KnittedKeyboard: Digital Knitting of Electronic Textile Musical Controllers

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ABSTRACT
In this work, we have developed a textile-based interactive surface fabricated through digital knitting technology. Our prototype explores intarsia, interlock patterning, and a collection of functional and non-functional fibers to create a piano-pattern textile for expressive and virtuosic sonic interaction. We combined conductive, thermochromic, and composite yarns with high-flex polyester yarns to develop KnittedKeyboard, both with its soft physical properties and responsive sensing and display capabilities. The individual and combinations of keys could simultaneously sense discrete touch, as well as continuous proximity and pressure. The KnittedKeyboard enables performers to experience fabric-based multimodal interaction as they explore the seamless texture and materiality of the electronic textile.

Author Keywords
Keyboard, multimodal, electronic textiles, digital knitting, continuous and discrete controls, interactive surfaces, deformable interfaces.

CCS Concepts
• **Hardware** → **Sensor applications and deployments**; sensor devices and platforms; • **Human-centered computing** → Sound-based input/output

1. INTRODUCTION
Textiles are ubiquitous in our daily life. They are highly formable and palpable materials with a broad spectrum of patterns, structures, and textures. Advances in electronic textiles (e-textile) since the 1990s have pushed forward the development of novel interfaces, particularly for musical interaction [1, 2]. Inspired by soft and deformable properties as well as aesthetic features of textiles, we envision an interactive textile-based surface with a familiar layout of an existing instrument. We fabricated a piano-pattern fabric (Figure 1) that allows multi-modal sensing for sonic physical interaction. As a second iteration of our previous work [3], KnittedKeyboard explores the realization and applications of interactive textiles for musical controllers with rapid and personalized digital knitting technology.

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Figure 1: Performing with the KnittedKeyboard.

Knitting is an established textile manufacturing technique that has been pervasive in the garment and technical fabrics industry. Current industrial knitting machines are optimized for mass-manufacturing of garments, socks, and shoes. In comparison to weaving, knitting has several advantages, including the ability to create intricate patterns, textures, and structures. With the growing areas of digital fabrication and computer-aided design, a new generation of knitting machines now enable users to personalize and rapidly develop their textile design through a specialized visual programming environment and various types of functional and common yarns. We present a design principle for textile-based interactive surfaces starting from electronics at the fiber-level and towards their integration into fabrics with digital knitting techniques. This process enables personalized, rapid fabrication, and mass-manufacturing of seamless intelligent textiles for novel interaction purposes, particularly for fabric-based musical controllers and interactive surfaces. Connected to a hardware system and computer, the KnittedKeyboard can simultaneously detect touch, proximity, and pressure, as well as control thermochromic change. It allows performers to play the discrete notes, harmonies, and soundscapes with virtuosity, while experiencing the unique visual and tactile properties of the knitted textile.

2. RELATED WORK
The history of conductive textiles dates back to the early modern period where gold and silver yarn were woven into tapestries or metallic organza for fashion, interior design, and decorative purposes [4]. However, it was not only after the late 20th century that the electrical properties of such textiles were harnessed, and

the concept of interactive textiles and e-broidery was introduced initially at the MIT Media Lab. Musical Jackets and Musical Balls [5,6], for instance, demonstrated the first embroidered touch and pressure-sensitive textile sensors for performing music. Other recent work includes the Musical Skin [7], a soft fabric sound controller for spatiotemporal pressure sensing across a two-dimensional space, and FabricKeyboard [3], a multi-layer textile keyboard that could simultaneously detect discrete and continuous touch, proximity, pressure, stretch, and electric field hand gestures for expressive musical performance. MusiCushions [8], a set of interactive sofa cushions, also enables deformable inputs for explorations of music interaction at home. The work mentioned above explored attachment of conductive fabrics and yarns at the fabric-level, by embroidery, iron-on melting, or sewing. As new textile manufacturing techniques such as digital knitting and weaving become accessible to researchers, efforts start to emerge in integrating conductive or any other types of functional yarns to develop interactive textiles from electronic fibers [8,9]. Previous work in interactive textiles has also shown thermochromic or electrochromic properties that could provide display functions [11]. However, there has not been any effort in integrating electronic yarns with both sensing and actuation capabilities into fabrics with digital knitting technology.

The inclusion of conductive material as capacitive touchpads in musical interface started in the mid-60s, as can be seen in Don Buchla's modular synthesizer [12,13]. This was then followed by commercial keyboard synthesizers such as EMS Synthi AKS and EDP Wasp. As an effort to leverage hand and finger dexterity, Moog and Rhea designed an expressive multimodal sensor layer for discrete and continuous controls in their Multiply-Touch Sensitive Keyboard [14]. Previous work also focused on transforming the key's surface and substrate, starting from The Continuum, an indiscrete keyboard layout for continuous finger gestures [15] to the recent Seaboard [16], a soft, rubbery, and wavy keyboard interface with its signature-style polyphonic modulations. In this work, we programmed a digital knitting machine and utilized functional (conductive, thermochromic, and melting yarns) and non-functional polyester yarns to seamlessly develop a knitted musical instrument digital interface (MIDI) keyboard. The fiber-based keyboard not only responds to contact and non-contact gestures such as pressure, touch, and proximity, but also changes its color with temperature to visualize various modes of play. It can be played on a flat surface or worn to explore on-body or wearable musical performance as a keyboard tie, previously performed by Laurie Anderson in the "Home of the Brave" [17]

3. FABRICATION

3.1 Digital Knitting

Digital knitting is a computer-aided, automatic process of building interlocked loops from multiple strands of yarns. It is a rapid process that is useful for large-scale, mass-manufacturing of textiles (Figure 2a). It employs an array of needles or hooks that goes up and down to catch the yarns based on an instruction file. Each yarn is fed to the machine from a cone, passing through a tensioning mechanism towards a yarn carrier. These yarn carriers move sideways as the needles grab the yarn to form new loops. The digital knitting programming interface consists of two grid sections. The left grid area is used to develop the shape and pattern of the knit fabrics through x-y color block programming, where each color and sign represents a specific knit instruction (Figure 2c).

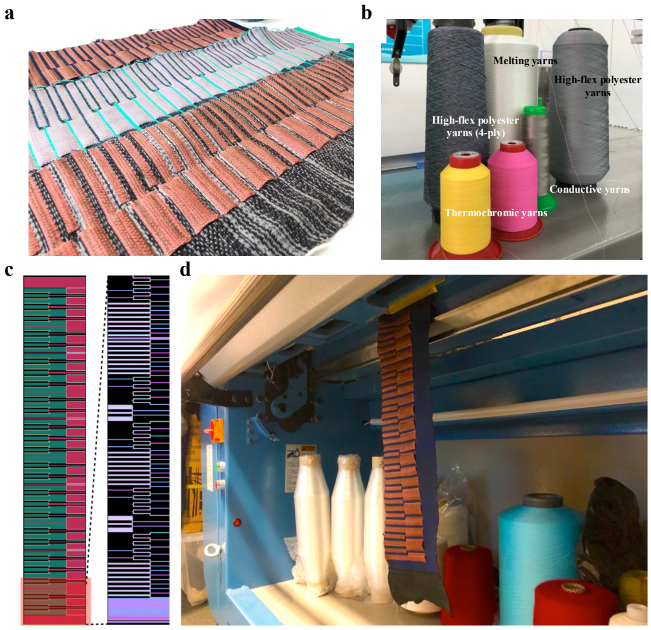

Figure 2: a) Mass-manufacturing of KnittedKeyboard, b) Example of conductive, thermochromic, and polyester yarns, c) Digital knitting program in simplified (left) and machine (right) format, and d) KnittedKeyboard output from the digital knitting machine.

We used a flat two-bed digital knitting machine (Super-NJ 212, Matsuya) and as shown in Figure 2b, fed this machine with the following yarns: two cones of silver-plated conductive yarns (150 denier, Weiwei Line Industry), two cones of thermochromic yarns (150 denier, Smarol Technology), and two cones of high-flex polyester yarns (540 denier, 4-ply) combined with melting yarns (150 denier, 1-ply). We fed a cone of silver-plated and thermochromic yarns together on each of the two carriers. Each cone connects to a different yarn carrier, with a total of four carriers used. As illustrated in Figure 2c, each carrier knitted a different section of the fabrics. Intarsia knitting was instructed on sections where more than one yarn type is needed, such as in any line where the piano key is plotted. Since it is a two-layer knitting machine, we performed interlock knitting to intersect the front and the back-fabric layers. It took the machine 1 hour and 40 minutes runtime to knit the entire prototype, which has five octaves of diatonic piano-keys pattern (Figure 2d). The resulting knitted fabric was steamed at the end to activate the melting yarn, giving structural rigidity to the final prototype.

3.2 Additional Structure

The one layer, piano-patterned conductive and thermochromic textile fabricated above could perform touch and proximity sensing, as well as color-changing display when heated. To complement the thermochromic function, we assembled and embedded five textile heaters (one per octave). In order to add pressure sensing capability for modulation, we also developed a fabric pressure sensor that we stacked at the back. It covers the entire active area of the keyboard and consists of a piezoresistive knit fabric (LG-SLPA 20k, Eeonyx) in between two conductive knit fabrics (Stretch, LessEMF).

4. HARDWARE INTEGRATION

4.1 Interconnections

The KnittedKeyboard has a total of 60 keys for 5 octaves. Each octave's key is connected to one of the twelve printed circuit board pads wired to a capacitive sensing chip (MPR121, NXP Semiconductor) with highly-conductive silver-coated fibers (Liberator 40). Five capacitive sensing chips and five heating elements are connected to the main microcontroller (Teensy 4.0) with thin insulated wires (32 AWG).

4.2 Controller-Computer Interface

Figure 3 demonstrates the various gestural inputs that can be performed on the KnittedKeyboard with their respective interface circuitry to the computer. Five MPR121 chips are connected to Teensy 4.0 through 4-wire inter-integrated circuit (I^2C) lines. Since an MPR121 can only have up to 4 different addresses (0x5a to 0x5d), we used two data (SDA) and clock (SCL) lines in the Teensy 4.0 microcontroller. The pressure sensing circuit consists of a potential divider with a reference resistor of 500 Ω, connected to the analog-digital converter (ADC) pin of the microcontroller through a voltage follower (TLV2374). The piezo-resistive pressure sensor resistance ranges from 1 to 3 kΩ. The heating circuit consists of an n-channel Power MOSFET (IRLB8721, International Rectifier) with a load resistor and is powered by a 6 V external supply.

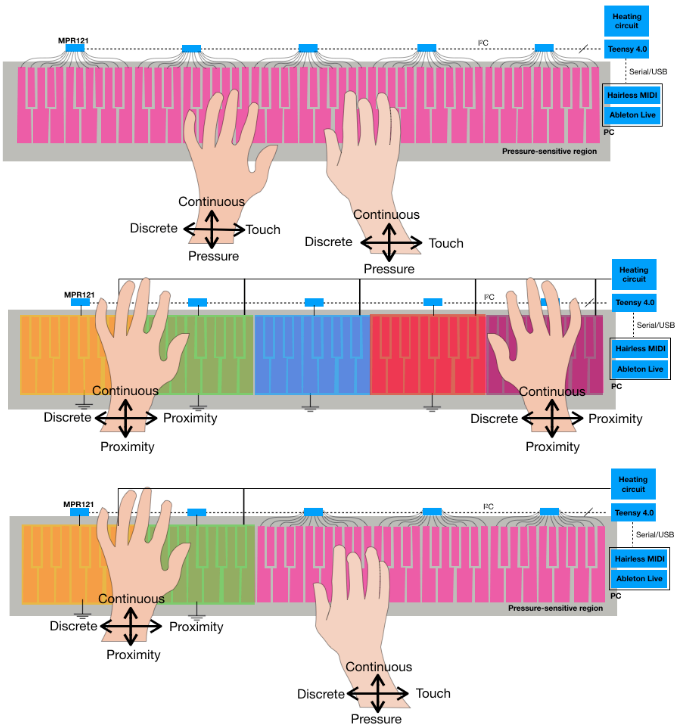

Figure 3: System architecture of the KnittedKeyboard that enables various mode of interactions.

The MPR121 performs constant direct-current (DC) current charging and discharging for capacitive sensing. By varying the amount of charge current and time, we can engineer the sensitivity of each electrode. It also features the 13th electrode, where all of the twelve electrodes are multiplexed together in-chip to represent a large capacitive sensing surface. This feature enables a near-proximity detection across an octave. We found that setting the charge current to 63 µA and the charge time to 1 µs gave the most dynamic range for large-area proximity sensing, while still reliably detecting touch events. The KnittedKeyboard, therefore, has 60 individual touch-sensitive keys that can be transformed programmatically to five proximity-sensing fields. The thermochromic display change is activated when the proximity sensing mode is enabled. It informs the user of different modes of play based on the color of the keys. With all of the touch, proximity, pressure, and heating channels activated, the KnittedKeyboard runs with a frequency of 83 Hz. The longest latency for a touch event, without taking into an account the serial and software delay is therefore 12 ms. Each of the touch events, velocity, proximity, as well as pressure values are converted to their corresponding MIDI messages in the microcontroller before sending them to the computer through serial communication with a baud rate of 115200. *Hairless MIDI* is then used as a bridge from the universal serial bus (USB) Serial Port to MIDI Out and In of *Ableton Live* 9, which is a digital audio workstation software that allows users to MIDI map all of the messages (channels, notes, and control change) to any of their instruments and effects libraries.

4.3 Sensor Outputs

Figure 4 shows the sensor outputs from various gestural inputs performed on the KnittedKeyboard before getting scaled and mapped into MIDI messages. As can be observed in Figure 4a, the keyboard can sense pressure exerted by the fingers, which is mapped to a MIDI channel expression (linked to an after-touch or a reverb for example) with a user-defined expression delay. The keyboard also has the ability to detect hand's approach or hover up to 10 cm above the fabric surface. The output value drops as the hand gets closer to the capacitive sensing area (Figure 4b). Finally, Figure 4c illustrates a technique to measure finger velocity by calculating the capacitance's slope of descent (Δt/Δval) in between a point where a touch event happens and the previous two proximity values. This technique requires a temporary array of variable in the program, that continuously stores capacitance values of each key before a touch event occurs.

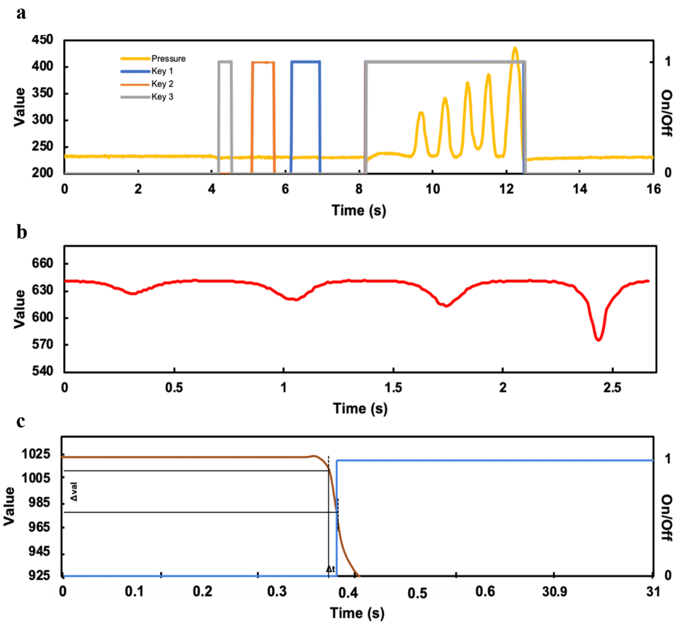

Figure 4: Signal response of a) touch events and pressure values from finger strikes and aftertouch, b) proximity values from hands approach, and c) touch event and capacitance value to determine note velocity.

5. MUSICAL MAPPINGS

In *Ableton Live 9*, there are two active channels. We assigned the touch events and velocities to Channel 1, which can be either synth keys and leads, such as *suburban* or *brassicana lead* or a classic piano rack. The pressure-sensing values as aftertouch or expressions are also mapped into Channel 1, for either track volume or filter frequency. A user can go into the proximity mode for sensing hand's waving and hovering, which we assigned to Channel 2. In this case, we applied ambient and evolving sound effects, such as *spacefolder* or *cosmos scape*. Amplitude modulation can also be mapped into this channel as our hands get closer to the surface. Figure 5 shows the possible modes of interaction enabled by the KnittedKeyboard.

Figure 5: a) Modes of interaction: one hand's hovering and the other playing keys, and b) thermochromic color change in action for proximity field sensing marker (from grey to pink).

6. CONCLUSION AND FUTURE WORK

We proposed and developed KnittedKeyboard, a machine-knitted, piano-patterned interactive textile surface with multi-functional sensing and display capabilities. It consists of 60 touch and velocity-sensitive keys that can be transformed into five proximity sensing pads. In addition, it has a pressure sensing layer underneath for aftertouch expression. The patterns are also thermochromic and can change color with applied heating to visualize different modes of play. Designed as a MIDI instrument, the piano-patterned electronic textile can be connected to any audio synthesis or sequencer software, such as *Ableton Live 9* or *Garage Band* and mapped to any instrument or sound effects. This work demonstrates the vision of seamless fabric-based interactive surfaces, that is not only applicable in novel musical controllers, but also in smart objects and responsive environments. The underlining technology would enable further exploration of soft, malleable, and on-body musical interfaces that leverages the unique mechanical quality of the material, as well as the electrical property of the sensors. We are interested to collaborate with composers, sound artists, and keyboardists, in exploring ways to compose and perform music with the KnittedKeyboard. Future work may also include simultaneous knitting of textile heating and pressure-sensing layers on top of the conductive and thermochromic layers, the design of flexible printed circuit board interface circuits for robust textile-hardware connection, and integration of an on-board audio generation system.

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9. APPENDIX

Video demonstration can be accessed in this link:
https://www.media.mit.edu/projects/knittedkeyboard/overview/