FabricKeyboard: Multimodal Textile Sensate Media as an Expressive and Deformable Musical Interface

Irmandy Wicaksono*†
*Wearable Computing Lab
D-ITET, ETH Zurich
Gloriastrasse 35
Zurich 8092
irmandy@mit.edu

Joseph A. Paradiso†
†Responsive Environments
MIT Media Lab
75 Amherst Street
Cambridge, Massachusetts 02139
joep@media.mit.edu

ABSTRACT

This paper presents *FabricKeyboard*: a novel deformable keyboard interface based on a multi-modal fabric sensate surface. Multi-layer fabric sensors that detect touch, proximity, electric field, pressure, and stretch are machine-sewn in a keyboard pattern on a stretchable substrate. The result is a fabric-based musical controller that combines both the discrete controls of a keyboard and various continuous controls from the embedded fabric sensors. This enables unique tactile experiences and new interactions both with physical and non-contact gestures: physical by pressing, pulling, stretching, and twisting the keys or the fabric and non-contact by hovering and waving towards/against the keyboard and an electromagnetic source. We have also developed additional fabric-based modular interfaces such as a ribbon-controller and trackpad, allowing performers to add more expressive and continuous controls. This paper will discuss implementation strategies for our system-on-textile, fabric-based sensor developments, as well as sensor-computer interfacing and musical mapping examples of this multi-modal and expressive fabric keyboard.

Author Keywords

Keyboard, multimodal, fabric sensors, e-textiles, continuous and discrete controls, tangible computing, deformable interface, musical expression

ACM Classification

Hardware ~ Sensor applications and deployments, Sensor devices and platforms, Human-centered computing ~ Sound-based input / output

1.INTRODUCTION

Textiles are soft and conformable materials that could also be stretchable, as opposed to standard electronics which are built on rigid structures or flexible substrates. The fact that textiles are omnipresent in our environments and that there has been a significant effort in making them more intelligent present many novel applications, including in the physical interaction media [1-3,8]. Post *et al.* initially explored the concept of e-broidery to develop several fabric-based musical interfaces [3]. These interfaces include The Media Lab's 1997 Musical Jacket, that consists of an embroidered conductive thread keypad and is connected to a wearable MIDI synthesizer and speaker circuits, and The Embroidered Musical Balls, which are composed of sewn conductive electrodes, acting as pressure sensors for modulating sound.

NIME'17, May 15-19, 2016, Aalborg University Copenhagen, Denmark.

Figure 1: The FabricKeyboard being stretched

New electronic textile materials and integration techniques also triggered several new developments of deformable musical interfaces such as Zstretch, a stretchy fabric musical controller [4], the Fabric Piezoresistive Multitouch Pad [5], and the xOSC Musical Glove [6]. Giovanni *et al.* performed user studies on how musicians interact with deformable interfaces, including some of the aforementioned controllers [7]. The main results of the studies showed that most of the musician used these deformable interfaces as an expression, particularly to manipulate and filter sound, rather than playing discrete notes. Fabric-based 'pianos' or keyboards also exist within the maker community; however, they are only discrete, touch sensitive, or simple textile switches [3,8]. It is therefore interesting, to incorporate both discrete and continuous controls into one deformable musical controller.

Inspired by the current developments of textile sensors and the stretchable nature of knitted fabrics, we envision a multimodal, textile-based, musical interface with a familiar layout of an existing instrument. We therefore designed and implemented a fabric-based keyboard as pictured in Figure 1. The fabric keyboard allows discrete controls with conventional keystrokes and rich continuous controls with unique physical interactions enabled by the fabric (e.g. squeezing, pulling, stretching, and twisting). Additionally, we explored further by integrating expressive, non-contact gesture sensing and developing fabric-based ribbon-controller and trackpad.

1.1. Related Work

The evolution of electronic keyboards dates back over a century ago when Elisha Gray, invented the Musical Telegraph in 1876 [9]. This instrument is composed of an array of self-tuned vibrating reeds activated by mechanical switches. Inspired by Leon Theremin's non-contact gestures instrument, Maurice Martenot developed the Ondes Martenot (1928), which contains a ring that pulls a string to continuously vary the pitch of a sound and a left-hand keyer to control the volume. Later versions included a monophonic keyboard with lateral pressure for vibrato effects. In 1940, Hugh LeCaine built the Electronic Sackbut [10], which is a great example of early expressive keyboard instruments. The expressive left-hand controls in this keyboard nicely illustrate the still dominant concept of a "left-hand controller", which is a set of knobs, sliders, touchpads, joysticks, and other input devices that the performer can use to articulate the produced sound.

Don Buchla used capacitive touchpads as input devices in his modular synthesizers dating to the mid/late 1960s. As electronics further advanced, capacitive contact sensing keyboards appeared in commercial synthesizers such as EMS Sythi AKS and EDP Wasp in the early 70s. Moog and Rhea subsequently designed a Multiply-Touch Sensitive Keyboard that incorporated a new layer of sensors on the key surfaces to detect XY finger gestures and pressure with 4-point capacitive sensing and force-sensitive film respectively [11]. Haken *et al.* constructed The Continuum, an indiscrete keyboard that measures finger slide position and pressure on a flat continuous surface; the keyboard had experienced several design alterations, but in the end used hall-effect sensors to sense proximity of magnets [12]. Instead of turning the knobs or moving sliders, these controllers allow expressive and fluid controls of the pitch and timbre of the sound generated by applying various gestural inputs from the same hand right on the keyboard surface.

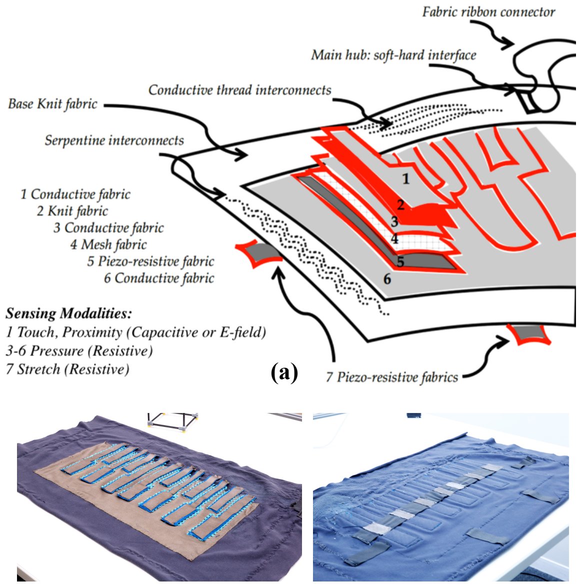
There are also recent efforts in integrating discrete and continuous controls of the keyboard. McPherson's TouchKeys, for example, integrated a new capacitive multi-touch sensing layer on each key to map finger positions and contact area [13]. Grosshauser and Tröster also explored the same principle, but developed an FSR pressure sensor matrix instead, giving additional pressure variations [14]. These techniques allow users not only to augment, but also to evaluate keyboard performances. Another remarkable example is the Seaboard, which transformed typical keyboard surface using silicone in a wavy pattern beyond an FSR layer to enable expressive, continuous finger gestures as polyphonic modulations [15]. Note that most of the expressive keyboard interfaces till date rest on a rigid and heavy structure; a keyboard made out of fabric, besides providing new interactions and tactile experiences for musical expressions, can be easily folded, rolled up, and packed in our luggage like a pair of socks or a scarf [16]. It can also be wearable, which extends the functionality of such fabric-based musical controllers.

2. FABRIC KEYBOARD DESIGN AND IMPLEMENTATION

Figure 2a) illustrates the structure of the fabric keyboard, whereas Figure 2b) and c) show the working prototype. The keyboard is a textile-based sensate surface, consisting of one octave of keys with multi-modal sensing capability. Multi-layer fabric sensors in a keyboard pattern were embedded and machine-sewn on a stretchable, base knit fabric. The outermost layer of each key consists of a fused conductive fabric that acts as a floating electrode to detect proximity, touch, or induced electric field. Below this layer, a fabric pressure sensor was embedded in a sandwich configuration. The configuration includes a mesh and piezo-resistive fabric in between two conductive fabrics, one of which is a common ground. Below the base fabric, fabric stretch sensors were attached: one at the right side, one at the left side, two at the bottom side, and a long one in the middle and in-between the keys with a zebra configuration (conductive/piezo-resistive fabric) to avoid parasitic influence from the other sensors.

All of these fabric sensors were then connected to the circuitry through conductive thread interconnects. To ensure firm connections, especially upon stretching, stretchable routings were machine-sewn using serpentine or zig-zag sewing patterns on all of the stretch sensor interconnects. There is a main hub at the edge of the fabric that separates the soft circuits (e-textiles) from the rigid circuits (PCBs). This hub is pluggable and can be connected by using the fabric-based ribbon cables. This separation not only allows fluid interaction between the performer and the fabric keyboard, but also enables customizable hardware for sensor processing. The fabrics that we used to construct the fabric keyboard are:

- **Non-conductive fabric:** Knitted 75% Nylon, 25% Spandex fabrics.
- **Mesh fabric:** Knitted 100% Polyester mesh fabric.
- **Conductive fabric:** Knitted Ag-coated fabric with 76% Nylon and 24% Elastane and surface resistivity of <0.5 Ω/sq.
- **Piezo-resistive fabric:** Knitted Eeontex fabric with 72% Nylon and 28% Elastane (LTT-SLPA) in a proprietary conductive coating and surface resistivities of 10^4-10^7 Ω/sq upon request.



(b) (c)

Figure 2: a) Multi-layer structure showing the fabric materials and sensing modalities. b) Top and c) bottom view of the fabric keyboard

Note that all of the fabrics used here, either electro-active or not, are knitted to keep the stretchability of the fabric keyboard. The conductive threads used in this project are made of purely stainless steel fibers. Even though they are relatively hard to solder and sew as a top thread, compared to silver-coated nylon core threads, these threads have a relatively low resistance, are robust, and can withstand high temperatures and multiple washings. We found consistent results in using them as bobbin threads. To connect them to the rigid main hub, we developed a customized connector with stripped metal loops. These threads were then tightly tied to these loops before applying a low temperature solder and encapsulation to ensure firm connections with low contact resistances.

3. SENSING ELEMENTS

Based on our multi-layer structure in Figure 2a), we propose multiple sensing modalities: proximity, touch, and electric field (Layer 1), pressure (Layer 3-6), stretch (Layer 7), and position, which is from the additional modular fabric-based interfaces such as the trackpad and ribbon-controller. A more detailed explanation of design, implementation, and characterization of each sensor can be seen in [17].

3.1. Proximity and Touch

A single electrode mechanism with one layer of conductive fabric was constructed for near-proximity and touch sensing where there is a capacitive coupling between the finger as a virtual ground and a charged electrode with specified charging time and current. The MPR121 Proximity Touch Controller, with 12 floating inputs, high sensitivity, and proximity/touch threshold detection feature, is used for this in the one-octave keyboard [18]. The proximity and touch data from this controller can be differentiated by the threshold detection, meaning that the off-state of a touch event represents the capacitance value of our hand's proximity.

Several tests were conducted to observe the influence of the sensing area on the sensitivity of readings. It was found that as the pad size represents a typical piano key's area (2x12 cm), the controller can sense hands approach or hover of up to 12 cm over the surface. Increasing the pad size to 12x12 cm further improves the sensitivity to up to 18 cm. Another interesting modality is to enable the 'multiplexed sensing' or the "13th" electrode feature of MPR121. By combining all of the floating electrodes to form a single large sensing surface, this option produced an observed improvement of sensitivity of up to 25 cm. Since this feature is accessible through programming, we can also automatically transform the sensing mechanism from poly to multiplex mode and vice versa as our hand comes within the sensor's reach.

3.2. Electric Field Sensing

Our body can act as either a shunt, disrupting an electric field between a transmitter and a ground, as a transmitter, by coupling our body to the transmitter itself, or as both when crossing over between these modes [19]. In this work, we exploited the electric hum or noise strength coming from the AC mains power that gets coupled to our body as the "antenna" in transmit mode. This electric hum typically ranges from 50-60 Hz. A passive electric field sensing circuit based on [20] and comprising trans-impedance amplifier, band-pass filter, and envelope detector, was designed for each individual key as shown in Figure 4. The voltage output from each sensing circuit is then fed to an analog multiplexer for sequential ADC voltage readings by the micro-controller.

The passive electric field sensing circuit can detect touch as well as proximity by carefully setting both trans-impedance and band-pass filter gains to improve the sensitivity. However, the most interesting scenario of using electromagnetic coupling is when our body acts as a receiver antenna. After our fingers strike the keys, the conductive fabrics connect our body to the sensing circuits, forming a network. The electromagnetic noise coupled into our body is then picked up by these sensing circuits and can be controlled by moving the other hand towards an electromagnetic source, which in this case is a minimally-shielded device connected to the main power. The sensitivity scales with the field strength of the source. However, in our case, it can detect proximity from 60cm to up to 1m. The output reveals the relative distance as our hand approaches the transmitter, resulting in an instrument that exhibits similarity to a Theremin. This enables us to continuously control certain sound parameters by performing non-contact gestures with one hand, while the other hand is in contact with the keyboard.

3.3. Pressure

The pressure-sensing element is a multi-layer structure made out of piezo-resistive fabric and mesh fabric sewn in between two conductive fabrics. The piezo-resistive fabric is a knit fabric coated with PPy, a conductive polymer in concentrations that can be requested. In this case, we used Eeonyx LTT-SLPA-20k, with surface resistivity of 20kΩ/sq. Since it is piezo-resistive, the resistance of this fabric sensor changes in correlation to the applied force. The decision to include mesh fabric in the structure manifested from the non-uniformity of the resistance baseline value on each key. The mesh layer solves this problem, as it physically separates the conductive fabric from the piezo-resistive fabric, avoiding tensions as well as accidental contacts between them. Nonetheless, introducing a mesh layer as a part of the pressure sensing element could possibly reduce the sensitivity of the pressure sensor to low finger pressures. We then experimented and characterized different types of mesh fabric to test the relationship between the gap size and thickness with each sensor's sensitivity and found that polyester knit mesh fabric gives the best sensitivity and pleasant tactile feel, as it has a relatively large gap size, is rather thick, and also squishy [17].

3.4. Stretch

Knitted spandex fabrics, due to their high elasticity, are good textile substrates for coated stretch sensors. The coated fabric can be cut to different sizes in order to engineer its base resistance and durability. Not only seamless, coating the fabric itself with conductive polymers also eliminates the necessity of an interfacial layer or complex transfer process in the case of a printed or cured carbon-elastomer composite strain sensor. Their ability to be sewn also makes it possible to integrate them to any fabric.

In this work, we are interested to see how the complex interlocked structures of knitted fabrics influence their response to strain, both mechanically and electrically. The Instron testing machine was used to study the response of several fabric stretch sensors with various strain elongations. This machine is universally used to evaluate mechanical properties of various materials. We compared PPy-coated fabric for stretch sensors in different cuts (course and wale), surface resistivities (coating concentrations), and maximum allowable strain (elastane compositions). The results showed that stretch sensors cut in the wale direction with low surface resistivity and high percentage of elastane, give the best performance both mechanically in terms of structural integrity and electrically in terms of dynamic range. The Instron test also proved that the fabric stretch sensor is repeatable when stretched back and forth 100 times with 40% and 80% strain. Hysteresis and relaxation behaviors can also be observed to some extent, but this is mainly caused by the structural property of knitted fabrics. In addition, we found that transferring this ribbon strain sensor onto another fabric as a substrate improves its reliability and durability, as the substrate provides additional support to recover the fabric stretch sensor back to its original length. The placement of the stretch sensors that are embedded in between the keys and on the edges of the fabric, as previously shown in Figure 2c), enables the keyboard to distinguish between stretching or expanding the keys, pulling specific sides of the fabric, and stretching the entire fabric.

3.5. Additional Fabric Interfaces

The additional fabric interfaces, which are ribbon-controller and trackpad, were designed to be modular. Silver or nickel-coated snaps were sewn as shown in Figure 2b) at the up right corner of the fabric keyboard, allowing performer to add these additional fabric controllers as necessary by snapping them. Figure 3 shows the final look of these fabric controllers. In order to develop these, we used:

- **Non-conductive fabric**: Woven 100% cotton denim fabric.
- **Mesh fabric:** 100% Nylon Tulle netting fabric.
- **Conductive fabric:** Woven Soft&Safe fabric with 70% Bamboo fiber and 30% Ag fiber, Copper Polyester Taffeta with 100% Cu fiber, and Cobaltex fabric with 100% Ni fiber. Their surface resistivities are <1 Ω/sq, 0.05 Ω/sq, and <0.1 Ω/sq respectively.
- **Resistive fabric:** Woven Exstatic fabric with 87% Polyester and 13% BSAF Resistat and surface resistivity of 10^5 Ω/sq.

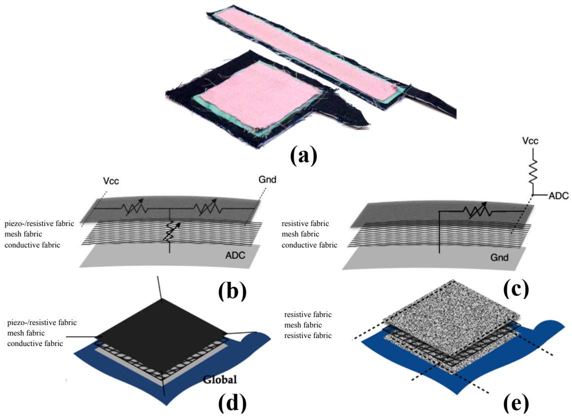


Figure 3: a) The fabric trackpad and ribbon-controller. b) Voltage gradient and c) total resistance approaches of measuring finger location with ribbon-controller. d) 5-wire and e) 4-wire configurations of the resistive fabric trackpad

3.5.1. Fabric Ribbon-controller

The fabric ribbon-controller is a long sensate surface that measures position along one axis for continuous expression by sliding our finger. We compared two methods of single axis location sensing as shown in Figure 3b) and c). The first method in Figure 3b), is based on a voltage gradient between two lines at both ends of a piezo-resistive/resistive fabric layer. When a finger strikes the pad, a connection is made between the resistive fabric and bottom conductive fabric through a mesh fabric. The bottom fabric is connected to an ADC, in which the voltage value directly correlates to the position of the finger in respect to Vcc and Gnd, If a piezo-resistive layer is used, we can implement current-steering circuits as discussed in [21] to calculate both position and pressure of the finger simultaneously. The second approach, as illustrated in Figure 3c), is based on the total resistance of a resistive fabric from one edge to the contact point. It requires external reference resistor to form a potential divider configuration. The latter approach was chosen because of its simplicity in hardware, as linearization can be easily be done through software, providing a prior knowledge of the reference resistor.

3.5.2. Fabric Trackpad

Based on the maturity of current resistive touchscreen technologies, we tested two main approaches: 5-wire and 4-wire configurations in our fabric trackpad design. The first approach, the 5-wire configuration, was realized by sewing a conductive fabric on top of a fabric substrate followed by mesh and resistive fabric. Four conductive connections were then embroidered onto each corner of the resistive layer, as illustrated in Figure 3d). To measure the coordinate of the finger, the corner points are periodically set to either represent a low or high. The bottom conductive fabric is then used to measure the voltage gradient of the axis as our finger strikes the pad. The 4-wire configuration in Figure 3e) consists of a mesh layer in between two resistive fabrics. Conductive threads were sewn through the two opposing sides of each resistive fabric orthogonally to each other. In this approach, one of the conductive thread lines on each resistive fabric becomes an ADC line, while the other is set to high-impedance. The upper resistive fabric provides a voltage gradient by setting each conductive line to either Vcc or Gnd. This mechanism occurs alternately, hence the voltage read by the other fabric pair as an ADC contact represents either the x or y-position value

We performed drawing tests to evaluate the performance of these two configurations. In the case of 5-wire, there is a non-linear behavior on the patterns drawn closer to the edges. The non-equipotential voltage distribution across the edges is the reason behind this. As the touch point is further away from the corners, the voltage starts to drop due to the resistance distribution across the layer. To solve this issue, a linearization pattern can be applied by sewing conductive thread in certain patterns across all sides. The 4-wire configuration, however, performed better compared to the previous configuration. It did not have issues in voltage distribution, since in this 4-wire technique, two resistive layers are required and the voltage gradient in both cases now becomes unidirectional. The fabric trackpad could read several simple to complex stroke patterns satisfactorily. The advantages of this method over the grid-based technique is that it has a high resolution (depending on ADC bits), seamless look, smooth tactile feel, and low complexity; however, the trackpad could only detect a single touch and is not as sensitive, as it needs a small amount of force to break through the mesh layer.

4.HARDWARE DESIGN

Based on the modular design of our fabric keyboard, we fabricated two different boards with their own features as shown in Figure 4 below. The first board (*FabricKeys*) consists of MPR121 proximity and touch controller channels as well as pressure, stretch, ribbon-controller, and trackpad channels,

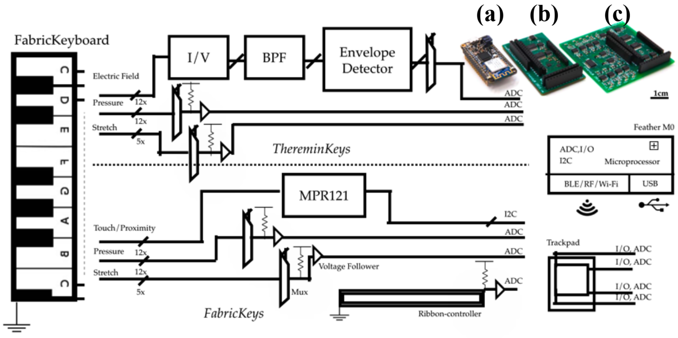


Figure 4: System interface of the multimodal array of fabric sensors, showing a) Feather M0 Wi-Fi, b) *FabricKeys*, and c) *ThereminKeys*

whereas the second board (*ThereminKeys*) comprises passive electric field sensing, pressure, and stretch channels.

Both of these boards have configured pin-headers for stacking the main hub and connecting it to the fabric musical controller through a customized fabric ribbon connector. We used an Adafruit Feather M0 Wi-Fi as the main hub, giving us flexibility in adopting either wired (Serial or MIDI) or wireless (OSC) protocols. We chose Wi-Fi because of its direct approach to interfacing with OSC through UDP. These headers are also compatible with other Feather modules, such as BLE or RF, enabling us to change communication protocols as necessary.

5.SENSOR-COMPUTER INTERFACES AND MUSICAL MAPPINGS

We tested three different protocols in this work: direct serial communications with a customized data structure, MIDI, and OSC. The hardware USB data-rates, with 115200 bps for reading all of the sensor data, are 53 Hz and 62 Hz, while the maximum possible latencies are 19 ms and 16 ms respectively for *FabricKeys* and *ThereminKeys*. With the ribbon-controller and trackpad attached, the maximum latency increases to 20.6 ms. If, instead of USB, the wireless approach is used, as the calculated round-trip delay was ~8.5ms, the maximum latency when using OSC through UDP is 23 ms. Note that the maximum latency here only applies to the multiplexed sensing elements; some of the continuous controllers, such as ribbon-controller and trackpad, have a lower latency (~2ms). The effective latency however could be a little bit higher than this, as we have not considered the latency after the data is transferred and converted into sound. We finally focused on the MIDI implementation, taking into an account its interoperability, simplicity, and wide software support. In this example, we used Ableton Live 9 as our audio workstation.

Sensing Modality	Data	No of Sensing Elements	Channel	Message Type	Converted Data
Touch	Bool	12	1	Note Off/On	Note Number
Pressure	Int Int	12	1 1	Note Off/On Polyphonic/ Channel Pressure	Velocity (0-127) Pressure (0-127)
Proximity	Bool Int	12	2 2	Note Off/On CC	Note Number Value (0-127)
Stretch	Int	5	1	CC/Pitchbend	Value (0-127)/MSB (0-127)
Ribbon-controller Position Touch/ Proximity	Int Bool/ Int	1 1	1 3	Pitchbend Note/CC	MSB (0-127) Note Number/ Value (0-127)
Trackpad Position Touch/ Proximity	Int Bool/ Int	2 1	4 4	CC Note/CC	Value (0-127) Note Number/ Value (0-127)

Table 1: Example of MIDI message mappings

Table 1 shows the on-board mapping of each sensor into MIDI messages. It can be seen that these are customizable and could change, depending on the intended sonic interactions. The stretch sensors can be set to MIDI CC messages that will correspond to certain timbral, dynamic, and temporal variations (filter resonance, frequency, glide, reverb, amp, distortion, *et cetera*), as well as pitch-bend. The additional controls, such as the ribbon-controller or trackpad, can be mapped as independent instruments, since they are integrated with touch as well as near-proximity sensing, or as a keyboard complement with CC or pitch-bend messages.

Figure 5 below demonstrates several examples of the gestural interactions performed with the fabric keyboard and its extension fabric interfaces. In this work, we explored several possible mappings based on the underlying sensing modalities. A performer can use the multiplexed proximity mode for sensing high-range hand approach. Amplitude modulation can be mapped into this non-contact parameter as our hand gets closer to the surface, giving an ambient sound effect before the performer starts playing physically with the keyboard. Another possibility is to map this as a pitch modulation, getting stronger as our hand approaches towards the surface. In addition, as each key on our fabric keyboard is also able to sense near-proximity, we can map our hand's presence on each key as an individual note, and its distance in respect to it as a modulation. For the electric field sensing, we mapped the non-contact gesture control to filter frequency and expanding of the keys to tremolo effects. Indeed, another novel interaction enabled by the fabric keyboard is stretching. We also demonstrated this physical gesture by correlating pitch modulation as we stretch multiple keys against each other, as well as vibrato intensity as we pull a specific side of the fabric subsequently. Lifting and stretching the fabric after playing with it can also be mapped to modulate an echo. Furthermore, one can twist the whole fabric, which will ground all of the keys and trigger them to turn on, as well as contracting some of the stretchable fabric sensors simultaneously, giving a new style of performance to the users.

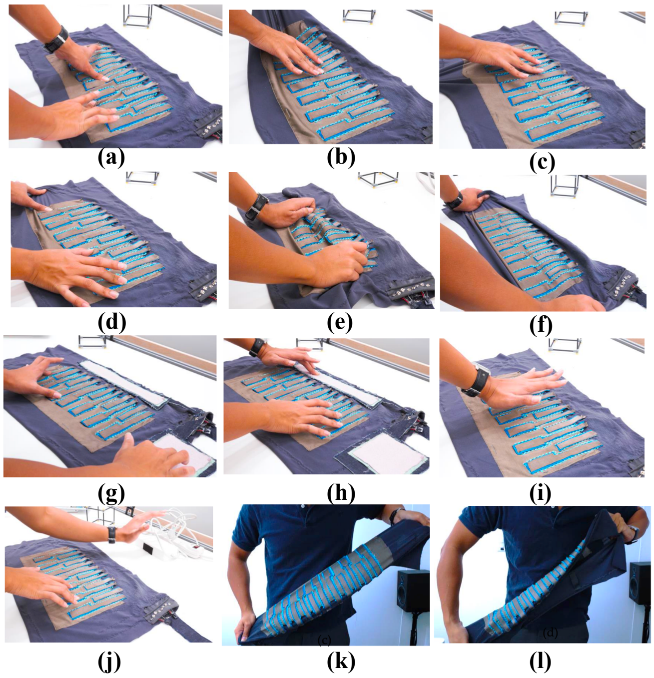

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

Figure 5: Several interactions demonstrated include a) Expanding the keys with fingers b) Pulling left side c) Pulling bottom side of fabric d) Expanding specific side with fingers while playing the keys e) Squeezing the keys f) Stretching the fabric g) Sliding on the trackpad h) on the ribbon-controller while playing the keys i) Hovering around and approaching towards the surface j) Playing the keys with one hand while the other waves towards/against an EMI source k) Lifting and stretching l) Twisting the whole fabric

There are evidently many possible mappings that can result from this fabric keyboard as we explore its modalities and their relationships to one another. Refer to [17] for more information of our mappings. Video demonstrations of several performances with the keyboard, including the ribbon-controller and the trackpad can also be accessed at the link of this project, provided in the Appendix of this paper.

6.EVALUATIONS

We have discussed the design and implementation of multi sensory fabric surface as a keyboard interface and demonstrated a working prototype. However, there are still several limitations in this work that need further work. Using bare conductive threads has been proved to cause several complications such as parasitic capacitances and short-circuits, affecting the sensor response especially upon extreme movements of the fabric. Thus, it is recommended to use insulated conductive threads, as developed in [1], or more effectively, to fabricate the shielded version of them. Even though the strain sensors worked reliably when stretched around their allowable range, stretching outside their range could influence their base resistance. Calibrating each sensor baseline value is therefore necessary to compensate this offset.

In terms of the usability, we found that it is relatively hard to play chords with the keyboard, due to the gap in between each key for the stretch sensor's placement. This gap is required so that we can expand the keys comfortably with our finger. However, choosing a more stretchable base fabric and reducing this gap distance could possibly solve this design issue. Finally, since our current maximum possible latency would not be suitable for staccato keyboard performances, further efforts in hardware are required by reducing the multiplexing load and the ADC processing time of each sensing modality.

7.CONCLUSIONS AND FUTURE WORK

In this paper, we presented *FabricKeyboard:* a novel, multi-modal, fabric-based keyboard controller comprising a multi-layer of fabric sensors patterned on a stretchable fabric substrate. Each key, as well as the bulk fabric, could detect touch, proximity, pressure, stretch, and coupled electric field simultaneously, resulting in rich discrete and continuous gesture sensing. To complement this fabric keyboard, other fabric interfaces such as ribbon controllers and trackpads were also built. These fabric interfaces are modular and can be snapped to the main keyboard controller. Our seamless design separates the soft-circuits (smart fabrics) from the rigid-circuits (circuit boards), allowing the performers to fully explore the fabric and express themselves. This enhances the relationship between the physical interaction and the music, as the fabric deeply embodies the sound it resonates. Supported by MIDI protocol, the fabric keyboard can be connected to any audio synthesis or sequencer software and mapped to essentially any instrument, sound, or effect.

There is much work that can be done in the future to further extend this project. Firstly, we would like to continue our reliability tests and perform washability tests on the fabric sensors. It is also interesting to extend this fabric keyboard to two or three octaves and incorporate haptic feedback by integrating fabric-based actuators. We would like to conduct in-depth user studies with musicians and sound artists to improve our device's ergonomics and to study the rich multimodal and sonic experiences that can result from this keyboard. In the end, we would like to collaborate with them for a musical performance. We hope that this work not only contributes towards fabric-based musical controllers, but also to other new physical interaction media involving electronic textiles.

8.ACKNOWLEDGMENTS

We would like to thank Lyle Mays for the original inspirations, Nan-Wei Gong for the initial discussions of this work, the Responsive Environments Group at the MIT Media Lab, and the Zeno Karl Schindler Foundation.

9.REFERENCES

1. Poupyrev, I., Gong, N.W., Fukuhara, S., Karagozler, M.E., Schwesig, C. and Robinson, K.E., 2016, May. Project Jacquard: Interactive Digital Textiles at Scale. In *Proc. CHI* (pp. 4216-4227). ACM.
2. Berzowska, J., 2005. E-textiles: Wearable computers, reactive fashion, and soft computation. *Textile*, *3*(1), pp.58-75.
3. Post, E.R., Orth, M., Russo, P.R. and Gershenfeld, N., 2000. E-broidery: Design and fabrication of textile-based computing. *IBM Sys*, *39*(3.4), pp.840-860.
4. Chang, A. and Ishii, H., 2007, June. Zstretch: a stretchy fabric music controller. In *Proc. 7th NIME* (pp. 46-49). ACM.
5. Roh, J.S., Mann, Y., Freed, A. and Wessel, D., 2011, June. Robust and Reliable Fabric, Piezoresistive Multitouch Sensing Surfaces for Musical Controllers. In *NIME* (pp. 393-398).
6. xOSC Glove. http://dev-blog.mimugloves.com
7. Troiano, G.M., Pedersen, E.W. and Hornbæk, K., 2015, April. Deformable interfaces for performing music. In *Proc. 33rd CHI* (pp. 377-386). ACM.
8. Perner-Wilson, H., Buechley, L. and Satomi, M., 2011, January. Handcrafting textile interfaces from a kit-of-no-parts. In *Proc. 5th TEI* (pp. 61-68). ACM.
9. Paradiso, J.A. American Innovations in Electronic Musical Instruments, http://www.newmusicbox.org/articles/american-innovations-in-electronic-musical- instruments/
10. Young, G., 1989. The Sackbut Blues: Hugh Le Caine, Pioneer in Electronic Music, National Museum of Science and Technology Press, Ottawa CA.
11. Moog, R.A. and Rhea, T.L., 1990. Evolution of the keyboard interface: The Bösendorfer 290 SE recording piano and the Moog multiply-touch-sensitive keyboards. *CMJ*, pp. 52-60.
12. Haken, L., Tellman, E. and Wolfe, P., 1998. An indiscrete music keyboard. *CMJ*, *22*(1), pp.30-48.
13. McPherson, A., 2012, May. TouchKeys: Capacitive Multi-Touch Sensing on a Physical Keyboard. In *NIME*.
14. Grosshauser, T. and Tröster, G., 2013, May. Finger Position and Pressure Sensing Techniques for String and Keyboard Instruments. In *NIME* (Vol. 13, pp. 27-30).
15. Lamb, R. and Robertson, A., 2011. Seaboard: a New Piano Keyboard-related Interface Combining Discrete and Continuous Control. In *NIME* (pp. 503-506).
16. Paradiso, J.A. and Borque, L. L., A Fabric Keyboard for Composing on the Road. (Unpublished manuscript)
17. Wicaksono, I., 2017. Master Thesis. Multisensory Fabric as Deformable Musical Interface.
18. MPR121 Datasheet. http://www.nxp.com/pages/proximity-capacitive-touch-sensor-controller:MPR121
19. Zimmerman, T.G., Smith, J.R., Paradiso, J.A., Allport, D. and Gershenfeld, N., 1995, May. Applying electric field sensing to human-computer interfaces. In *Proc. CHI* (pp. 280-287). ACM.
20. Gong, N.W., Steimle, J., Olberding, S., Hodges, S., Gillian, N.E., Kawahara, Y. and Paradiso, J.A., 2014, April. PrintSense: a versatile sensing technique to support multimodal flexible surface interaction. In *Proc. 32nd CHI* (pp. 1407-1410). ACM.
21. Freed, A., 2009, June. Novel and Forgotten Current-steering Techniques for Resistive Multitouch, Duotouch, and Polytouch Position Sensing with Pressure. In *NIME* (pp. 230-235)

10.APPENDIX

Demonstrations of this project can be accessed at https://www.media.mit.edu/projects/FabricKeyboard/overview/