Printgets: an Open-Source Toolbox for Designing Vibrotactile Widgets with Industrial-Grade Printed Actuators and Sensors

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New technologies for printing sensors and actuators combine the flexibility of interface layouts of touchscreens with localized vibrotactile feedback, but their fabrication still requires industrial-grade facilities. Until these technologies become easily replicable, interaction designers need material for ideation.

We propose an open-source hardware and software toolbox providing maker-grade tools for iterative design of vibrotactile widgets with industrial-grade printed sensors and actuators. Our hardware toolbox provides a mechanical structure to clamp and stretch printed sheets, and electronic boards to drive sensors and actuators. Our software toolbox expands the design space of haptic interaction techniques by reusing the wide palette of available audio processing algorithms to generate real-time vibrotactile signals. We validate our toolbox with the implementation of three exemplar interface elements with tactile feedback: buttons, sliders, touchpads.

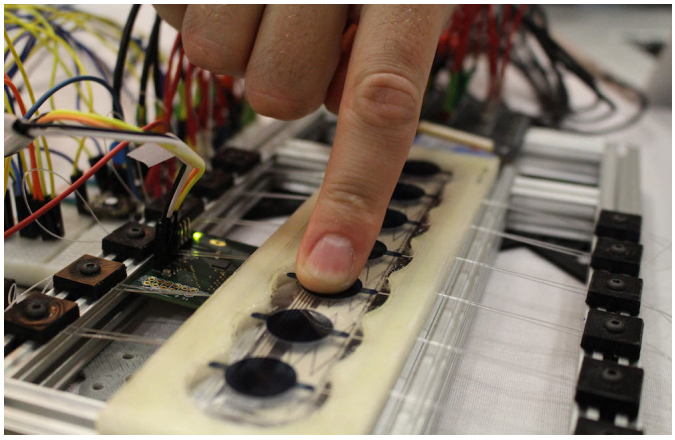

Figure 1: A tactile slider with printed actuators and a capacitive sensor.

Introduction

We are surrounded by physical buttons, sliders and knobs in our everyday life. They are extensively used, from household appliances to computer peripherals and even in our cars. The haptic feedback provided by their physical attributes such as their shape, material or position gives subtle but valuable cues about their affordance or their current state [1, 28]. Despite these appealing properties, physical controls may have some shortcomings. They require complex assembly and automation specific to each design, are prone to mechanical wear, and their physical properties are frozen once fabricated and can not be customized after purchase.

Multitouch surfaces provide layout flexibility. However they also have their own disadvantages compared to physical controls. They provide no haptic feedback except for the passive force feedback due to the contact of fingers with the surface. Research shows that adding vibrotactile feedback restores the qualities of physical controls [10, 15]. Unfortunately, current implementations use mechanical actuators which share the same issues as physical buttons mentioned above.

Printed actuators and sensors are a new alternative, employing piezoelectric ink on a flexible foil so that they can be embedded in polymer-injected objects (Figure 1). The industrial design process of actuators requires several iterations, including 3D modeling, 2D layout design, mechanical clamping, electronic and software implementation.

Our main contribution of this paper is the engineering of an open-source toolbox for the design and implementation of vibrotactile feedback with printed actuators and sensors. Our open-source toolbox provides interaction designers with a mechanical structure to clamp printed sheets, electronic boards for driving actuators and sensors, a software library, and data flow objects and patches for prototyping interaction with vibrotactile feedback. While the fabrication of actuators and the final product require industrial-grade equipment, we use maker-grade tools for their integration into iterative designs. We validate our toolbox by the implementation of three exemplary widgets: a push button, a slider and a touchpad.

Related work

In this section we review related work on printed electronics, on vibrotactile widgets implementation, and on tactile feedback design.

Printed electronics, actuators and sensors

Increasing access to conductive thread, paint, ink or glue enables designers to print circuits [19]. The maker community has used this technique for a long time for elementary capacitive sensing [6]. The common advantage of these technologies is that they generally use foldable and flexible substrates. For example, Olberding *et al.* designed printed interactive objects, which use printed circuits as sensors [32]. With printed electronics, designers can also embed circuits on the body [31, 44], in wearables [45] or in any object [37].

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These projects use capacitance measurement for sensing. A single electrode can be used for proximity or contact sensing. 1D and 2D multitouch capacitive sensors typically use zigzag and diamond grid patterns. Zhang *et al.* describe a method with arbitrary electrode position on the surface of a 3D object [46]. They measure the electric field perturbation created by fingers between pairs of electrodes. This method makes it possible to sense touches on arbitrary shape objects.

There is little work on printed tactile actuators in the HCI literature. Kato *et al.* created electrical stimulus and electrostatic force sensations with printed electronics [18]. This technique is easily reproducible because it uses maker-grade equipment. However the range of sensations is still limited compared to physical actuators.

In this paper, we use actuators printed with piezo ink (ElectroActive Polymer, EAP) and standard techniques that use silver ink for touch, 1D and 2D capacitive sensing. This setup enables a wide range of tactile sensations: electrovibration with a large range of frequencies, amplitudes and waveforms; and a squeeze film effect with precise rendering. They are produced using industrial-grade equipment, which enable more precise, durable, and mass-produceable results; than with maker-grade equipment. Details about the material and actuator design are available in [35]. The technology is still in development and we hope that it will be ready for the market in the upcoming years. The work we present in this paper is both useful for helping the development of this technology by the implementation of demonstrators and experimental setups and for preparing the forthcoming of printed vibrotactile actuators on the market by easing the design and implementation of interaction techniques.

Our actuators and sensors are fabricated by third-party partner organizations in a process of printing several layers of piezoelectric and conductive traces over a flexible substrate [35] (Figure 2). Our suppliers use as piezo ink an Electroactive Polymer (EAP), specifically VinyliDene Fluoride-TriFluoroEthylene copolymers P(VDF-TrFE) [35]. Silver is used as a conductive ink for printing wiring threads and capacitive sensing matrices, but Indium Tin Oxide (ITO) can be used when transparency is required. Our suppliers fabricate the flexible substrate with PolyEthylene Naphthalate (PEN). Due to the high precision required, the printing process currently requires high-end equipment for screen printing in a cleanroom.

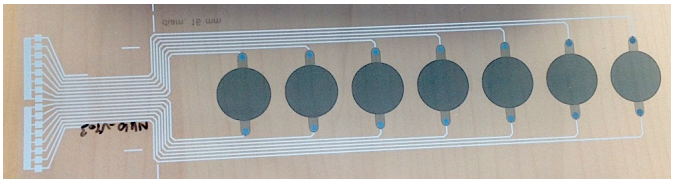

Figure 2: Printed slider, made of 7 individual actuators. The actuators are made of a P(VDF-TrFE) ink for a total thickness between 4 µm and 10 µm.

The piezoelectric electro-active polymer layer expands when an electrical field is applied, resulting in the bending of the actuator. The thickness of our actuators varies between 4 µm and 10 µm depending on the number of stacked actuators. Stacking piezo layers enables higher amplitudes without using higher voltages, at the cost of less transparency. The number of actuators, their spacing, size and clamping shape and size require careful design and simulation. The bootstrap of a cycle of actuators and clamping design and FEM simulation starts with an initial design, motivated by application requirements. In our experience, this cycle can last a few months. Before our toolbox, actuator designers would only be able to test their actuators with basic signals embedded in piezo driver demonstration boards such as the Texas Instruments DRV2667 Evaluation Module [43].

Vibrotactile widgets

The early combinations of vibrotactile feedback and touch input showed to be promising [10]. The immediate tactile feedback resulting from a touch input helps people to feel in control of the interface. This close relation between perception and action makes it possible to design tactile displays with direct manipulation capabilities [13] and contributes to improving text entry performance on soft keyboard [15].

The variety of tactile sensations makes it possible to render different tactile properties of an object [23]. To detect the shape of an object, Harrison *et al.* created tactile buttons with an inflatable technology [14]. The texture of an object has been rendered with electrovibration [3], squeeze film effect [36] or a simple vibrotactile actuator [41]. And friction has been modeled as well by Levesque *et al.* [25]. Nonetheless, the most noticeable haptic sensation of a button is probably the click sensation when pressing it. Kim *et al.* studied force feedback models of physical buttons [20] and successfully designed vibrotactile feedback which makes touch buttons feel like physical buttons.

Piezo materials are convenient for creating haptic effects. Their shape changes in contact with electricity. The STIMTAC [2] and T-Pad [25] projects use it for squeeze-film effect. Lylykangas *et al.* use it for touch buttons [27], and Dai *et al.* for touch buttons and sliders [7]. These systems use piezo ceramics, such as the piezo discs in musical birthday cards. Using these ceramics requires gluing them carefully to the surface to vibrate. With time, these ceramics tend to detach themselves due to mechanical fatigue. Printgets actuators use a piezo ink, which is flexible and, to some degree, transparent. It combines the advantages of printed electronics and piezo materials.

Tactile feedback design

The design of tactile feedback requires a careful identification of tactile properties. Research on tactile icons (tactons) showed rhythm, spatial location and roughness to be efficient vibrotactile properties [4]. The appropriateness of these properties depend on the technology, and the way they stimulate mechanoreceptors of the skin. Smaller actuators like pin arrays can use a pattern shape and size, as well as animation to convey information [33]. Lateral motion scanning with programmable friction uses efficiently the difference of friction levels as well as pattern shape and density [36].

The choice of these low level parameters of the tactile signal highly depend on the actuators used and their capabilities, mostly in terms of frequency, amplitude and size/density. A vibrotactile signal is similar to an audio signal. The main difference is in the frequency range: haptic (1 Hz to 1000 Hz) compared to auditive (20 Hz to 20 000 Hz). For vibrotactile feedback, a subset of haptic feedback, designers typically use frequencies around 250 Hz because of the peak sensitivity of the skin [12]. A higher level design of tactile feedback consists in mapping values of these parameters to information or objects and their exploration.

Israr *et al.* created Stereohaptics, a simple hardware device with two voice coil vibrators, combined with software solutions for interaction design: first using PureData or Max to generate vibrotactile audio data flows [17], then using WebAudio technologies to embed patches directly in web-based tutorial slides [9]. Schneider *et al.* proposed a tool for the design of tactile animations on a 2D display [40] and Macaron, a web-based vibrotactile effect editor [39]. Similar tools are emerging in the industry: Interhaptics Composer [16], Lofelt Composer [26]. Our toolbox supports adjustment of input parameters to design interaction techniques with haptic feedback that react to input.

The Printgets Toolbox

Our Printgets toolbox provides 1) a mechanical structure to clamp printed sheets, 2) electronic driver boards, 3) a software library and 4) data flow and patches for interaction design.

Mechanical structure to clamp and stretch printed sheets

Simulations from our printed actuators suppliers revealed that the actuator area must cover 60 % of the clamping area for optimal actuation [35]. Similarly to a drum shell, it is necessary to clamp and stretch the printed sheet in order to get a desirable vibration. The vibration propagates to the whole clamping area. However, the ratio between the actuator size and the clamping area size affects the resonant frequency. The pressure applied by the finger, together with the stiffness of the frame on which the vibrotactile elements are mounted, determine the deformation of the layer. Usual clamping and stretching techniques include glueing, screwing or compression with magnets. Final products embed foils in injected plastic (Polycarbonate), which maintain the actuators in place, achieving clamping and stretching in one step.

Interaction design iterations require cheaper and faster fabrication methods (i.e. equipment available at any time). Thus we split clamping and stretching into two separate steps. We glue the actuators foil on a 3D printed actuator frame made of polylactic acid (PLA) plastic. But it is complicated to keep the foil tight, which is required for obtaining optimal vibrations. Indeed, the form factor of the frame provokes uneven bending when applying force to the interface, which leads to bistable conditions on the foil. Hence, to provide a uniform tactile feeling of the foil, external tension must be added. However, an excessive tension can inhibit the motion of the actuators, hence affecting the tactile perception. Worse, an extreme tension can break the frame. We opted for string tension, which must be carefully adjusted to obtain the desired output. We required a clamping and stretching structure whose frame would be rigid enough to support adjustable string tension necessary to stretch printed sliders (Figure 3).

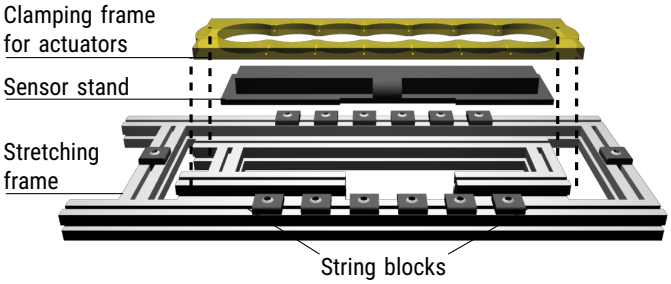

Figure 3: Exploded view of the clamping and stretching structure.

During ideation, we were inspired by diverse sources for the design of the structure: the metal frames of trampolines for stretching its inner fabric mat, the courses of doubled strings (Figure 4) from musical instruments such as mandolins, and soft robotics and soft tangibles engineering [22]. We prototyped the structure with maker-grade equipment: T-slot aluminum profiles beams from MakerBeam and parts 3d printed with PLA. We used fishing line thread (Caperlan Line Resist Cristal, made out of "Japanese copolymer", diameter ≈0.45 mm, breaking strain: 16 kg, and fluorcarbon coating "for better gliding") (Figure 4). Each of the 14 courses of doubled strings was adjusted to 3 kg using a portable electronic scale. The choice of this weight value felt like a right balance between break-safe tension and ease of manual clamping. This configuration allowed us to determine a spacing between the actuators and sensors layer of 2mm, allowing a certain elasticity for the vibrotactile elements to actuate correctly.

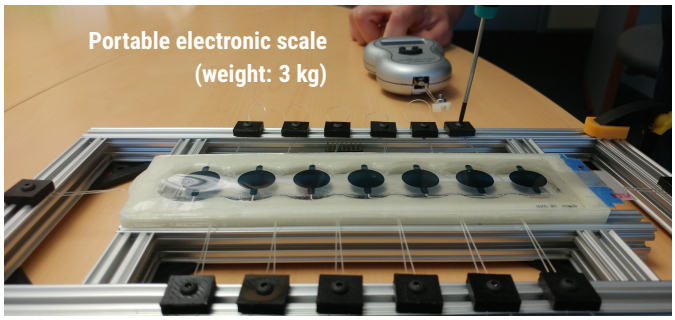

Figure 4: Slider Printget on clamping and stretching structure. The tension of the courses of doubled strings is being adjusted with a portable electronic scale.

Electronic boards to drive sensors and actuators

Piezo actuators require a driver chip and an external power supply. We use the TI DRV2667 [42] chip, either on the TI evaluation board [43], or the Fyber Labs Piezo Haptic Flex Module [11] . We use a 5 V/2 A power supply, which the driver amplifies up to ±100 V. Capacitive sensing uses the Microchip CAP1188 [29] or CAP1214 [30] drivers, depending on the amount of electrodes. The capacitance values allow us to detect several levels of finger pressure on the surface. This is an essential part of the interaction techniques below. Both drivers communicate with the host computer (Raspberry Pi 3 [38]) with an I2C bus.

The DRV2667 haptic driver proposes two main modes of operation. The first mode uses an embedded 8-bit digital to analog converter (DAC). This mode offers several operation modes: either using an embedded waveform synthesizer, triggering the replay of waveforms stored in RAM, or playing a stream through I2C. It is convenient for final implementations because it is self-contained. The second mode uses an analog input. With this mode it is possible to adapt the input signal in real time with a sound card. Differences between operation modes are summarized in Table 1.

Mode	Digital			Analog
Sub-mode	Waveform	RAM	FIFO	
Resolution (bits)	8	8	8	16*
Memory	2 kB	2 kB	100 B	N/A
Sampling rate (kHz)	8	8	8	44.1*
Min duration	32 ms	125 µs	125 µs	23 µs*
Max duration	4096ms	250ms	125ms	N/A

Table 1: Comparison of vibrotactile signal generation modes. (*depending on the choice of soundcard or digital-to-analog converters)

Since some layouts such as the slider use multiple actuators, several DRV2667 are required. An I2C multiplexer is required to communicate with all of them independently. We take advantage of the flexibility of the analog mode for the design phase of the tactile feedback, using a sound card with enough analog outputs to operate each haptic driver independently.

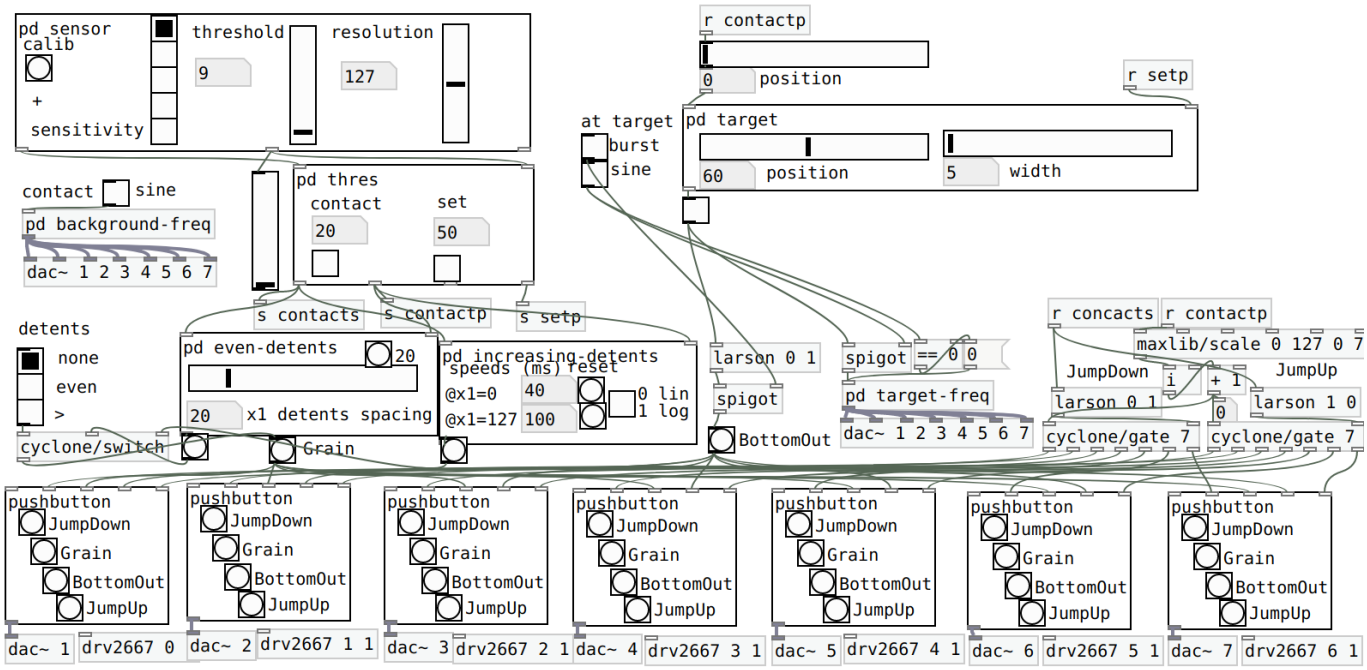

Figure 5: Input sensing and haptic feedback parameters are tunable at runtime in the dataflow though widgets to facilitate interaction design.

Software library

We developed an open-source software library that enables getting input from capacitive buttons and slides, and producing vibrotactile feedback with piezo actuators[1].

Capacitive input Our software library implements processing of raw data from capacitive sensor drivers with adjustable parameters: *sensitivity* and *threshold*. Raising sensitivity enables the detection of touches on a larger distance over the surface. Ajusting threshold modifies the sensor value considered as a touch event and enables the detection of both mid-air and pseudo-pressure input.

Vibrotactile feedback The creation of vibrotactile feedback is the main motivation for this work. Our software library takes advantage of all the operation modes of the piezo driver for the design and implementation of tactile widgets. In particular, the Analog mode is used in the design tool we describe below. It used to adjust input and output parameters in real time for faster design iterations. The Digital modes are favored for the implementation of final products. At this stage of the design process, all the input and output parameters are known, and can be hard-coded in the device firmware.

Data flow objects and patches

We rely on open-source tools for visual programming of audio and control data flows to adjust tactile feedback and input sensing parameters in real time, rather than compiling and uploading new code to the device for each value change. We use the PurrData visual programming environment for audio and control dataflows [5], following up on several research works on vibrotactile feedback design that use similar visual programming environments: PureData [17, 20] or Max/MSP [41]. PurrData [5] is a fork of PureData that brings major advantages: PurrData supports embedded platforms like the Raspberry Pi that we use to embed our printed actuators and sensors in standalone applications. PurrData also uses JavaScript rather than Tcl/Tk as development language and ecosystem for its graphical user interface, opening perspectives towards facilitating the implementation of advanced widgets, for signal previewing and annotation. PurrData and PureData already implement objects for typical input devices such as mice and keyboards, and for audio input and output.

We developed data flow software objects for each input and output drivers present in our software library. We visual program data flows by interconnecting vibrotactile audio objects with capacitive input control objects, so that all parameters are accessible through widgets in the PurrData GUI (Figure 5).

The source code of our software library, including data flow objects and patches, is released under the terms of the opensource LGPLv3 license: `https://gitlab.inria.fr/Loki/happiness/libhappiness`

Interaction design: three exemplary Printgets

We have combined printed actuators and capacitive sensors to create vibrotactile widgets that we call Printgets: printed widgets. We validate our toolbox by the implementation of three exemplary designs: 1) a force-sensitive pushbutton with dynamic states (Figure 6), 2) a slider with dynamic detents (Figure 8), 3) a touchpad with dynamic directional cues (Figure 9).

While buttons, sliders and touchpads are widespread in physical and digital interaction, their implementation with this new printing technology is not a trivial task. Printgets serve as proof of concepts to demonstrate use-cases of printed actuators and sensors to design interaction.

[1] `https://gitlab.inria.fr/Loki/happiness/libhappiness`

Pushbuttons

We designed tactile buttons using a single capacitive sensor and a single sheet of tactile actuators (Figure 6).

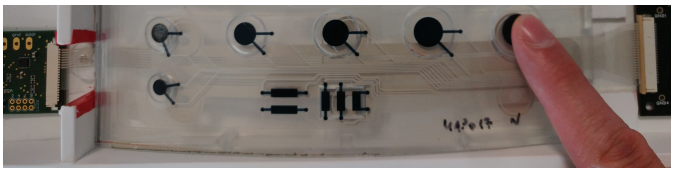

Figure 6: Push buttons of various sizes clamped individually.

We replicated the method for model-based design of tactile feedback from Kim and Lee [20]. Kim and Lee define force-displacement curves with two types of sections: *slopes* and *jumps*, which are delimited by *tactile points* (Figure 7).

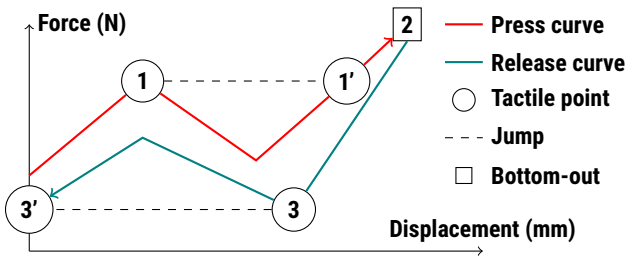

Figure 7: Force-displacement curve of a pushbutton

Slopes generate the sensation of material resistance. The resistance of the surface creates passive force feedback. In addition to that, *slopes* (1'→2) and (2→3) have friction grains (e.g. 20 grains per mm, each rendered with a 150Hz sinusoidal wave with a release envelope of 18ms). *Tactile points* (1, 2, 3) reproduce the click-like sensations and are rendered as bursts of a sinusoidal waveform of higher frequencies aligned with the resonant frequencies of the device. (1) and (3) represent the click sensation when pressing and releasing the button. (2) represents the end of the button. The values of all these tactile feedback parameters are borrowed from the implementation by Kim and Lee [20]. We demonstrated this pushbutton at ACM UIST 2017 [8].

Sliders

We extended the design of pushbuttons into tactile sliders, with several actuators laid out inline (Figure 8). If we clamp inline actuators individually, clamping boundaries between actuators feel like physical detents with fixed positions embedded in devices at printing-time. We selected a sheet of vibrators surrounded by a large clamping area, so that we generate dynamic detents depending on the finger position and with adaptable detents spacing.

Figure 8: Slider made of 8 actuators in the same clamping area, and a capacitive slider underneath.

We use capacitance input value to determine finger pressure information. We implement pressure-sensitive states as for pushbuttons: hovering to sense the current position of the slider cursor, pressing harder to set the cursor state to its current position. We demonstrated this slider at ACM UIST 2017 though it as not described in our demo paper [8].

Touchpads

We also extended the design of sliders to touchpads. While touchpads usually feature capacitive matrices with diamond grid patterns [37], we prototyped touchpad capacitive input using two sliders with zigzag patterns, with small form factor. The actuator sheet is designed with one electrode layer surrounded by top and bottom piezoelectric layers respectively with 2 horizontal and vertical lines, resulting in 4 actuated quadrant zones. When two fingers are positioned on the pad, the location of stimuli can be discriminated, and haptic illusions like tactile apparent movement can be produced.

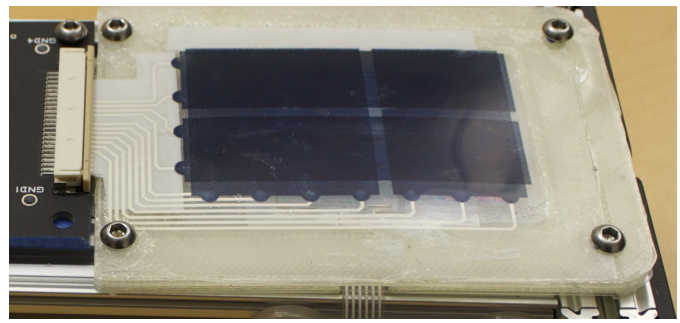

Figure 9: Touchpad with an array of four actuators.

Limitations

Printing actuators is not currently achievable with maker-grade tools as it requires screen printing with a precision of less than 1 µm. Readers interested in this aspect will find detailed information in [35, 34]. However, we assume that off-the-shelf printed actuators will be available on the market in the upcoming years. We believe that the toolbox that we have presented will help application designers to rapidly prototype interfaces with this new technology in the meatime.

We do not report results from evaluations with human participants in this paper. In future work we aim to address the evaluation of the performance of our particular implementations.

The third-party sensor and actuator foils that we used are made of materials including polycarbonate, silver ink and fluoropolymers. We are not aware if end-of-life treatment procedures exist to recycle materials from foils, which may end up disposed to landfill. In future work, we should transform our workflow more make it more sustainable with these potential measures: 1) choose eco-friendly materials, such as Rochelle salt embedded in wood that exhibits piezoelectric effects [24]; 2) minimize waste during physical design, as explored in other fields such as furniture design [21].

Conclusion

We have proposed Printgets, a toolbox for the iterative design of vibrotactile widgets with printed actuators and sensors. We described the design and assembly of the clamping frame that propagates the vibrations, our choice of electronic boards for driving sensors and actuators, the implementation of a software library and data flow objects and patches for designing interaction techniques with vibrotactile feedback.

We have validated our toolbox through three implementations of Printgets. The first is a pushbutton, with a simulation of a force-displacement curve as described in [20], using capacitance input values as pseudo-pressure. The second is a slider with detents, using capacitance input values to discriminate hover, touch and press states. The third is a touchpad with dynamic tactile feedback mapped to finger gestures.

Graphical user interfaces designers usually rely on tools that allow them to choose and drag elementary interactive elements (widgets) from a palette and drop these on a canvas to directly define their layout and set their properties. These properties affect how designers interact with these widgets through visual output and gestural input, the latter usually restricted to standard input events (from mice, keyboards, multitouch surfaces) in most frameworks. While this work is a first step in this direction, future work remains to be done on investigating how the Printgets toolbox can be generalized to provide equivalents to such frameworks.

Acknowledgments

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