KnitUI: Fabricating Interactive and Sensing Textiles with Machine Knitting

Yiyue Luo*
yiyueluo@mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

Kui Wu*†
kuiwu@csail.mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

Tomás Palacios
tpalacios@mit.edu
MIT MTL
Cambridge, Massachusetts, USA

Wojciech Matusik
wojciech@csail.mit.edu
MIT CSAIL
Cambridge, Massachusetts, USA

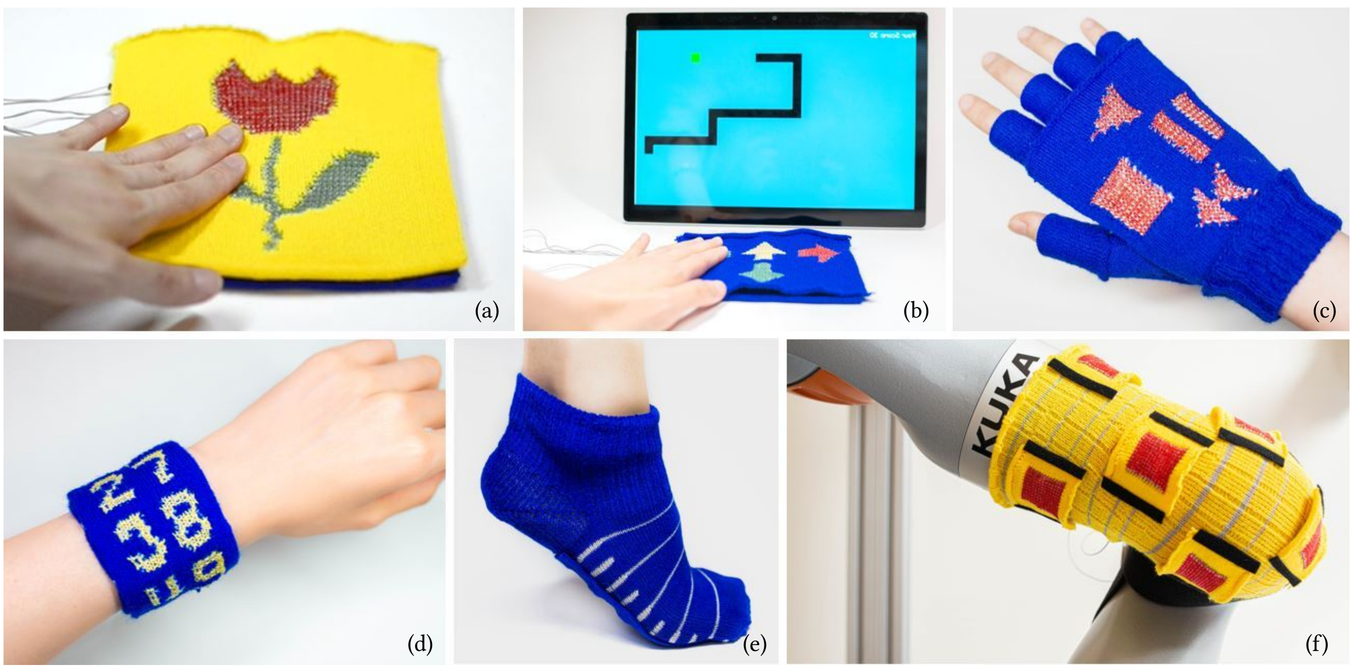


Figure 1: ***Example applications of KnitUI:*** *(a) interactive educational toys, (b) game controller, (c) music controller glove, (d) numpad wrist wrap, (e) tactile sensing socks, and (f) tactile robotic skin.*

ABSTRACT

With the recent interest in wearable electronics and smart garments, digital fabrication of sensing and interactive textiles is in increasing demand. Recently, advances in digital machine knitting offer opportunities for the programmable, rapid fabrication of soft, breathable textiles. In this paper, we present *KnitUI*, a novel, accessible machine-knitted user interface based on resistive pressure sensing. Employing conductive yarns and various machine knitting techniques, we computationally design and automatically fabricate the double-layered resistive sensing structures as well as the coupled conductive connection traces with minimal manual post-processing. We present an interactive design interface for users to customize KnitUI's colors, sizes, positions, and shapes. After investigating design parameters for the optimized sensing and interactive performance, we demonstrate KnitUI as a portable, deformable, washable, and customizable interactive and sensing platform. It obtains diverse applications, including wearable user interfaces, tactile sensing wearables, and artificial robot skin.

*Both authors contributed equally to this research.
†Corresponding Author: Kui Wu, kuiwu@csail.mit.edu

CHI '21, May 8–13, 2021, Yokohama, Japan

ACM ISBN 978-1-4503-8096-6/21/05…$15.00
https://doi.org/10.1145/3411764.3445780

CCS CONCEPTS

• **Human-centered computing → Interaction devices**; **Human computer interaction (HCI)**.

KEYWORDS

Machine knitting, wearable device, smart textiles, stitch meshes

ACM Reference Format:
Yiyue Luo, Kui Wu, Tomás Palacios, and Wojciech Matusik. 2021. KnitUI: Fabricating Interactive and Sensing Textiles with Machine Knitting. In *CHI Conference on Human Factors in Computing Systems (CHI '21), May 8–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3411764.3445780

1 INTRODUCTION

Envisioned in ubiquitous and wearable computing, the seamless integration of technology in our everyday environments enables less obtrusive and less constrained interactions in richer contexts [43]. To overcome the boundary between rigid electronic devices and the ideal soft form factor, previous researchers developed diverse flexible and wearable interfaces [11, 36]. Among them, smart textiles exhibit a few clear advantages. As the fabric is flexible, lightweight, and breathable, it provides comfort during natural human activities. Textiles also offer seamless integration of functionalities in daily human life due to their wide variety of everyday applications, spanning apparel, furniture, and plush toys, which can be fabricated and tailored using existing manufacturing methods. There are several common textile manufacturing methods (*e.g.*, weaving, sewing), but we focus on knitting, which offers several clear advantages. First, the latest advances in digital machine knitting allow designers to create the whole garment with versatile geometries, patterns, and colorworks in one machine run [38], which can eliminate manual tailoring. Furthermore, the continuously interlocking "loop-through-loop" structure makes knitted fabrics extra deformable and stretchable.

Several previous works address knitted functional textiles, but most existing methods rely on intensive and delicate labor work, such as the electrical wiring to readout circuit and the manual integration of pre-manufactured functional components. These steps are typically expensive and vulnerable, with sophisticated manufacturing procedures. To overcome the above limitations, we present *KnitUI*, a user interface for machine-knitted textiles that leverage Jacquard and plating knitting techniques to create a two-layered structure. Conductive yarns are embedded automatically into the knitted fabric during knitting to form resistive pressure sensing units. To provide a solution for connecting the sensing matrix with the readout circuit, we introduce a design for knitted conductive traces, which also leverage a two-layered structure with conductive yarns and conventional knitting yarns. We investigate the design parameters for optimized sensing and interactive performance. Thanks to the stable knitting structure with the conventional yarn and conductive yarn, our resulting sensors are deformable, portable, and washable. To help users better utilize KnitUI, we present an interactive design interface for users to customize sensing units' colors, sizes, positions, and shapes. We demonstrate the capability of KnitUI with various example applications (Fig. 1) designed by our interface, including interactive educational toys, portable soft game controllers, and wearable user interfaces. Coupled with the existing machine learning techniques, KnitUI can also be used as tactile sensing wearables to record, monitor, and learn physical human-environment interactions. Further, using knitting shaping technique (*i.e.*, short-rows), we integrate KnitUI with a full-sized conformal sensing sleeve for a commercial robot arm, offering an inexpensive, large-scale, light-weight, and conformal tactile robotic skin.

The main contributions of this paper are listed as follows.

- We present *KnitUI*, a knitted deformable, portable, and washable user interface, integrating interactivity and sensing capability with digital machine knitting;
- We introduce the designs of knitted resistive pressure-sensitive sensing units and the corresponding conductive traces, which require minimal manual post-processing to assemble and connect to the readout circuit;
- We introduce an interactive design interface for users to customize the graphic designs (*e.g., shapes and colors*) of KnitUI, and to convert the designs into low-level machine knitting instructions;
- We characterize and evaluate the impact of various design variables for the optimized sensing performance, including sensor sizes, number of conductive rows, and the type of conductive yarns;
- We finally demonstrate the capability of KnitUI, with a diverse set of example applications, including interactive textiles/wearables interface, tactile sensing wearables, and artificial robot sensing skin.

The rest of the paper is organized as follows: after discussing related work, we present our basic sensing principle, sensing architecture, and readout circuit design. Section 5 presents the interactive design interface for customization by users. Section 6 presents the measurement and characterization of different design variables. Lastly, we show various applications in Section 7 and conclude with a discussion of limitations and future works.

2 RELATED WORK

In this section, we briefly overview prior work of interactive textiles based on the sensing mechanisms. We also provide an overview of prior work on computational machine knitting, which is also used as the manufacturing method in this paper.

2.1 Interactive Textiles Mechanism

The interactive textiles can be classified into three categories by their sensing principle: resistive, capacitive, and inductive sensing.

Resistive sensing. A typical resistive sensing matrix is composed of three layers, where two orthogonally aligned conductive electrodes sandwich a single semi-conductive or piezoresistive layer. The pressure stimulus is converted into the change of resistance for touch-based input [32, 33], sensory augmentation of prosthetic limbs [18], sitting posture monitoring [23, 47], and surface and deformation gestures detection [29]. Klamka et al. [16] recently presented an iron-on approach to attach functional components to textiles for input, output, wiring, and computing. Honnet et al. [14]

provide a method to polymerize fabrics and yarns as a dyeing process to enable given textiles to sense pressure and deformation. Moreover, the resistive sensing capability can be integrated into fibers [37], and the specialized conductive metallic fiber with the resistive coating can be embedded into fabrics through embroidery [28], knitting [30], and weaving[1] for versatile interactive applications. Hamdan et al. [8] use machine learning to help to detect the folding angle of patterns embroidered using conductive yarn. Note that there are only two needle beds in a typical v-bed knitting machine that can be used to create fabrics by interlocking the yarn loops; therefore, it is impossible to automatically create the conventional three-layered resistive sensing structure used in [32, 33] without shorting. In this work, we introduce KnitUI with a novel machine knitted double-layered resistive sensing structure.

Capacitive sensing. Compared with resistive sensing, capacitive sensing generally obtains higher accuracy and reliability at the expense of higher manufacturing costs and more complex readout circuits. Orth et al. [26] first integrated capacitive touch-sensitive keypads into jackets through embroidery. They used a three-layered structure, where two conductive electrodes sandwich an insulating dielectric layer; this architecture is commonly used later in related followup research for capacitive sensing [3, 34]. *Project Jacquard* [31] interlaces customized conductive yarns as sensing matrices through weaving so it can seamlessly integrate interactive interfaces into garments and fabrics at scale. Using a similar sensing approach and structure, *Project Zanzibar* combines capacitive sensing and near field communication (NFC) to allow the localization and identification of tangible objects, user's touch, and hover gestures [41]. Hamdan et al. [9] proposed a system that lets user design sensors interactively and realize the design automatically using an embroidery machine. Capacitive sensing is enabled in a single fiber with frequency sweep [17]. Recently, SensorKnit [27] utilizes knitting to create a pocket structure, in which one side is knitted with the conductive yarn, and the other is nonconductive polyester. This work still requires manual injection of nonconductive polyesters into the pocket in order to reflect the pressure with a smooth change of capacitance.

Inductive sensing. Based on Faraday's law of induction, the contact of the conductive objects can be detected through the change of resonant frequency of the coupled circuit. The inductive sensing technique has been widely applied in position sensing [12], metal/electrical objects detection [42], and classification [20]. Recently, *Indutivo* [7] introduces various spiral-shaped coils designs with different shapes and layouts to balance sensitivity, sensing range, and accuracy. An array of those spiral-shaped coils is used to recognize small conductive objects precisely. This idea is further extended by embroidering spiral-shaped coils on fabric with conductive threads [6].

2.2 Machine Knitted Functional Textiles

Knitting is a common manufacturing technique for daily textile goods, spanning from plush toys to daily wearables. Recent advances in computational design tools open up the vast potential of digital machine knitting in the fields of design and manufacturing. Knitting has been widely used to create versatile, functional textiles with actuation and sensing modalities. For example, researchers embedded shape memory alloy wires and inlaid strong tendons into knitted fabrics for soft robotics [2, 10]. Vallet et al. [39, 40] use Jacquard knitting to create a capacitive sensing matrix. Large-scale spatiotemporal physiological sensing was realized with the insertion of pre-fabricated sensors into designed knitted fabrics [44].

Regarding knitting design, McCann et al. [22] first introduced a compiler that translates high-level shape primitives into low-level knitting machine instructions, named *Knitout* [21]. The work was extended later for converting 3D shapes into machine instructions automatically [24] with complex surface textures [13]. Lin et al. [19] also introduced an efficient transfer planner for flat knitting. Kaspar et al. [15] proposed an interactive Web design interface based on high-level primitives. To provide an efficient 3D design and modeling interface, Yuksel et al. [48] introduced *stitch meshes* to abstract yarn-yarn interlocked structures. The stitch meshes framework was extended to support arbitrary shape conversion [45] and hand knitting [46]. Recently, Narayanan and Wu et al. [25] introduced an augmented stitch meshes framework for machine knitting design. Each face is embedded with corresponding low-level knitting machine instructions to allow users to edit interactively. KnitUI also builds on the stitch meshes framework.

3 MACHINE KNITTING

The v-bed weft knitting machine is a common industrial knitting machine, which consists of two beds of needles (front and back beds), forming an inverted "V" shape as shown in Fig. 2. Each *needle* is composed of a *hook*, which catches the yarn and holds the topmost loop in a column, and a *slider*, which can be actuated to move vertically, close/open the hook, and assist in holding loops. During knitting, the yarn flows through the yarn carrier after passing a tension-control apparatus; the yarn carrier moves along the bed synchronously with needles' operations.

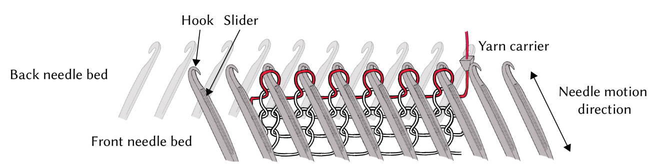


Figure 2: *The needle beds in the industrial v-bed weft knitting machine*

Specifically, most machine knitted fabric can be made with three basic needle operations, *knit*, *tuck*, and *transfer*. In a *knit*, the needle is actuated to catch the fed yarn to form a new loop and then pull the new loop back through the existing loops. Similarly, a *tuck* actuates the needle to grab the fed yarn, but the needle holds the yarn down without forming a new loop. In a *transfer*, the needle is actuated to pass the existing loop from one bed to the needle on the opposite bed. The back bed can be programmed to shift laterally as a whole, called *rack*, creating needle offsets for loop transferring. Different sequences of the above operations can create versatile knitting patterns, curved surfaces, and even complex geometries. We refer readers to [22] for more detailed information about machine knitting. Note that our proposed method also uses these basic machine operations.

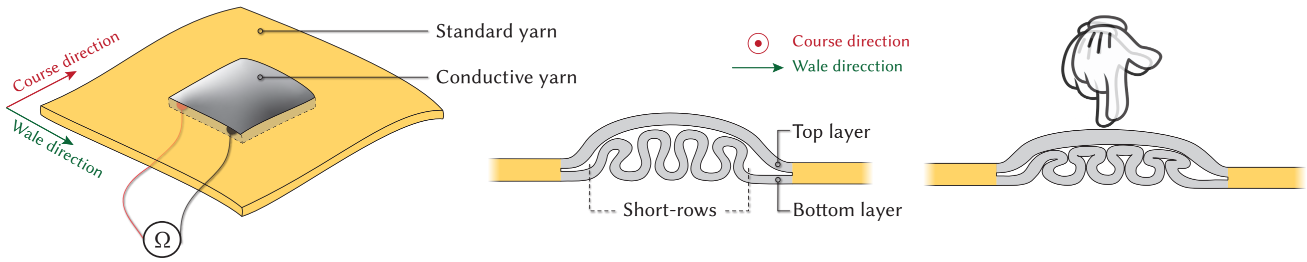


Figure 3: *The sensing structure:* *(from left to right) a double-layered sensing unit knitted with conventional and conductive yarns; the cross-sectional view (along the wale direction) of the sensing unit, with conductive short-rows on the bottom layer to increase sensitivity; when pressure is applied, the interactions between conductive yarn loops increase, leading to the drop of resistance.*

One advantage of knitting is that various colorworks can be constructed by manipulating yarns during knitting. For *Fair Isle* colorwork, two yarns are knitted alternatively. As shown in Fig. 4, only the desired yarn will be knitted at the needle, while the other yarn floats along inside the fabric. Meanwhile, *Plating* colorwork uses both yarns in every stitch, with the desired one running slightly in front of the other to make it appear on the stitch. Moreover, in *Jacquard knitting*, the colorwork is realized with a layered structure, where two yarns are knitted between the front and back beds, with the desired one knitted in the front and the undesired one knitted in the back. In this work, we utilize the above colorwork techniques to manipulate the standard knitting yarns and conductive yarns and create our knitted sensors and conductive tracks.

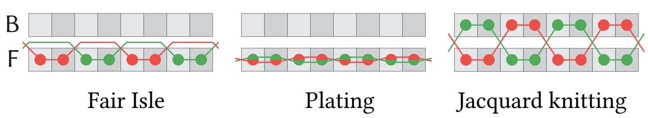


Figure 4: *This is the needle bed view of colorworks knitted with the red and green yarns at the front (F) and back (B) bed. In plating, the circles with two colors indicate that both yarns are knitted at each stitch; the bottom semicircle indicates the yarn running slightly in front.*

4 SENSING PRINCIPLE

Our user interface includes two important knitted components, sensing units, and coupled conductive traces. We will also describe the readout circuit for signal transmission from the sensing fabrics.

4.1 Knitted Sensing Unit

Our method builds on a double-layered knitting structure that utilizes both front and back needle beds from the v-bed knitting machine (*SWG091N_2*, Shima Seiki). As shown in Fig. 3, the sensing capability is enabled by inserting conductive yarns at specific locations on both top and bottom layers separately. At the rest state without any externally applied pressure, only a limited number of conductive paths exist inside the sensing unit because the knitted conductive yarn loops interlock loosely. When applying a load, the top and bottom layers collapse, and the interactions among the conductive yarn loops increase, creating more electrically conductive paths and significantly reducing the resistance.

To further increase the sensitivity and expand the detection range of sensing units, we utilize a traditional knits shaping technique, *short-row*, to pile up more conductive yarn loops at the bottom layer, which can provide more potential conductive paths. *Short-row* refers to partial rows, where only some stitches of the full row are worked. This structure is commonly used to expand the surface locally and induce curvature, *e.g.*, in the heel of a sock. In this work, multiple conductive short-rows at the bottom layer naturally form visible bumps. These offer similar geometry of a typical interactive button. Also, more potential interactions among loops enable the sensing unit to be sensitive to the physical perturbation and sustainable within the large sensing range.

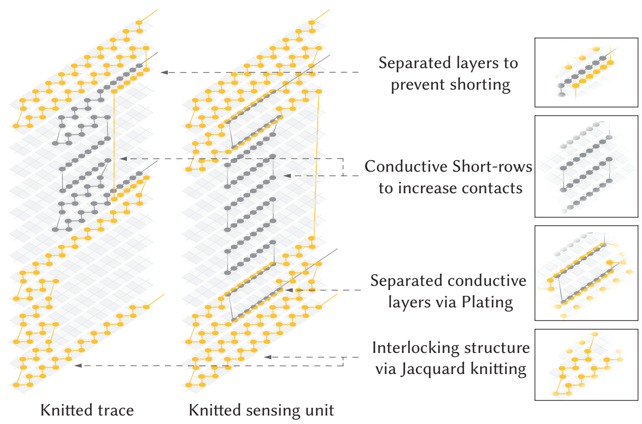


Figure 5: *Needle × time "bed view" for the sensing units and traces knits (starts from bottom). Note that we highlight each component created by knitting techniques on the right as small insets.*

Fig. 5 right demonstrates knitting our sensing unit with needle × time "bed view", where each row represents the front and back needle beds, and each circle represents the corresponding needle holding a loop. Yellow indicates the standard yarn, and grey indicates the conductive yarn. The bed views are aligned vertically to show the construction time along the upward direction. In the beginning, a two-layered interlocked structure is constructed via Jacquard knitting, which provides a mechanically flattened structure without the curling that typically happens in single-sided all-knits fabrics. To create the sensing unit, we split the interlocked structure to the front and back beds to establish a double-layered structure. Then, we plate both standard and conductive yarns at the same stitches in the sensing unit for two reasons. First, it makes the conductive layer as thick as the rest of the fabric, as the conductive thread is typically much thinner than the standard yarn. Further, plating allows us to further embed graphic designs (*e.g.*, patterns and colors) in front of the sensing unit with different yarns.

4.2 Knitted Traces

To connect the knitted sensing unit to the readout circuit with minimal labor, we create coupled conductive traces at the bottom layer on the same fabric (Fig. 6 left). However, for sensing matrices with more than one sensing unit aligned in the same row, it is hard to knit an isolated conductive path for each sensor due to the limited space. Hence, to avoid shorting among sensing units, we further design an extra fabric with coupled conductive traces to connect sensing units with the external readout circuit (Fig. 6 right). Each unit connects to one unique conductive trace and shares another conductive trace with all other sensors on the same row. By that, our method not only accomplishes the essential electrical routing with minimal manual work but also preserves the soft and flexible form factor of our sensing units.

For each conductive trace, the conductive thread is always knitted at the bottom layer to form the complete conductive paths. Meanwhile, the conductive yarn is only knitted at the top layer at specific locations to construct the electrical connection with the sensing units. Short-rows are added at the top layer with conductive yarns to create local curvatures for better contact between the sensing units and the knitted electrical traces. Fig. 5 right illustrates the needle × time "bed" view for knitting one trace at the fabric.

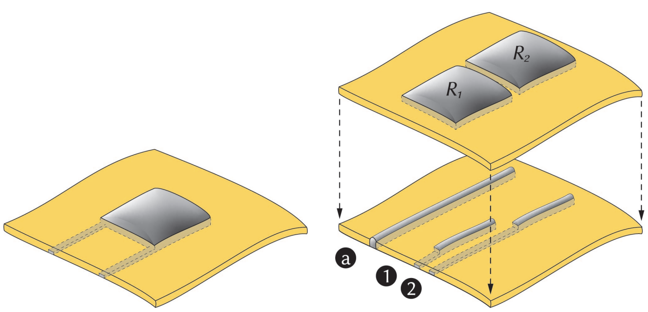


Figure 6: *Two ways provided in KnitUI for connecting knitted sensors with conductive traces:* *left, for the single sensing unit, the conductive traces are knitted on the backside; right, due to the limited space, conductive traces are knitted on a separated fabric for designs with multiple sensing units. Conductive yarn is knitted on the bottom layer for the connection on the side but is only knitted around the contact area (with the sensing unit) on the top layer to avoid shorting.*

4.3 Readout Circuit Design

To read the pressure from our knitted sensors, we design an electrical-grounding-based circuit to reduce the crosstalk and parasitic effect of the passive sensing matrix [5]. The design is shown in Fig. 7. A reference voltage V_{ref} (2.5 V) is applied to each column (labelled with letters). Controlled by the single-pole double-throw (SPDT) switches, each sensor is grounded one by one with V_0 (0 V) at the horizontal line (labeled with numbers) while all other lines are maintained at V_{ref}. The voltage difference across all lines except the measuring one is maintained at 0 V to isolate the signals. An analog switch is used as a multiplexer to raster through the columns one by one, and an amplifier is added to each column, the gain of which can be tuned by the feedback resistor R_g (20 $k\Omega$ by default). A capacitor of C_g (10 μF) is added in parallel with each feedback resistor to reduce noise. An Arduino Nano controls the SPDT switches and the analog switch. Each measurement is then transformed into a 10-bit digital signal and transmitted serially to a computer.

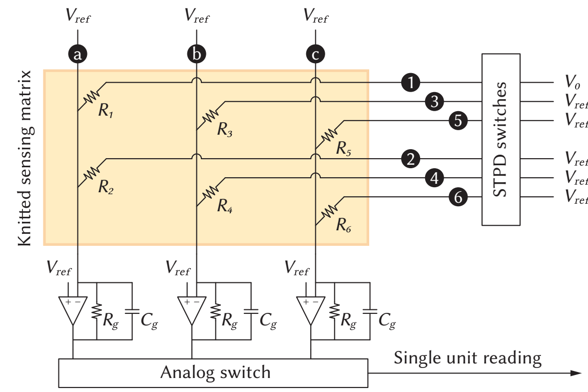


Figure 7: *The modified electrical-grounding-based isolation circuit architecture for passive sensing array readout.*

5 DESIGN PIPELINE

Our system allows users to design knitted patches with sensors in different shapes and colors, along with the corresponding knitted connection traces. In this section, we illustrate our user design interface and typical workflow for creating a KnitUI. We will also describe how our framework generates low-level machine instructions from a given design.

5.1 Design Interface and Workflow

Our design interface is built on Stitch Meshes [48], where the knitting structure is abstracted as a quad mesh. However, our system differs from the original paper in that each quad represents a pair of stitches on the front and back beds. Users are allowed to mark each individual quad with different types. In particular, our design system supports the following four types:

- *Normal stitch*, the base structure to build the patch; it is knitted using the Jacquard technique to create two layered interlocking structure with standard acrylic yarns.
- *Sensor stitch*, knitted in two separated layers, where the front layer uses the plating technique to combine standard acrylic yarn and conductive yarn, and the back layer only uses conductive yarn but with extra short-rows on the backside.
- *Contact stitch*, the interlocking structure knitted with conductive yarn in the electrical trace patches; this stitch integrates the conductive short-rows to connect the sensing units with the readout circuit.
- *Trace stitch*, knitted with two separated layers, where the front layer uses standard acrylic yarn to prevent shorting, and the back layer uses conductive yarn to create conductive traces.

Here is the workflow when the user wants to create a knitted functional sensing patch:

#1 Create a sketch patch. The user starts by creating a sketch patch with specified width and height, as shown in Fig. 8. Each quad represents one stitch and is marked as a normal stitch by default. Stitch types are marked in different colors. Then, the user can design a pattern by labeling faces.

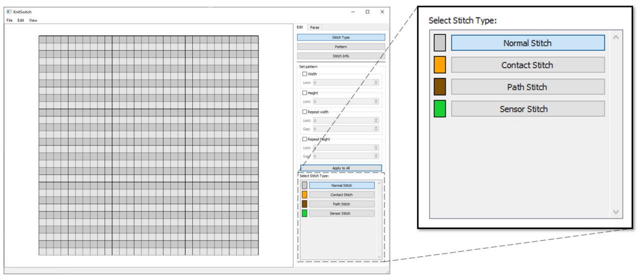


Figure 8: *Our interactive design interface:* *left, the sketch where users can paint with different stitch types, where each face represents one stitch; right, the selection area that users can choose current stitch types for painting.*

#2 Label patterns. Our system provides several convenience tools to help the user label individual faces or sets of faces, as illustrated in Fig. 9.

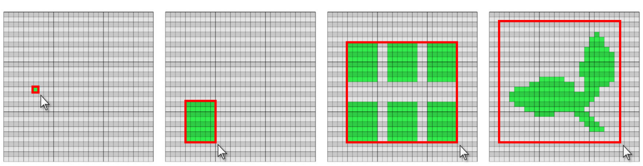


Figure 9: *Labeling tools:* *(from left to right) labeling individual face, labeling a block of faces, labeling repeated blocks, and labeling faces with input bitmask.*

#3 Select yarns and number of short-rows. The user is allowed to specify the types of yarns for each pattern. For instance, if sensor stitches are knitted with the same yarn that knits normal stitches, only one standard yarn needs to be determined. Otherwise, the user needs to choose extra yarn to determine the color of the sensors. Similarly, the number of short-rows can be specified by the user, too. In practice, we set 2 conductive short-rows as default because it provides the best sensing performance. We will discuss the characterization of choosing the number of conductive short-rows in the next section.

The same flow can be used to design the knitted trace. Note that the knitted patch with sensors is not required to have the same size or shape as the patch of traces. This provides more flexibility for users to integrate KnitUI with existing knitting designs, *e.g.*, interactive glove controller (Fig. 15) and robot skin (Fig. 20).

Fig. 10 shows an example of a number pad (Numpad) designed using our system, where each sensing unit is designed in a number shape. Since units are close to each other, there isn't enough space to create knitted electronic paths in a single fabric patch. Hence, we design the conductive traces on another patch. The sensors are divided into five rows, and each row has two sensors. In the traces patch, all sensors in the same row are connected to a trace entirely with contact stitches. Each sensor is then connected to a separated trace in which only the connection area uses contact stitches, and the rest of the path uses path stitches.

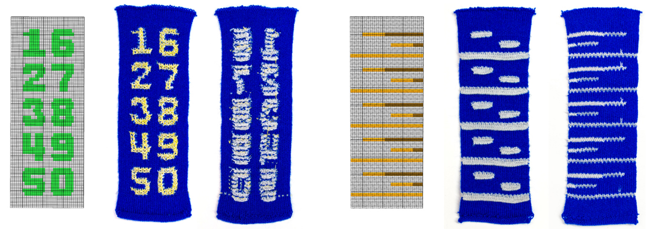


Figure 10: *An example of Numpad designed by KnitUI interface:* *left, the patch with 10 separated sensors (the front and back of the corresponding knitted result), and right, the design of knitted traces to connect the sensors with the readout circuit and the corresponding fabricated result.*

5.2 Knitting Instructions Generation

Since our structure leverages Jacquard knitting and plating techniques with two types of yarns, the designs must be converted into machine instructions accordingly. The knitting instruction generation is divided into three steps:

- *trace* the sketch patch to generate a knitting path;
- *schedule* needles to perform the knitting instructions for each stitch;
- *output* the .knitout [21] file based on the knitting path and scheduled needle locations.

Most of our stitches – normal, contact, and sensor stitches – need to be traced twice. For normal and contact stitches, this is due to the Jacquard structure, which must knit on all needles of both beds. To avoid needle collisions, only the odd-numbered front needles and the even-numbered back needles perform knitting during the forward pass; the remaining needles activate during the carrier's backward pass. For the sensor stitches, all front-bed needles knit during the forward step, and back-bed needles knit on the backward pass. All of the sensor stitches use both standard and conductive yarns. Unlike others, path stitches are only traced once because it knits the standard yarn on the front needles and the conductive yarn on the back needles.

Note that our method also allows users to knit conductive traces on the typical single layer knitted surface, though it requires identical paired adjacent rows to create the continuous knitting path. This enables the integration of conductive traces in any existing knitting design by adding a pair of conductive short-row in the specified location.

6 MATERIALS AND CHARACTERIZATION

We fabricate our knitted sensors with an industrial v-bed knitting machine (*SWG091N_2*, Shima Seiki) and characterize it as an electric

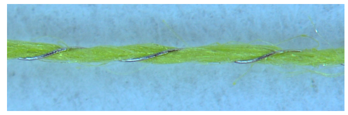
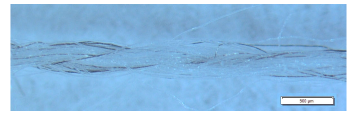
Conductive yarn		Type 1	Type 2	Type 3
Microscope image				
Materials		Stainless steel 100%	Stainless steel 35% Silk 65%	Stainless steel 20% Polyester 80%
Thickness (μm)		450	180	300
Resistance (Ω/m)		30	700	4000
ON	Mean ($k\Omega$)	0.021	19.3	64.7
	STD ($k\Omega$)	0.002	19.8	13.3
OFF	Mean ($k\Omega$)	0.549	9.9e6	533
	STD ($k\Omega$)	0.107	< 0.001	42.9

Table 1: *The characteristics of different conductive yarns and the performance profile of the typical sensing units fabricated with each of them.*

switch and a tactile sensor unit, respectively. The resistance profiles are measured with a digital multimeter (DMM 4050, Tektronix), while an adjustable normal force is applied to the fabricated sensing unit by a mechanical testing system (Instron 5944).

6.1 Electrical Switch

We first place knitted sensing structure on conductive traces and characterize our device as an electric switch, which is only evaluated by the discriminative capability between the "ON" and "OFF" states. The resistance is measured when a load of 0 kPa and 17.5 kPa is applied to specify the "OFF" and "ON" states, respectively. We investigate the performance of sensing units fabricated with various types of conductive yarns, different numbers of conductive short-rows on the backside, and different sensor sizes. Finally, we demonstrate the robustness of our sensing units by evaluating their performance after a set of regular washing and drying cycles.

Conductive yarns. Our proposed knitting structure is functional with standard off-the-shelf conductive yarns. To evaluate how the characteristics of different conductive yarns impact the sensing performance, we knit sensing units with 28×28 stitches and two backside short-rows using three different commercial conductive yarns. The characteristics of yarns and the performance evaluations are listed in Table 1. The first conductive yarn (type 1) is made of 100% stainless steel and thus has high conductivity; however, the sensor resistance is too small ($\ll 1\ k\Omega$) for the readout circuit to capture the difference when pressure is applied. Besides material composition, the sensing performance highly depends on the yarn structure. For instance, Yarn 2 is made by intertwining a single stainless steel fiber with silk fibers. As shown in the first row of Table 1, the conductive component is only exposed to the exterior in a small region. This structure restricts the stable interactions between the conductive yarns within the knitted sensing unit, leading to a significant variation in the resistance at the "ON" state. On the other hand, Yarn 3 is made of short steel fibers mixed with polyester. It obtains higher unit resistance (4 $k\Omega$) due to the lower conductive composition percentage. However, compared with the intertwined structure of Yarn 2, the conductive composition in Yarn 3 is distributed throughout the yarn volume more homogeneously, which provides uniform and reliable electrical contacts among the conductive yarns when the unit is compressed. Therefore, we use Yarn 3 in the rest of the paper because of its reasonable resistance range and response variations.

Number of short-rows. Conductive short-rows on the backside of the sensing unit can improve the electrical contact. Here, we evaluate the performance of sensing units (28×28 stitches) with 0, 2, and 4 backside conductive short-rows. As shown in Fig. 11 left, with no conductive short-rows, only a small amount of conductive yarn is embedded in the sensing unit; this causes the electrical interactions to be unstable. Therefore, the resistance is relatively high with significant variation in both "ON" and "OFF" states. In contrast, with more short-rows, the sensing unit demonstrates lower resistance. This is expected because more conductive yarns are integrated, enabling more extensive potential electrical contacts. However, integrating with too many short-rows also reduces the resistance difference between the "ON" and "OFF" states. The crowded conductive yarns consistently interact with each other to some extent, even when no physical perturbation is applied. This increases the undesirable false-positive detection rate. Hence, to achieve a well-distinguished resistance gap between "ON" and "OFF" states with low variance, we use the design of two short-rows for the rest of the paper.

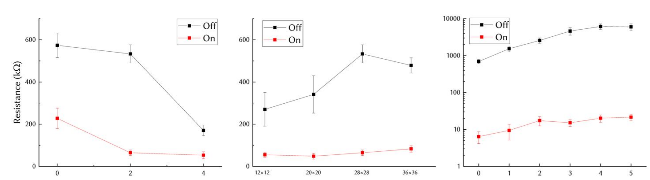


Figure 11: *Resistance at the "ON" and "OFF" states of the sensors fabricated with different number of short-rows (left), sensing size (middle), and washing cycles (right).*

Size of sensing unit. We also measure the performance of sensors of different sizes. To be specific, we knit and measure the resistance profiles of sensing units with 12×12, 20×20, 28×28, and 36×36 stitches, respectively. The actual physical size of the sensor with 12×12 stitches is $17\ mm \times 15\ mm$. As shown in Fig. 11 middle, all of them maintain reasonable resistance differences between two states with low variations. A clear threshold between the "ON" and "OFF" states can be retrieved at the resistance of $150\ k\Omega$.

Washing test. Like other knitted daily goods, our sensors are also washable. We perform a washing test with an industrial washing machine (*GFWN1600J1WW*, GE Appliances) and gas dryer (*GFD45ESSK0WW*, GE Appliances). Each washing cycle lasts for 52 mins in the delicate mode with liquid laundry detergent (Tide), and laundry sanitizer (Lysol), and each drying cycle lasts for 60 mins in the *delicate* mode. After each washing cycle, we measure the resistances of the sensing unit at the "ON" and "OFF" states. Fig. 11 right shows that the resistance slightly increases in both states but remains stable after the third cycle. The interlocked structures of the conductive yarn get disturbed by the first few washing (and drying) cycles but become stable eventually. Most importantly, even after our washing tests, the sensing unit remains fully functional, with a significant resistance difference and a small variation at the two states.

Performance under deformation. We investigate the influence of deformation by measuring the sensing unit' at "OFF" state under different levels of bending and stretching. Due to the anisotropy of the knitting structures, we perform the characterization along with the wale and course directions, respectively. Generally, as demonstrated in Fig. 12 (left and middle), the sensing unit's resistance drops under deformation because the electrical contacts among the knitted conductive yarns increases during bending and stretching. In the worst case, the sensor ensures the largest resistance drops from $420\ k\Omega$ to $160\ k\Omega$ to $38\ k\Omega$ under 40% strain along the course direction. To demonstrate the usability of our device under large deformation, we evaluate the performance of a sensing unit under 40% strain along the course direction (Fig. 12 right); The signal under the increasing pressure from $0\ kPa$ to $17.5\ kPa$ is still detectable with a 10-fold change in magnitude, with the resistance drops from $38\ k\Omega$ to $0.7\ k\Omega$. It is also worth noting that knits are usually used as conformal coverings so that we wouldn't expect KnitUI under large deformation in real usability scenarios.

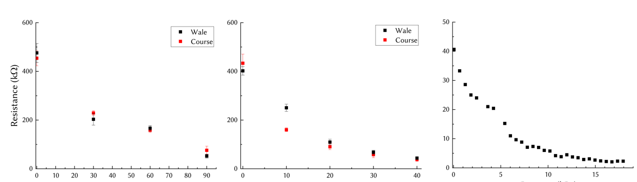


Figure 12: *Resistance of a sensor at the "OFF" states of the sensors under bending (left) and stretching (middle). The resistive profile of a sensor under 40% strain along the course direction in response to the applied pressure (right).*

6.2 Tactile Sensor

Lastly, we characterize our 28×28-stitch sensing units as tactile sensors. Fig. 13 shows that the resistance profile of a typical sensing unit under continuously increasing and decreasing of applied pressure. The resistance drops from $190\ k\Omega$ to $25\ k\Omega$ in response to a continuously increasing applied pressure from $0\ kPa$ to $17.5\ kPa$. The peak hysteresis is around 16%. Among six tests on the same sensing unit, when the applied pressure is small, resistance variation is inevitable due to the flexibility of the knitted fabric and the local movement of the layered structures. This artifact is alleviated eventually when the applied pressure increases. It is worth noting that the response variation can be compensated easily by deploying current machine learning techniques. We will show a few applications in tactile sensing in the next section.

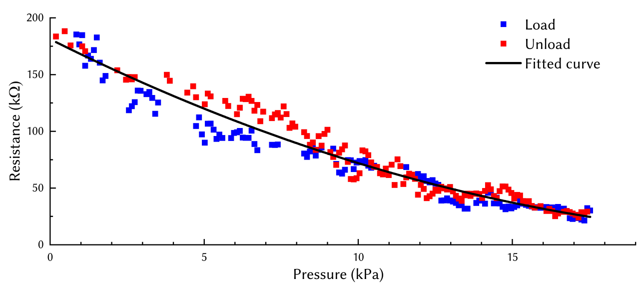


Figure 13: *Continuous resistance profile of a typical knitted sensing unit in response to the load and unload of pressure*

7 EXAMPLE APPLICATIONS

In this section, we demonstrate our interactive and sensing textiles with a diverse set of applications, including interactive textiles, tactile sensing wearables, and artificial robot skin.

7.1 Interactive Textiles

KnitUI provides an entirely knitted interface that is soft, washable, and ecofriendly. More importantly, it allows users to customize the color and shapes of each sensing unit and interface. All the mentioned features make KnitUI perfect for early education toys. Here, we present four knitted patches with diverse graphic designs (Fig. 14). In particular, each patch contains two sensing units for children's interactive learning. For example, the "apple" patch contains two sensing units in the "apple" and "leaf" regions, respectively; the corresponding word will be pronounced when the sensing units are pressed. As shown in Fig. 14 right, the coupled conductive traces are integrated on the backside of the same fabric with the sensing units, which enables the simple and removable electrical connection to the readout circuit.

KnitUI can be used as a soft controller. Fig. 15 demonstrates the user plays "Snake" game using our knitted controller. Since there are three sensing units aligned in the same row, instead of knitting the conductive traces in the same patch as the sensing units, we knit a separate patch to connect to the readout circuit. Both the sensing and connection patch are knitted fully automatically. Electrical connections are created by stacking the two patches together.

Figure 14: ***Interactive educational toys:*** *(from left to right) the front and back of "Apple", "Flower", "Cloud and Sun", and "Shark and Jellyfish".*

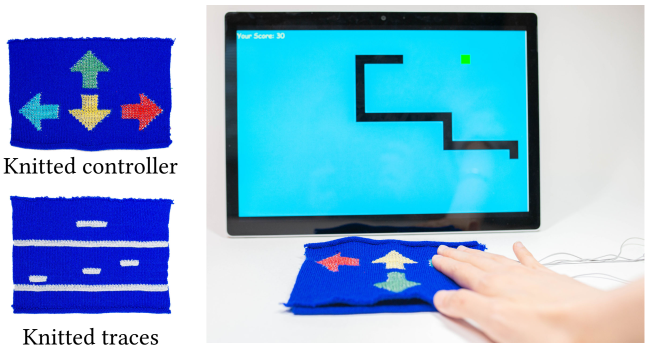


Figure 15: *Playing "Snake" game using our knitted controller.*

Fig. 10 shows an interactive number pad input interface in the form of wrist wrap. The interactive wrist wrap is composed of two separate textiles with the sensing units and coupled electrical traces. Each sensor is in the shape of a number, which provides visual guidance for the users.

Thanks to the recently introduced whole garment digital knitting machine, the fabrication of whole garments with complex geometries, *e.g.*, gloves and apparel, can be realized without further manual cutting and sewing. These garments are fully customizable and can be adapted to individual shape, size, surface texture, and color preferences, meeting the needs of personalization and fashion design. KnitUI can be integrated into a whole garment seamlessly, which enriches the interactive modalities and broadens the application scenarios of KnitUI. We demonstrate an example on the daily human goods with the most complex geometry – glove, in Fig. 16. The interactive glove is composed of a patch with the sensing units of desired shapes and colors and a full-sized glove embedded with electrical traces at specific locations. The full-sized glove is designed by adapting the existing design (Shima Seiki) through *KnitPaint* [35]. This design process reiterates the straightforward design transfer to an existing complex knitting design using our method, which maximizes the usage of existing designs and boosts design efficiency. Moreover, the double-layer structure offers an opportunity to use the same glove in conjunction with multiple sensing units designed for different applications. Here, the interactive glove can be used for either direction indications or music control, just by switching the directional pad to the other designed controller pad, respectively.

Figure 16: ***Glove controller:*** *left, conductive traces are added to existing knitted glove design; middle and right, glove with different controller designs.*

7.2 Tactile Sensing Wearable

KnitUI can be further used as tactile sensing wearables for recording, monitoring, and learning on physical human-environment interactions. As a proof of concept, we present a pair of socks (Fig. 17), each of which contains a 2×5 sensing array, to capture the real-time tactile information when the wearer performs a diverse set of actions. A deep neural network is trained to classify the wearer's actions given sequential sensing data as input. Specifically, we use the Temporal Convolutional Network (TCN) [4], a benchmarking network, and one of the most widely used ones for the sequential modeling tasks. To train the TCN, we collect a training dataset (5400 tactile frames) that includes actions of *stand*, *lean left (left)*, *lean right (right)*, *stand on toes (toes)*, *sit,* and *walk* (Fig. 18). The training details primarily follow the settings in the original paper of Bai et al. [4], except that we set the number of input channels to 20, the total number of input sensors. The training converges in 20 epochs.

Figure 17: *Tactile sensing socks*

After obtaining the trained TCN model, we test its predictions on real-time recordings with randomly ordered types of actions (3000 tactile frames). The confusion matrix of this test is shown in Fig. 19. As illustrated, the trained TCN model achieves a 91.8% top-1 classification accuracy. The network prediction is stable and accurate in each action; most of the error frames are from the transitions between actions. By excluding 30 frames at each action transition,

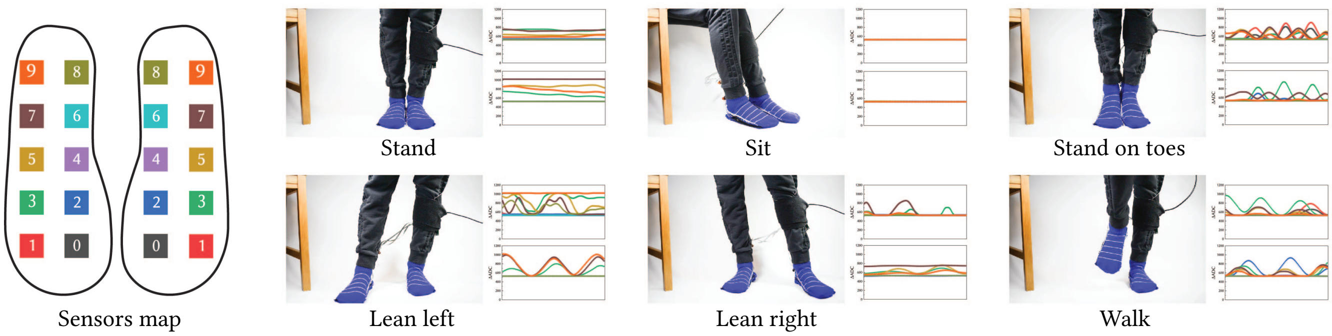


Figure 18: *Sensor map and the corresponding pressure signals during six actions*

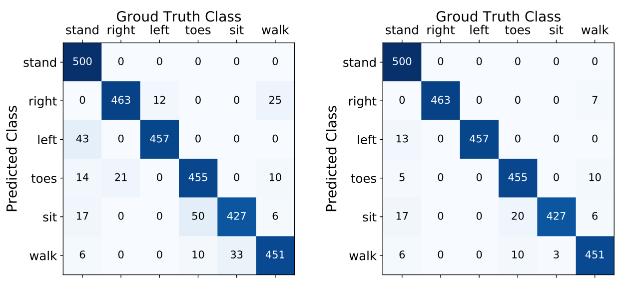


Figure 19: ***Confusion Matrix:*** *left, result on test data of whole 3,000 frames; right, result on test data excluding 30 frames at each action transition*

the top-1 classification accuracy achieves 96.8%. The overall results demonstrate the ability of our knitted sensing wearables to identify human actions. Facilitated by powerful deep networks, KnitUI exhibits a strong potential for learning and analyzing complicated human-environment interactions.

7.3 Artificial Robot Sensing Skin

Unlike humans, modern robots lack tactile feedback; touch sensors have been demonstrated as a critical step towards the promotion of physical human-robot interactions and the improvement of robot manipulation. However, it is still challenging to obtain a 3D conformal soft robot skin. In this work, we demonstrate that KnitUI can produce full-sized soft conformal robot skins, which are light, inexpensive, customizable, and easy-to-manufacture. This capability will facilitate physical human-robot interactions through collision detection and real-time tactile sensing. As shown in Fig. 20, We present a full-sized conformal sensing sleeve for a commercial robot arm (a link with a dimension of 50 $cm \times 20\ cm \times 20\ cm$, LBR iiwa, KUKA). The artificial robot skin is composed of two parts: individual patches with sensing units and a conformal robot arm covering with integrated conductive traces. The machine knitting instructions for the conformal covering is generated from the KUKA arm mesh directly using Stitch Meshes [25, 45]. By placing individual sensing units at desired locations, we endow the robot arm with real-time tactile feedback. Since our sensors are knitted separately, we can easily adjust the densities and positions of individual sensing units along the conductive traces to perform recordings at desired spots over the robotic arm surface. Our method demonstrates the potential for applications in unobtrusive tactile sensing, multi-point collision detection for robot manipulation and control, and physical human-robot interaction.

8 DISCUSSION AND FUTURE WORK

Comparison with previous works. The closest work to ours is SensorKnit [27], which demonstrates various textile sensors using diverse knitted textures and patterns with conductive yarns. However, it still requires manually injecting nonconductive polyester for stable, optimized capacitive sensing performance. Inspired by SensorKnit, KnitUI utilizes sophisticated knitting techniques to fully automatically create resistive sensing structures with inexpensive conductive yarns. Another close work is from [39, 40] and their sensing structure is a pure Jacquard knitted structure; we not only use a Jacquard structure for the knitted trace structure but also use short-rows to improve the connectivity. Beyond knitted traces, our proposed two-layered sensing structure builds pressure sensor matrices, where the signal from each sensor is serialized independently. Such structure enables robust sensing on multi-touch and the localization of each of the interactions. Furthermore, Vallet's works rely on capacitive sensing, while ours is based on resistive sensing, which requires a simpler readout circuit design. Compared to the closest work on resistive knitted strain sensors [3, 27] (although these works do not use resistive knitted pressure sensors), our device obtains a larger range of resistance change (10 fold) thanks to our layered structures. However, the double-layer structure also

Figure 20: ***Kuka with knitted sensing covering:*** *grey is the conductive yarn and red rectangles are sensors.*

introduces a larger standard deviation compared to the related work. Compared with previous works, KnitUI has the following advantages in general: first, the sensing units can be created fully automatically using the knitting machine and only require minimal manual assembly with coupled knitted conductive traces; second, KnitUI can be easily integrated into existing knitting garment design; last, we provide an interactive interface for users to design KnitUI with various shapes, colors, sizes, and geometries, and the design can be converted into machine instructions automatically.

Limitations. Due to the thickness of yarn and the knitting mechanism, the minimum size for a knitted sensor that can produce stable sensing is limited to 2 to 3 stitches (5*mm* width). Although our digital knitting machine enables knits of up to 90*cm*, sensor performance degrades with too-small or too-large sensing units. Also, KnitUI relies on the interactions among the integrated conductive yarns, whose performance variation is unavoidable due to the softness and flexibility of the knitted textiles and the double-layered structure. Therefore, it is vital to record a training dataset coupled with machine learning techniques for reliable quantitative measurement extraction.

Future work. It would be interesting to explore more sensing modalities (*e.g.*, capacitive sensing) using versatile knitted sensor structures and functional fibers in the future. We would also like to embed the current system into the existing functional knitted textiles for multimodal capabilities. For example, integrating KnitUI with the actuation platform presented by Albaugh et al. [2] as a soft sensing skin will open up possibilities in soft robotics control.

9 CONCLUSION

We presented KnitUI, a knitted interactive and sensing user interface based on resistive pressure sensing. KnitUI offers a user interface that is deformable, portable, breathable, washable, robust, and lightweight. This is useful in a wide range of application spaces, including education, entertainment, tactile sensing, and human-robot interaction. KnitUI builds on a machine knitted double-layered structure using conventional yarns and conductive yarns. KnitUI also includes a machine knitted conductive trace design, which allows users to connect the sensor with a read-out circuit quickly with minimal manual post-processing. The resulting knitted fabrics can be integrated with any existing knitted garment designs easily. We also presented an interactive design interface for users to customize the sensor's shape. We performed characterization and evaluation of the impact of various design variables for the sensor, including sensor sizes, number of conductive rows, and the types of conductive yarns. We demonstrated several example applications of KnitUI, including interactive textiles, tactile sensing wearable, and artificial robot skin. We believe KnitUI opens up possibilities in endowing everyday objects with sensing capability at a low cost by bridging the gap between interactive textile and industrial-scale manufacturing.

ACKNOWLEDGMENTS

We thank Alexandre Kaspar for the insightful discussions and Liane Makatura for proofreading. We also thank Minghao Guo for helping with the data training.

REFERENCES

[1] Roland Aigner, Andreas Pointner, Thomas Preindl, Patrick Parzer, and Michael Haller. 2020. Embroidered Resistive Pressure Sensors: A Novel Approach for Textile Interfaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13.

[2] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. ACM, New York, NY, USA, Article VS01, 1 pages.

[3] Ozgur Atalay, Asli Atalay, Joshua Gafford, and Conor Walsh. 2018. A highly sensitive capacitive-based soft pressure sensor based on a conductive fabric and a microporous dielectric layer. *Advanced Materials Technologies* 3, 1 (2018), 1700237.

[4] Shaojie Bai, J. Zico Kolter, and Vladlen Koltun. 2018. An Empirical Evaluation of Generic Convolutional and Recurrent Networks for Sequence Modeling. *arXiv:1803.01271* (2018).

[5] Tommaso D'Alessio. 1999. Measurement errors in the scanning of piezoresistive sensors arrays. *Sensors and Actuators A: Physical* 72, 1 (1999), 71–76.

[6] Jun Gong, Yu Wu, Lei Yan, Teddy Seyed, and Xing-Dong Yang. 2019. Tessutivo: Contextual Interactions on Interactive Fabrics with Inductive Sensing. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 29–41.

[7] Jun Gong, Xin Yang, Teddy Seyed, Josh Urban Davis, and Xing-Dong Yang. 2018. Indutivo: Contact-Based, Object-Driven Interactions with Inductive Sensing. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. 321–333.

[8] Nur Al-huda Hamdan, Jeffrey R. Blum, Florian Heller, Ravi Kanth Kosuru, and Jan Borchers. 2016. Grabbing at an Angle: Menu Selection for Fabric Interfaces. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers* (Heidelberg, Germany) *(ISWC '16)*. Association for Computing Machinery, New York, NY, USA, 1–7.

[9] Nur Al-huda Hamdan, Simon Voelker, and Jan Borchers. 2018. Sketch & Stitch: Interactive Embroidery for E-Textiles *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13.

[10] Min-Woo Han and Sung-Hoon Ahn. 2017. Blooming Knit Flowers: Loop-Linked Soft Morphing Structures for Soft Robotics. *Advanced Materials* 29, 13 (2017), 1606580.

[11] Christian Harito, Listya Utari, Budi Riza Putra, Brian Yuliarto, Setyo Purwanto, Syed ZJ Zaidi, Dmitry V Bavykin, Frank Marken, and Frank C Walsh. 2020. The Development of Wearable Polymer-Based Sensors: Perspectives. *Journal of The Electrochemical Society* 167, 3 (2020), 037566.

[12] Gerard J Hayes, Ying Liu, Jan Genzer, Gianluca Lazzi, and Michael D Dickey. 2014. Self-folding origami microstrip antennas. *IEEE Transactions on Antennas and Propagation* 62, 10 (2014), 5416–5419.

[13] Megan Hofmann, Lea Albaugh, Ticha Sethapakadi, Jessica Hodgins, Scott E. Hudson, James McCann, and Jennifer Mankoff. 2019. KnitPicking Textures: Programming and Modifying Complex Knitted Textures for Machine and Hand Knitting. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 5–16.

[14] Cedric Honnet, Hannah Perner-Wilson, Marc Teyssier, Bruno Fruchard, Jürgen Steimle, Ana C. Baptista, and Paul Strohmeier. 2020. PolySense: Augmenting Textiles with Electrical Functionality Using In-Situ Polymerization. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13.

[15] Alexandre Kaspar, Liane Makatura, and Wojciech Matusik. 2019. Knitting Skeletons: A Computer-Aided Design Tool for Shaping and Patterning of Knitted Garments. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 53–65.

[16] Konstantin Klamka, Raimund Dachselt, and Jürgen Steimle. 2020. Rapid Iron-On User Interfaces: Hands-on Fabrication of Interactive Textile Prototypes. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14.

[17] Pin-Sung Ku, Qijia Shao, Te-Yen Wu, Jun Gong, Ziyan Zhu, Xia Zhou, and Xing-Dong Yang. 2020. ThreadSense: Locating Touch on an Extremely Thin Interactive Thread. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12.

[18] Joanne Leong, Patrick Parzer, Florian Perteneder, Teo Babic, Christian Rendl, Anita Vogl, Hubert Egger, Alex Olwal, and Michael Haller. 2016. ProCover: Sensory Augmentation of Prosthetic Limbs Using Smart Textile Covers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY,

USA, 335–346.

[19] Jenny Lin, Vidya Narayanan, and James McCann. 2018. Efficient Transfer Planning for Flat Knitting. In *Proceedings of the 2Nd ACM Symposium on Computational Fabrication* (Cambridge, Massachusetts) *(SCF '18)*. ACM, New York, NY, USA, Article 1, 7 pages.

[20] Takuya Maekawa, Yasue Kishino, Yutaka Yanagisawa, and Yasushi Sakurai. 2012. Recognizing handheld electrical device usage with hand-worn coil of wire. In *International Conference on Pervasive Computing*. Springer, 234–252.

[21] James McCann. 2017. The "Knitout" (.k) File Format. [Online]. Available from: https://textiles-lab.github.io/knitout/knitout.html.

[22] James McCann, Lea Albaugh, Vidya Narayanan, April Grow, Wojciech Matusik, Jennifer Mankoff, and Jessica Hodgins. 2016. A Compiler for 3D Machine Knitting. *ACM Trans. Graph.* 35, 4, Article 49 (July 2016), 11 pages.

[23] J. Meyer, B. Arnrich, J. Schumm, and G. Troster. 2010. Design and Modeling of a Textile Pressure Sensor for Sitting Posture Classification. *IEEE Sensors Journal* 10, 8 (Aug 2010), 1391–1398.

[24] Vidya Narayanan, Lea Albaugh, Jessica Hodgins, Stelian Coros, and James Mccann. 2018. Automatic Machine Knitting of 3D Meshes. *ACM Trans. Graph.* 37, 3, Article 35 (Aug. 2018), 15 pages.

[25] Vidya Narayanan, Kui Wu, Cem Yuksel, and James McCann. 2019. Visual knitting machine programming. *ACM Transactions on Graphics (TOG)* 38, 4 (2019), 1–13.

[26] Maggie Orth, Joshua R Smith, E Rehmi Post, JA Strickon, and Emily B Cooper. 1998. Musical jacket. In *ACM SIGGRAPH 98 Electronic art and animation catalog*. 38.

[27] Jifei Ou, Daniel Oran, Don Derek Haddad, Joseph Paradiso, and Hiroshi Ishii. 2019. SensorKnit: Architecting textile sensors with machine knitting. *3D Printing and Additive Manufacturing* 6, 1 (2019), 1–11.

[28] Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner, Siegfried Bauer, and et al. 2018. RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 745–756.

[29] Patrick Parzer, Adwait Sharma, Anita Vogl, Jürgen Steimle, Alex Olwal, and Michael Haller. 2017. SmartSleeve: Real-Time Sensing of Surface and Deformation Gestures on Flexible, Interactive Textiles, Using a Hybrid Gesture Detection Pipeline. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 565–577.

[30] Andreas Pointner, Thomas Preindl, Sara Mlakar, Roland Aigner, and Michael Haller. 2020. Knitted RESi: A Highly Flexible, Force-Sensitive Knitted Textile Based on Resistive Yarns. In *ACM SIGGRAPH 2020 Emerging Technologies* (Virtual Event, USA) *(SIGGRAPH '20)*. Association for Computing Machinery, New York, NY, USA, Article 21, 2 pages.

[31] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson. 2016. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 4216–4227.

[32] M. Rofouei, W. Xu, and M. Sarrafzadeh. 2010. Computing with uncertainty in a smart textile surface for object recognition. In *2010 IEEE Conference on Multisensor Fusion and Integration*. 174–179.

[33] Stefan Schneegass and Alexandra Voit. 2016. GestureSleeve: Using Touch Sensitive Fabrics for Gestural Input on the Forearm for Controlling Smartwatches. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers* (Heidelberg, Germany) *(ISWC '16)*. Association for Computing Machinery, New York, NY, USA, 108–115.

[34] Maximilian Sergio, Nicolo Manaresi, Marco Tartagni, Roberto Guerrieri, and Roberto Canegallo. 2002. A textile based capacitive pressure sensor. In *SENSORS, 2002 IEEE*, Vol. 2. IEEE, 1625–1630.

[35] Shima Seiki. 2011. SDS-ONE Apex3. [Online]. Available from: http://www.shimaseiki.com/product/design/sdsone_apex/flat/.

[36] Matteo Stoppa and Alessandro Chiolerio. 2014. Wearable electronics and smart textiles: a critical review. *sensors* 14, 7 (2014), 11957–11992.

[37] Zhenhua Tang, Shuhai Jia, Si Shi, Fei Wang, and Bo Li. 2018. Coaxial carbon nanotube/polymer fibers as wearable piezoresistive sensors. *Sensors and Actuators A: Physical* 284 (2018), 85–95.

[38] Jenny Underwood. 2009. *The design of 3D shape knitted preforms.* Ph.D. Dissertation. Fashion and Textiles, RMIT University.

[39] Richard Vallett, Denisa Qori McDonald, Genevieve Dion, Youngmoo Kim, and Ali Shokoufandeh. 2020. Toward Accurate Sensing with Knitted Fabric: Applications and Technical Considerations. *Proc. ACM Hum.-Comput. Interact.* 4, EICS, Article 79 (June 2020), 26 pages.

[40] Richard Vallett, Ryan Young, Chelsea Knittel, Youngmoo Kim, and Genevieve Dion. 2016. Development of a Carbon Fiber Knitted Capacitive Touch Sensor. *MRS Advances* 1, 38 (2016), 2641–2651. https://doi.org/10.1557/adv.2016.498

[41] Nicolas Villar, Daniel Cletheroe, Greg Saul, Christian Holz, Tim Regan, Oscar Salandin, Misha Sra, Hui-Shyong Yeo, William Field, and Haiyan Zhang. 2018. Project Zanzibar: A Portable and Flexible Tangible Interaction Platform. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, Article 515, 13 pages.

[42] Edward J Wang, Tien-Jui Lee, Alex Mariakakis, Mayank Goel, Sidhant Gupta, and Shwetak N Patel. 2015. Magnifisense: Inferring device interaction using wrist-worn passive magneto-inductive sensors. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. 15–26.

[43] Mark Weiser. 1999. The Computer for the 21st Century. *SIGMOBILE Mob. Comput. Commun. Rev.* 3, 3 (July 1999), 3–11.

[44] Irmandy Wicaksono, Carson I Tucker, Tao Sun, Cesar A Guerrero, Clare Liu, Wesley M Woo, Eric J Pence, and Canan Dagdeviren. 2020. A tailored, electronic textile conformable suit for large-scale spatiotemporal physiological sensing in vivo. *npj Flexible Electronics* 4, 1 (2020), 1–13.

[45] Kui Wu, Xifeng Gao, Zachary Ferguson, Daniele Panozzo, and Cem Yuksel. 2018. Stitch Meshing. *ACM Trans. Graph. (Proceedings of SIGGRAPH 2018)* 37, 4, Article 130 (jul 2018), 14 pages.

[46] Kui Wu, Hannah Swan, and Cem Yuksel. 2019. Knittable Stitch Meshes. *ACM Trans. Graph.* 38, 1, Article 10 (Jan. 2019), 13 pages.

[47] W. Xu, M. Huang, N. Amini, L. He, and M. Sarrafzadeh. 2013. eCushion: A Textile Pressure Sensor Array Design and Calibration for Sitting Posture Analysis. *IEEE Sensors Journal* 13, 10 (Oct 2013), 3926–3934.

[48] Cem Yuksel, Jonathan M. Kaldor, Doug L. James, and Steve Marschner. 2012. Stitch Meshes for Modeling Knitted Clothing with Yarn-level Detail. *ACM Trans. Graph. (Proceedings of SIGGRAPH 2012)* 31, 3, Article 37 (2012), 12 pages.