occur in the gap. This creates the conditions of an acoustic impedance matching between the plates and the polymer.

A new prototype has been built, in which the plates was placed with a gap of 13 mm. Laser interferometer measurement clearly demonstrates that the polymer sheet vibrates in the gap as expected by the FEM model (Fig. 4a). Interestingly, when only one pixel is energized, the vibration doesn't propagate to the other one as seen on Fig. 4c). Hence, every Haptic Pixel can produce a haptic feedback independently of the other. This property is validated through psychophysical evaluation in the next section.

Then by combining several times this elementary pattern of two Haptic Pixels on the surface, we obtain a haptic interface of the desired size: for example three by three as presented on Fig. 1 and on Fig. 5. The realization on the bottom right of Fig. 5, on a cylindrical support with a diameter of 40 mm, is the one obtained after a few steps of realization in clean room.

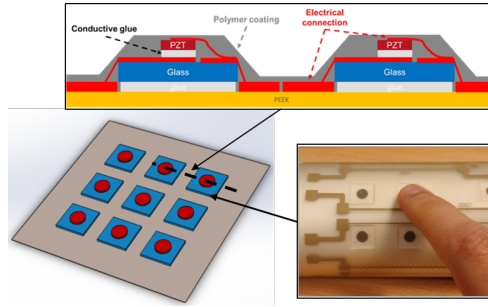


Fig. 5: Schematic views of an interface of three by three pixels and photography of a realization after a few steps of manufacturing

3 Haptic evaluation of the device

3.1 Tribological evaluation

To validate the ability of a Haptic Pixel to produce friction reduction in condition of active touch, a tribological study is carried out. For that purpose, a Haptic Pixel is mounted on a rigid frame, and a 3-axis sensor (K3D40 Me-System) placed under the surface can measure the normal and tangential forces produced by the finger on the polymer sheet (Fig. 6).

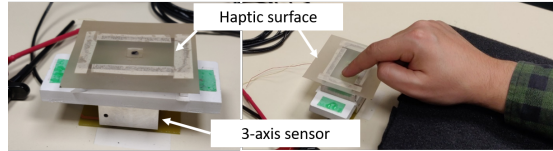


Fig. 6: Set up for the tribological test

A sinusoidal voltage at the first resonant frequency of the Haptic Pixel is modulated by a 5 Hz square signal in order to create the friction modulation. The voltage amplitude is set between 20 V peak to peak (20 Vpp) to 140 Vpp. During the tests, the participants explore the surface laterally during 20 s at

a velocity of 50 mm/s, while applying a normal force of 0.2 N. To ensure the velocity and the normal force, a training phase is performed for each participant. The typical response for 1 participant is depicted in Fig. 7a) with a voltage of 100 Vpp and which corresponds to one swipe across the surface. It should be emphasized here that the friction reduction produced by the ultrasonic vibration occurs all over the pixel, and not only on top of the plate, as expected from the results of Fig. 3.

The friction contrast [10] is then calculated and plotted for the 8 subjects on Fig. 7.b) as a function of the applied voltage. On each graph a cross represents a value of the friction contrast on a swipe of the surface. The median of these values is then plotted. As expected, the friction contrast increases as the applied voltage increases. However, depending on the participants, the friction contrast evolves in a more or less important way. It hardly reaches 0.2 for some participants while for others it reaches 0.4 at 140 Vpp. The sweep velocity may have been too high. Indeed, the sweep velocity plays a very important role in the performance of friction reduction [13].

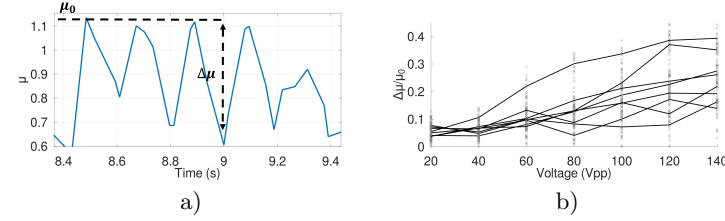


Fig. 7: a) Friction coefficient during 1 s for one subject at 100 Vpp; b) Friction contrast at different applied voltage for each subject

3.2 Psychophysical evaluation

It has been shown in section 2 that if not energized, a Haptic Pixel produces no ultrasonic vibration. We want to check in this part if this property can result in independent zones, that can produce a tactile feedback or not. For that purpose, we have conducted a psychophysical study on the 2 Haptic Pixels prototype of Fig. 4 and Fig. 8a).

The protocol is as follows. We energize the left (L) pixel, or the right (R) pixel or none (\emptyset). The solution where both pixels are energized is not evaluated since we aim to validate the perception of a single Haptic Pixel. The voltage supplied to the plates is at a voltage amplitude $V = \{20, 30, 40, 60, 80\}$ Vpp and is modulated by a square signal at a frequency $f = \{50, 250, 500\}$ Hz. The participants are presented with each condition, in a random order, and each set is repeated 10 times, leading to $3 \times 3 \times 5 \times 10 = 450$ tests. The experiment duration is approximately 60 minutes. Data were collected from 9 consenting and inexperienced volunteers (3 females and 6 males) between 22 and 28 years old. The participants were asked to slide their index finger over the whole surface, were phonically isolated with earphones playing white noise and blindfolded. They were asked to answer 'L', 'R' or 'None', depending on where they perceived the stimulus.

As expected, the mean correct ratio answer increases when the voltage applied to the PZT ceramics increases, this voltage being directly related to the vibration amplitude of the pixel. This rate reaches 1 above 80 Vpp. The confusion matrix is given for a voltage of 40 Vpp in Fig.9. The Pixel R seems less detectable. This might be due to a lower vibration amplitude than for L pixel, which can be due to an incorrect driving frequency. The modulation at 250 Hz allows to have the best rates of correct answers. This was also expected since this frequency is the optimal frequency for detection with the haptic sensation finger [4]. Thus for an applied voltage of 30 Vpp, the mean correct answer ratio reaches 92 %.

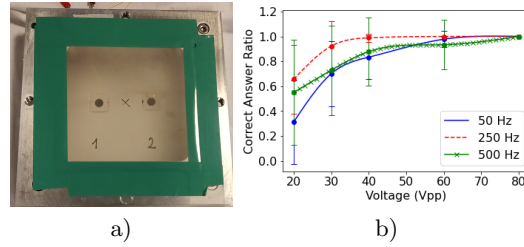


Fig. 8: a) Surface used for the psychophysical test; b) Mean Correct answer ratio

f=50Hz				f=250Hz				f=500Hz			
	Ø	L	R		Ø	L	R		Ø	L	R
Ø	82%	18%	0%	Ø	84%	8%	8%	Ø	86%	14%	0%
L	13%	83%	4%	L	4%	84%	12%	L	28%	72%	0%
R	26%	8%	66%	R	17%	6%	77%	R	21%	0%	78%

Fig. 9: Confusion Matrix at 40 Vpp

Hence this study validates the concept of Haptic Pixel for a flexible haptic surface. The sensation can be localized around a pixel and is well detectable by the users. Different signals allow to modulate the haptic feeling.

4 Conclusion

A flexible haptic surface has been designed in this paper. This surface is composed of elementary Haptic Pixels assembled on a PEEK film polymer. The Haptic Pixel and the surface are developed and validated electromechanically. A tribological study is carried out and allows to validate the capacity of a Haptic Pixel to produce the illusion of texture thanks to the friction reduction. Similarly, a psychophysical study validates the detection of the Haptic Pixels.

Future work will validate the friction reduction on a complete surface and on bending conditions. Complementary psychophysical studies will also be performed. The surface designed will be manufactured in a cleanroom and will be adapted for uses where the flexibility of the surface is necessary: Haptic Wristband for example. A specific electronic will be developed to drive each Haptic

Pixel independently or to combine them to create large area of friction modulation.

Acknowledgements This work, related to the HAPTIFLEX project, was supported by the French Agency for National Research (ANR) via Carnot funding. The second author acknowledge the support of IRCICA, USR CNRS 3380.

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