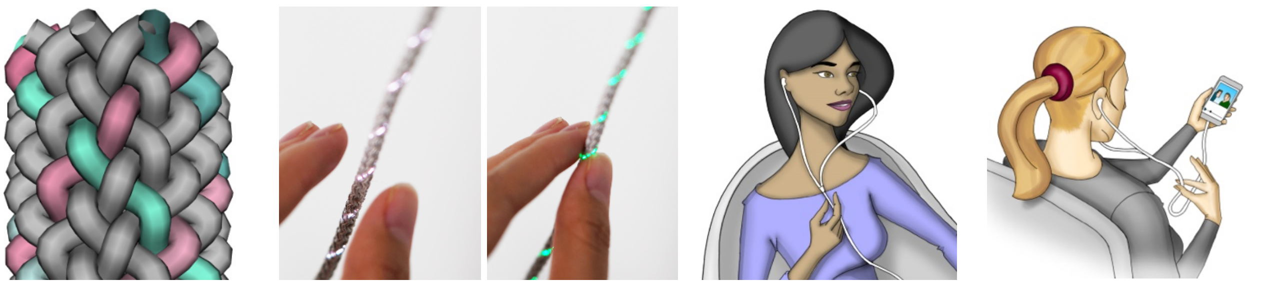
I/O Braid: Scalable Touch-Sensitive Lighted Cords Using Spiraling, Repeating Sensing Textiles and Fiber Optics

Alex Olwal **Jon Moeller** **Greg Priest-Dorman** **Thad Starner** **Ben Carroll**

Interaction Lab, Google Inc.
Mountain View, CA 94043, USA
{ olwal, moellerj, gregpd, thadstarner, bencarroll } @ google.com



a) Scalable Topology **b) Hover (white)** **c) Touch (green)** **d) Touch, tap and grab** **e) Rotation**

Figure 1. a) I/O Braid with spiraling capacitive sensing lines forms repeating 3×3 sensing matrices. b) Braided fiber optics allows integrated lighting. c) Visuals serve as feedback with intensity and color. d) I/O Braid is suitable for eyes-free interactions, as it allows rich gesture input anywhere along the cord. e) Besides touch sensing, the topology provides a robust rotation mechanism.

ABSTRACT
We introduce I/O Braid, an interactive textile cord with embedded sensing and visual feedback. I/O Braid senses proximity, touch, and twist through a spiraling, repeating braiding topology of touch matrices. This sensing topology is uniquely scalable, requiring only a few sensing lines to cover the whole length of a cord. The same topology allows us to embed fiber optic strands to integrate co-located visual feedback.

We provide an overview of the enabling braiding techniques, design considerations, and approaches to gesture detection. These allow us to derive a set of interaction techniques, which we demonstrate with different form factors and capabilities. Our applications illustrate how I/O Braid can invisibly augment everyday objects, such as touch-sensitive headphones and interactive drawstrings on garments, while enabling discoverability and feedback through embedded light sources.

Author Keywords
Interactive textiles; sensor; input; wearables; capacitive sensing; soft electronics; ubiquitous computing

CCS Concepts
- Human-centered computing → Interaction devices; Interaction techniques; User interface design

UIST '18, October 14–17, 2018, Berlin, Germany

ACM ISBN 978-1-4503-5948-1/18/10.
https://doi.org/10.1145/3242587.3242638

INTRODUCTION
Mark Weiser's seminal vision of ubiquitous computing, "The Computer of the 21st Century" [36], opens with "*The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.*" Weiser and colleagues were focused on the proliferation of electronics at various scales. In our work, their metaphorical use of "fabric" and "weave" also has an important literal relevance—braided textiles that can augment cords with touch sensitivity and dynamic visual feedback [26].

Textiles allow technology to better fit in our everyday environments. The desire to improve aesthetics, comfort, and ergonomics through textiles is exemplified through fabric-covered smart speakers, braided headphone cords, textile-covered VR headsets, and "fashion" electrical cords. Advances in materials and flexible electronics have enabled the incorporation of sensing and display into soft form factors, such as jackets, dresses, and blankets [4, 17, 18].

I/O Braid builds on this body of work to bring interactivity to devices and surfaces that do not conform to the typically rectangular form of rigid electronics or touch surfaces. It enables the augmentation of existing cords without compromising design, aesthetics, or the object's function.

By exploiting techniques from textile braiding, the I/O Braid integrates both gesture sensing and visual feedback along the surface of the cord through a repeating matrix topology (Figure 1).

Contributions

- **Sensing architecture** that leverages industrial maypole braiding techniques to create a spiraling, repeating sensing geometry with conductive yarns. The topology enables scalable gesture sensing with a small number of sensing lines.
- **Display architecture** that provides visual feedback through braided fiber optic filaments for co-located I/O with the sensing.
- **Implementation of custom embedded hardware** chip with on-board gesture sensing that enables practical form factors (e.g., headphones and a hoodie garment with interactive drawstrings).
- **Applications** that demonstrate interactive capabilities using a variety of gestures, such as taps, holds, grabs, slaps, and rotation.
- **Qualitative user evaluation** with gesture elicitation and prototype feedback.

BRAIDING CONDUCTIVE YARNS AND FIBER OPTICS

Braiding can refer to any process of interweaving three or more material strands diagonally to the overall product axis [10]. In this paper, we use the term braid to refer to a tubular maypole braid, as opposed to a flat maypole braid (as might be used in hair). A tubular braid of this construction must have an even number of yarns. A yarn refers to one of the constituent strands of the braid. For example, the braid shown in Figure 1a consists of 18 yarns. These braids have repeating structures, where the yarns spiral around the center. This structure can be observed by following the colored yarns along the length of the braid. The axial distance between the yarn's reoccurrence at the same position, after a 360º rotation around the core, is referred to as the braid length. A tubular braid typically consists of yarns running around the core in two directions, or chiralities, referred to as S and Z. This notation fully describes the direction of twist around the core, irrespective of the braid axis orientation.

While braids are typically used for aesthetics or structural integrity, in this work we use them to enable new sensing and display capabilities by replacing passive yarns with conductive yarns or fiber optic strands.

Conductive yarns

The conductive yarn is the necessary element for electronic textiles. It has a conductive core for its electrical capabilities and is surrounded by interlocked fibers for the textile qualities. Conductive yarns can be constructed and designed using various techniques that affect manufacturability, robustness, and flexibility. Conductive yarns can be used in combination with textile yarns as long as their physical properties' influence on the braid, such as thickness and abrasion tolerance, is taken into account.

Fiber optics

A fiber optic filament makes it possible for light to propagate throughout the strand using total internal reflection. Fiber optics for visual display are designed with a consistent imperfection, such that they emit ("leak") a fraction of the light along the length of the strand. This imperfection allows them to glow along their length from a single light source at its end.

Fiber optics strands are sensitive to mechanical stress from impact and deformation, such as bending. They are thus often enclosed in thin flexible transparent sleeves for protection. Depending on sleeve material and thickness, this can interfere with the braiding operation, and in our prototypes we typically use bare fiber optic strands.

CAPACITIVE SENSING BRAID ARCHITECTURE

A significant contribution of this work is the physical architecture of the braid, which enables robust detection of rotation of the braid between a user's fingers. This architecture also allows for detection of gestures involving temporal patterns (tap and long press) and contact area variation (pinch and grab).

The Helical Sensing Matrix (HSM)

While cords can be made to detect touch through capacitive sensing, common approaches are typically limited to temporal gestures and can suffer from false positives from contact in the environment. Our Helical Sensing Matrix (HSM) enables a larger space of gestures and reduces false positives. The HSM is a braid consisting of both conductive textile yarns [18] and passive support yarns (Figure 2). The conductive textile yarns are electrically insulated, so they do not short when lines in opposite directions intersect (S- vs. Z-direction). The HSM uses mutual capacitive sensing, which transmits a known AC signal on a set of electrodes and listens for the signal on a set of receive electrodes. With n transmit and n receive electrodes there is a total sampling of n^2 independent capacitive couplings.

Conductive yarns running in the S-direction are used as transmit electrodes, while conductive yarns in the Z-direction are used as receive electrodes. When the user manipulates the cord, the capacitive coupling between the threads running in the S- and Z-directions is modulated by the user's hand and fingers and can thus be used to determine what kind of interaction has occurred. Interactions can be sensed anywhere on the cord since the braided HSM pattern repeats along the cord's full length. This repetition also presents an opportunity to take advantage of the structure inherent to the industrial braiding process to improve robustness and SNR of the capacitive sensing.

For illustration purposes, we flatten our helical sensing matrix into two dimensions (Figure 2, center). The flattened HSM has eight conductive yarns, four in each direction. We label each transmit (TX)/receive (RX) intersection with hexadecimal numerals. The pattern is repeated, as it would be repeated in a real braid, with the exception of the column shown in dashed lines, which represents the place where the right side of the flattened matrix joins the left side. Each column of mutual capacitive intersections is colored, and

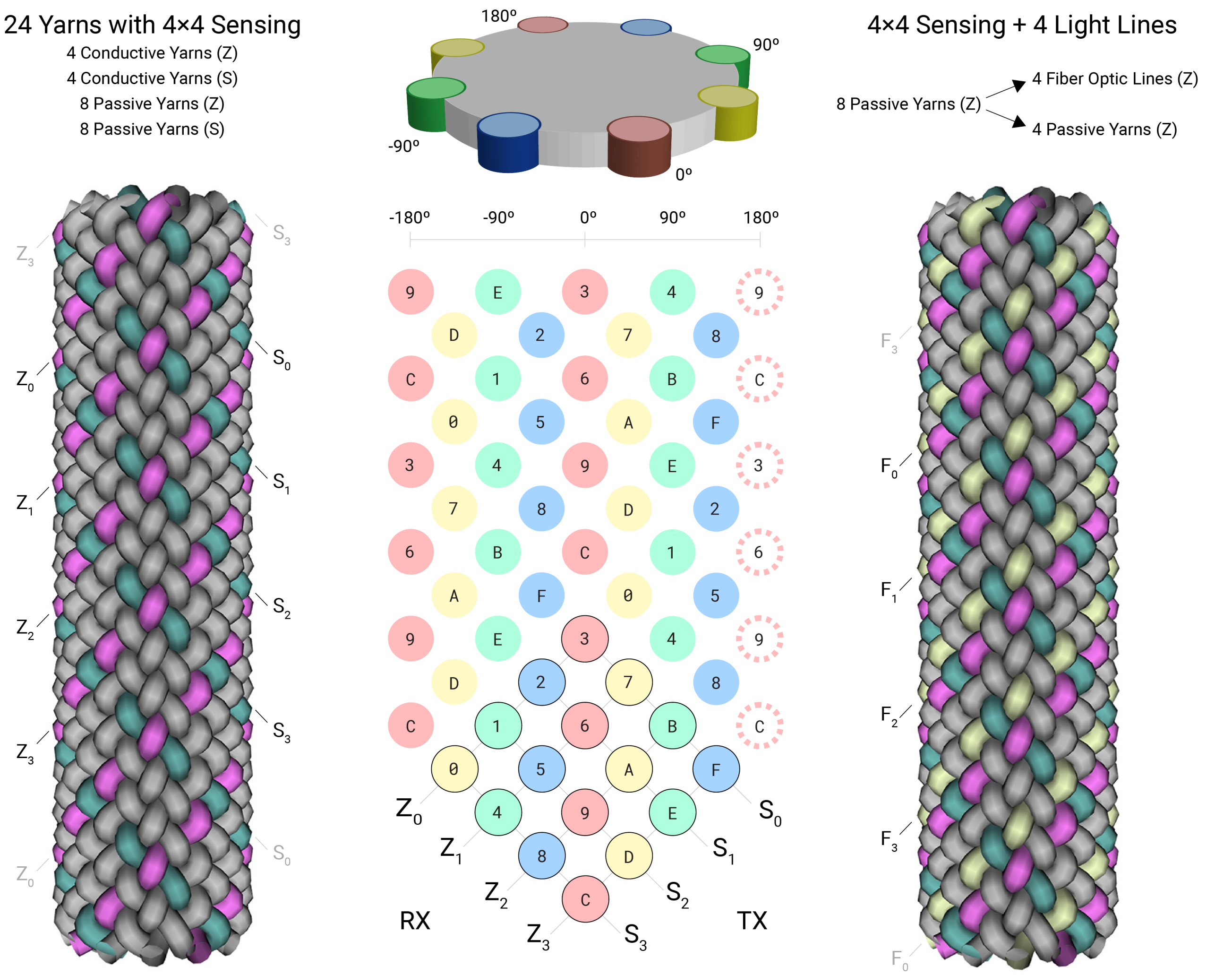


Figure 2. Left) A Helical Sensing Matrix based on a 4×4 braid, which uses 8 conductive threads spiraled around the core. Conductive yarns are shown in color, while support yarns are shown in grey. Z_0–Z_3 (magenta) are conductive yarns in the Z-direction, which are used as receive lines in the sensing matrix. S_0–S_3 (cyan) are conductive yarns in the S-direction, which are used as transmit lines in the sensing matrix. Center) Flattened Helical Sensing Matrix, that illustrates the infinite number of 4×4 matrices (colored circles 0-F), which repeat along the length of the cord. Rotation gestures are detected by tracking horizontal finger motion across the columns (red, yellow, green, blue). Right) We can also use fiber optic lines instead of passive yarns, to embed visual feedback in the same topology. Here, four passive yarns have been replaced by fiber optic lines F_0–F_3 (yellow).

some of these colors repeat. These columns show axially oriented intersections along the cord. One could similarly color the intersections on a real braid, and the intersections would make a straight line along the cord axis. For example, the blue columns contain the intersections 2 5 8 F. There are four colors for columns, but there are two columns of each color running axially along the braid.

Rotation detection

The angle relative to the center red column of touch points is shown at the top of Figure 2, center. A key insight is that the two axial columns that share a common set of electrodes are located 180º opposite each other along the braid. Thus, pinching the cord between two fingers will activate one set of electrodes much more than the others. While users cannot easily identify the rotation of a cord and selectively grab it at a particular angle, we can track their relative motion over time and deduce if they are rolling the cord between their fingers (Figure 3).

Rotation detection is thus based on identifying the current phase of the fingers with respect to the set of time-varying sinusoidal signals which are offset by 90º. Confounds include noise, DC offset, and capacitance effects that vary across the sensor intersections. In addition, as the user rotates the braid in one direction or another, all yarns in the torsional direction are tightened within the braid, while all other yarns are loosened.

I/O Braid is designed to allow the user to initiate rotation at any part of the cord, and to be scalable with a small set of

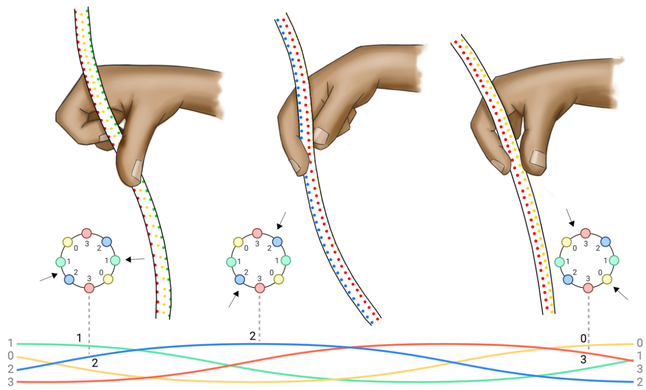


Figure 3. Rotating the I/O Braid: Relative capacitive signal strengths are shown in graph at bottom. As each pair of columns approaches a finger, its signal strength increases.

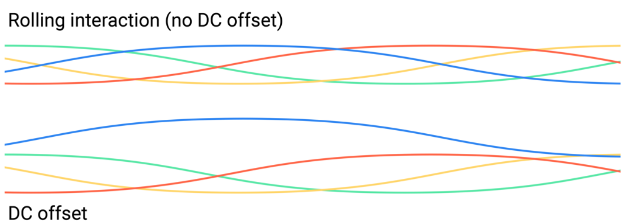


Figure 4. The top graph shows the expected phase relationships for rolling interactions. The bottom graph shows how a DC offset for one of the signals (blue) affects the apparent phase relationships.

electrodes. However, this feature also limits our current implementation to a single grip location, since the capacitive environment along the entire length of the braid affects our sensing. Figure 4 shows how holding a braid between two fingers in one hand while performing rotation with the other hand can introduce a DC offset to the capacitance on a subset of the electrodes (blue).

Topology and characteristics, thickness and density

The simplest architecture is a 3×3 design: 6 conductive yarns with 3 in each chiral direction (S/Z), as shown in Figure 1a. A 120-degree separation is maintained between conductive yarns in each direction, where the equal spacing enables the rotation detection. A second architecture, shown in Figure 2, uses a 4×4 design for improved rotation sensitivity and robustness against broken conductive yarns.

Braiding angle [10] refers to the angle at which a given yarn crosses the core. To minimize added thickness, we want our yarns as spread out as possible while providing sufficient sensing coverage. With decrease in braiding angle:

- Sensing matrix spreads out (reduced density)
- Amount of yarn used and braid diameter decrease

Using fewer lines for sensing results in lower power consumption and lower computational complexity, which is beneficial for wearables.

DESIGN GUIDELINES

Our braid makes the whole cord surface touch-sensitive, but its softness and malleability limit the suitable interactions compared to a more traditional, rigid touch surface. With the unique material and topology in mind, we established a few initial guidelines to inform our I/O Braid interface design:

- **Simple gestures.** We should design for short interactions where the user either makes a single discrete gesture or performs a continuous manipulation. We should avoid complex compound gesture combinations, which, for example, would combine short and long presses (a.k.a. Morse code mappings).
- **Single actions.** Given our support of taps, it might be tempting to implement double- or triple-clicks. Our informal experiments show that the lack of rigid mechanical support, or haptic actuation, makes it challenging to perform such gestures consistently.
- **Closed-loop feedback.** We want to help the user discover functionality and get continuous feedback on their actions. Where possible, we should leverage visual, tactile, and audio feedback integrated in the input device.

We believe that these guidelines would help ensure that our interaction techniques are usable, useful, and discoverable.

INTERACTION TECHNIQUES

The I/O Braid enables interaction techniques along a number of dimensions (See Figure 5). The following sections describe these techniques.

Proximity and contact area (absolute, continuous)

The capacitive sensing gives us the ability to sense hover and contact, including contact area. Contact area enables distinguishing between a finger or a hand that is grabbing the I/O Braid.

Contact time (temporal, discrete)

Similar to traditional touch-screen interactions, we can map different contact times to different actions. This capability enables short presses, long presses, or press-and-hold as mechanisms to trigger different discrete actions.

Roll (relative, continuous)

Once the I/O Braid is grabbed, we enable continuous manipulation by detecting a rolling motion of the braid between the fingers that can be described as a “twist.” With the spiraling sensing topology, this twisting maps to a relative motion across the touch matrix.

Pressure (relative, continuous)

Relative manipulation can also be enabled by tracking how pressure increases over time after contact.

Visual feedback in I/O Braid

Our braided fiber optics enable different types of visual feedback in response to the user’s interactions. We can modulate intensity and color for a single fiber optic strand. Two parallel strands enable motion feedback by lighting alternately. A third parallel strand allows directionality.

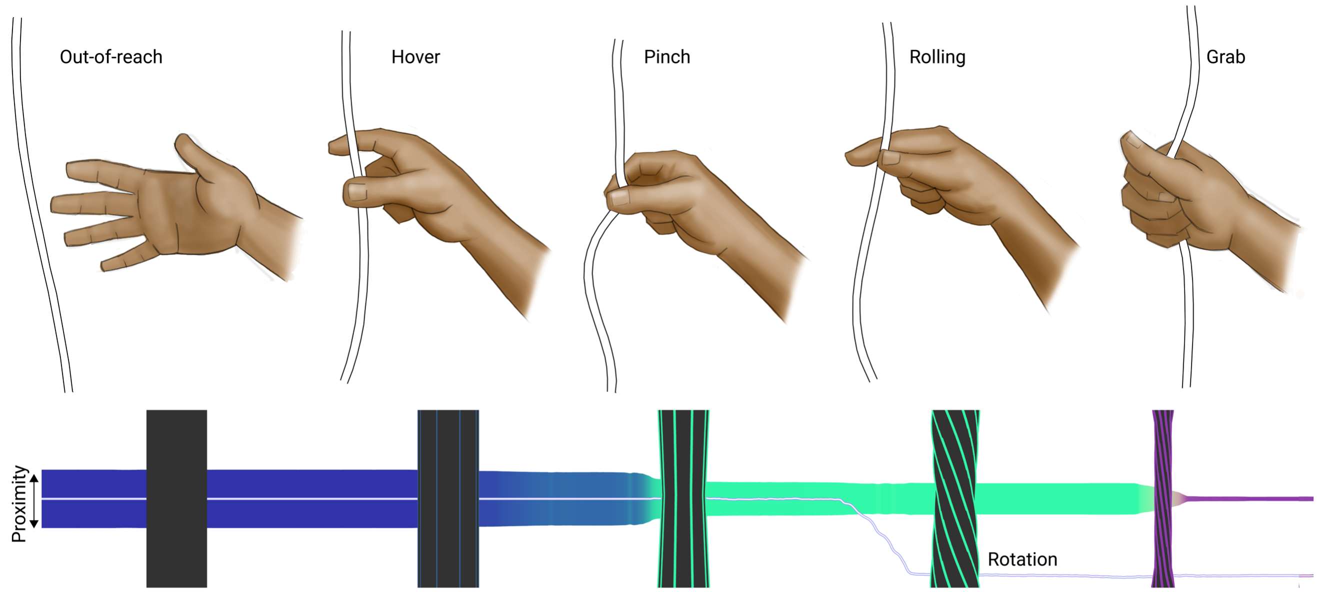


Figure 5. I/O Braid enables interaction techniques based on the capacitive sensing of proximity, contact area, contact time, roll, and pressure. For each event shown at the top, the bottom graph shows rotation through a center line plot, and nearing proximity by narrowing the height of the area plot. Additionally, a 3D representation of the cord is rendered at each event, with increasing line thickness for proximity, and varying thickness based on contact area.

We found it interesting to explore new interaction techniques where the light provides feedback for the user's interaction. Upon contact we use the color to help the user anticipate the effects of their actions and the capabilities of the recognizer We can distinguish between contact size by varying the tint of the color:

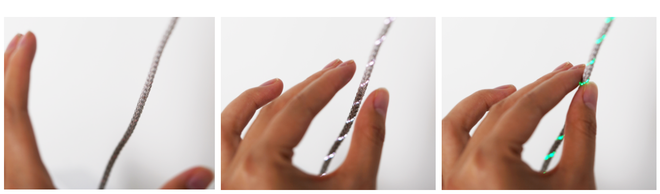
- Finger → Teal (lighter blue)
- Hand → Navy (darker blue)

We can also provide feedback as users switch from discrete contact to continuous manipulation, using twist or pressure. For twist, we manipulate the hue:

- Clockwise (++) → Tint towards green
- Counterclockwise (– –) → Tint towards red

For proximity and pressure, we manipulate saturation, starting from white upon contact (Figure 6):

- Increasing pressure (++) → Tint more green
- Decreasing pressure (– –) → Tint less green



a) Out-of-reach (off) b) Hover (white) c) Touch (green)

Figure 6. Integrated visual feedback through braided fiber optic strands. The I/O Braid changes color on proximity and touch.

Audio feedback

Audio feedback can be mapped with discrete sounds when parameters are being changed. There are also opportunities to use manipulations of synthesized audio to provide feedback (e.g., changing amplitude or frequency).

Tactile feedback

The braid structure has been designed to provide passive tactile feedback through its surface structure as the user manipulates it. It could also be interesting to explore dynamic material changes (for example, using electrostimulation or jamming techniques [5]).

APPLICATIONS

To demonstrate the capabilities of the system we developed a set of interactive applications.

Accessory: Headphones with music controls in the cord

We were interested in exploring how we could extend common wired accessories with the I/O Braid. We implemented I/O Braid capacitive touch sensing in a custom "Nanoboard" PCB with USB-audio capabilities and an implementation of a USB-HID device. By interfacing ground and left/right channels from standard headphones to the board, we use it as a USB-C headphone when connected to an Android phone (Figure 7). In our experiments we use a Google Pixel phone. The USB-C connection lets the phone identify our Nanoboard also as an HID device (keyboard), such that we can send standard media key events over USB. Our mappings:

- Finger tap → Play/pause
- Twist clockwise → Volume+ (increase)
- Twist counterclockwise → Volume– (decrease)

Figure 7. I/O Braid USB-C headphones with embedded gesture recognition and audio feedback for music control, enabled by Nanoboard. The user starts playback by pinching, then rolls the I/O Braid to increase the volume.

While we are avoiding repeated gestures in our designs (see design guidelines), certain applications, like YouTube Music, automatically map a double-tap to next track.

We provide low-latency and immediate gesture feedback to the user through on-chip audio tones. This approach avoids delays from roundtrips through the phone's audio system.

Our current platform could also allow different behavior depending on the user's activity and the current mobile application. Possible mappings for various scenarios:

- Scrolling text: e-mails, e-books or web pages.
- Fast-forward/rewind instructions during map navigation.
- Fast-forward/rewind video or audio books.
- Audio transparency in noise-cancelling headphones.
- Scanning frequencies for mobile FM radios.

Garment: Hoodie garment with interactive drawstrings

We identified opportunities for richer interactions in scenarios where the braid was mechanically attached to a garment. Our design replaces the drawstring in a hoodie garment with an I/O Braid. Since the drawstring hangs freely, we explored gestures that take advantage of it being always accessible (Figure 8). Our current hoodie supports six actions:

- Finger tap → Play/pause
- Finger + hold → Track+ (next)
- Hand + hold → Track– (previous)
- Hand tap → Playlist+ (next)
- Twist clockwise → Volume+ (increase)
- Twist counterclockwise → Volume– (decrease)

For rapid prototyping purposes, this exploration connects a 4×4 I/O Braid to a PSoC 4 development kit, which interfaces with a laptop over USB for visualization and control. The development kit is integrated in a custom-sewn pouch in the back of the hoodie. For a real hoodie garment we could either provide USB-C connectivity directly to the phone or, more

Figure 8. Hoodie with replaced left drawstring invisibly adds gesture capabilities to the garment. I/O Braid controls music playback, volume control, and switching between playlists.

practically, use a battery-powered Nanoboard with a wireless Bluetooth connection.

Integrated visual feedback: Music and call status

While our two music controller applications can rely on implicit audio feedback, we also wanted to investigate opportunities using integrated visual feedback (Figure 9).

We thus created an I/O Braid with 4×4 sensing yarns and four fiber optic lines (See Figure 2, right). One could replace the normal functionality of an LED on a music player with the fiber optic lines. Color and pulsing could indicate status, such as pause, play, or low battery. While such behavior may be appropriate for a small LED in a dedicated discreet location, in our case it would light the whole I/O Braid, as the fiber optics cover its whole length using a single strand.

Our solution is a design where the light is off by default. When the user approaches the I/O Braid, it increases in intensity as hover is detected. Its color or light pattern can now be used to preview the state of the connected device depending on its current mode.

For example, on hover in music app:

- Solid green = Playing
- Blinking green = Paused

As another example, on hover during phone call:

- Solid green = Headset audio
- Solid red = Mic muted

Similarly, we can provide visual feedback as the user performs a continuous manipulation.

Today, when people listen to music in headphones, and someone talks to them, they either need to stop the audio stream, turn down the volume, take out the headphones, or try to talk over it. While this may be acceptable for music, it does not work for a phone conversation. It may also not be clear to the approaching party that the person could not hear them in the first place.

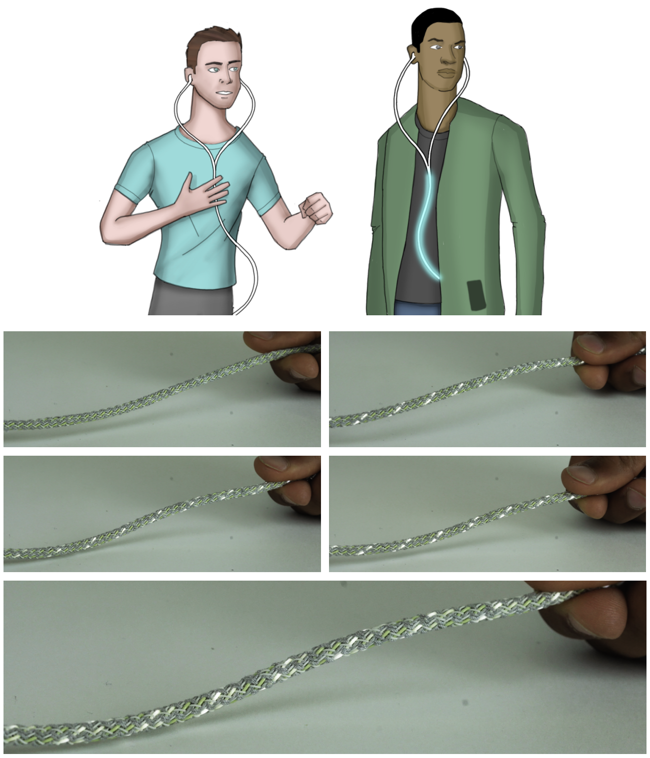


Figure 9. I/O Braid's capability to sense touch and rotation input along the length of a headphone cord allows less precise input when on the go, for example, when jogging. The integrated visual feedback can be used to communicate phone connection or music status. This functionality could help signal social cues such as interruptibility, to onlookers. The photos show how flowing light can be used for directional feedback.

We wanted to provide a more flexible approach to temporarily switching the attention to the other party without completely disengaging from the current audio. Simultaneously we saw an opportunity to provide better feedback to both the user and surrounding people. Here, similarly to related work [28], we use the affordance of squeeze as a metaphor for reducing the signal flow through the cable. As the user approaches the cable, it lights to indicate the state (e.g., green for music or headset audio). The user can start squeezing the cable to quickly and temporarily decrease the volume while listening to music or a phone call. Upon squeeze, we gradually decrease light intensity. This display provides immediate feedback to the user and also signals to the other party that attention has shifted. Upon release, the light ramps back up to full color, before fading out after a few seconds.

In this manner, I/O Braid helps the user communicate the meaning of their shift in attention and the implicitly associated change of visual feedback.

General-purpose input: Game controller

Finally, we wanted to explore the use of I/O Braid for general-purpose control, such as for games. While there has been an explosion in mobile and tablet games, it is well-known that the lack of tactile affordances on the touch screens affect the gameplay. There exists a plethora of accessories to add physical controls for mobile gaming. We saw the opportunity for I/O Braid headphones to bring analog control to games and applications without the need for a dedicated input device. To demonstrate these capabilities, we integrated the I/O Braid with a Java version of Tetris.

PRELIMINARY EVALUATION AND USER FEEDBACK

We conducted a preliminary formative evaluation where we focused on gesture elicitation, to get an indication of discoverability, and qualitative feedback, to inform future studies.

Gesture elicitation: Discoverability for volume control

We recruited 36 participants (11 female) from our institution who were compensated with a gift card. The participants were asked to demonstrate to the experimenter how they would imagine changing the volume on a set of headphones where the cord was touch-sensitive. The device provided no feedback on the actions.

The most common gestures were "swipe," "pinch-and-slide," and "index-hold & thumb-slide." No participant performed the rotation/twist gesture. This result indicated that there need to be clear instructions on how to perform the rotation gesture in our current mapping.

Experiencing prototype I/O Braid headphones

Next, we were interested in how users would perceive the interaction after they received instruction on its operation and experienced performing it.

We recruited an additional seven participants from our institution (one female). The 43 participants were compensated with a gift card. Participants were shown how to rotate/twist the cord to control volume using the I/O Braid headphones. Participants provided qualitative feedback on a seven-point Likert scale, as shown in Figure 10. The majority of participants were positive regarding the technique's intuitiveness (86%), found it better than existing headphone controls (72%), and overall liked the rotation gesture (76%).

Comments and Concerns

Participants mentioned gripability, firmness, feedback, torque, and twistability as important factors for rotational

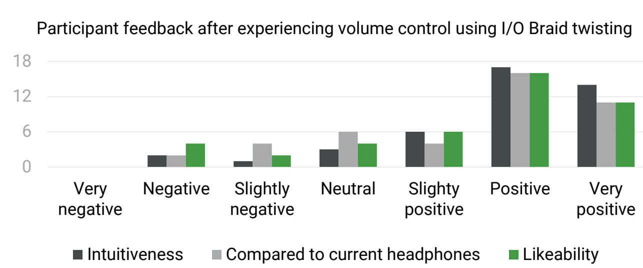


Figure 10. Qualitative feedback from preliminary user evaluation. 43 participants reported on their experience from using the rotation on I/O Braid headphones to control volume.

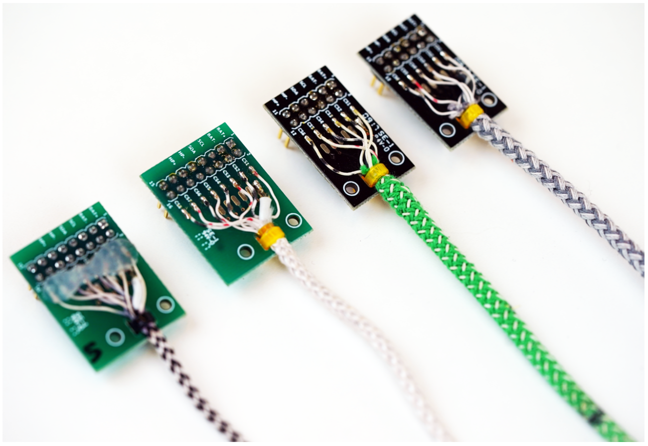


Figure 11. I/O Braids with different materials, texture, colors, and topologies connected to breakout boards. Black/white 4×4 (green PCB), White 4×4 (green PCB), White/green 3×3 (black PCB), Grey/white 3×3 (black PCB).

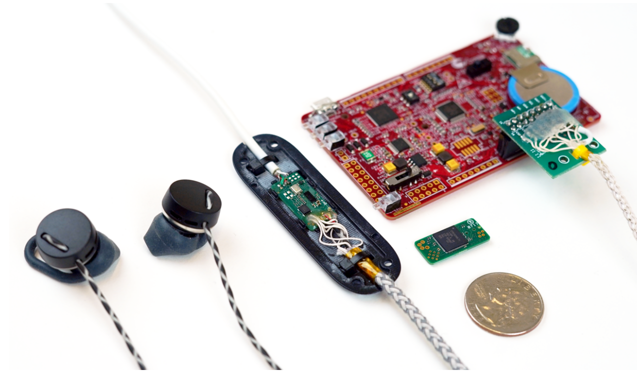


Figure 12. From left to right: (1) I/O Braid USB-C headphones. (2) Nanoboard, custom PCB for 3×3 I/O Braids with onboard tap/gesture sensing and sound tone generation. Configurable as a USB audio interface and as a USB Human Interface Device (e.g., keyboard). (3) 4×4 I/O Braid connected to a PSoC S-Series Pioneer Kit through a custom breakout board.

gestures with the I/O Braid. There were also concerns about durability and longevity of a textile sensor, especially for headphones in challenging weather and exercise conditions. Participants expressed concern for false positives from cord contact with the skin, clothing, face or hands, and how twisting may affect headphone stability and fit in the ear. A few participants asked about using I/O Braid with their preferred hand.

Discussion

This preliminary evaluation provided experiential feedback about our prototypes and identified important areas for future work. We are especially intrigued that no participant proposed rolling/twisting during the gesture elicitation, but when they were introduced to it, the majority were enthusiastic. This result suggests a benefit from active promotion of the mechanism, similar to how pinch-to-zoom was introduced with multi-touch products. Future studies will include quantitative evaluations and baseline comparisons against existing in-line earbud control experiences for play/pause and volume. Feedback mechanisms, for both continuous and discrete actions, are an another important direction for future work. A study could provide insights about the effectiveness of different modalities, such as fiber lighting in the cord, audio feedback in headphones, or visual feedback in a different wearable device.

IMPLEMENTATION

Conductive yarns

I/O Braid relies on insulated conductive yarns, similar to other textile touch matrices. Our yarn consists of a core with 7 copper-tin wires (∅ 0.07 mm) that are individually coated with silver. They are bundled and covered with an insulative coating using transparent PFA (Perfluoroalkoxy alkane). The insulated bundle is over-braided with a 16-polyester braid (50 deniers×2). These yarns are used as electrodes in our 3×3 or 4×4 electrode sensing topologies (Figure 2 and 11). While insulation is critical for our sensing technique, the particulars of yarn construction are primarily relevant to structural reliability and ergonomics (softness and hand feel for manipulation). While our yarn is not yet commercially available, comparable results should be achievable with other conductive yarns, such as the VOLT Apache series. These yarns consist of two, four, or eight copper wires, each 44 AWG and 3.8 ohms/meter, in an insulating polyester coating that can be stripped by fire for soldering [31].

Fiber Optics

We use Corning Fibrance Light-Diffusing Fiber from Versalume. The fibers are available with different light-diffusion-length properties, based on desired length (e.g., 1, 5 or 10 m). We use the 1 m light-diffusion length for I/O Braid to maximize the brightness for our short lengths.

The fibers come with a protective 900 micron clear optical grade PVC (Polyvinyl chloride) outer jacket, which we typically remove to match the thickness, quality, and texture of the capacitive and passive yarns. We assume that a protective post-processing step would be used for braids that include fiber optic strands, where a transparent insulator (e.g., PVC), could be applied. See Figure 2, right.

Braiding

Our current prototypes are hand-braided using a *marudai*, the traditional stand used for the *kumihimo* braid production method. We use conductive thread [18], with yarn tension adjusted appropriately for both the conductive and non-conductive threads to ensure a tight braid with good coverage. Note that the braids used are reproducible with commercial braiding machines in the textiles industry, and the thread is designed to tolerate commercial textile processes [18].

Capacitive sensing

We use the Cypress PSoC 4 architecture due to its hardware support for both self and mutual capacitive sensing (Figure 12). Our developer kits are based on a breakout board for connecting 3×3 or 4×4 I/O Braids to a PSoC 4 S-Series Pioneer Kit (CY8CKIT-041-40XX). To explore self-contained, embedded and miniaturized applications, we also developed an I/O Braid Nanoboard, a custom printed circuit board (PCB). It interfaces with a 3×3 I/O Braid and implements gesture sensing (tap, rotate CW, CCW) and different interfaces over USB.

BENEFITS AND LIMITATIONS

Wearable interfaces are often designed for scenarios when the user is focusing on another, more primary task. Many are designed to be used on-the-go, such as when walking or driving. Gesture is often suggested for such situations as it is silent and fast. However, interface designers often abuse this modality [13]. We address Norman and Nielsen's points in "Gestural Interfaces: A Step Backwards In Usability" as a guideline for discussing I/O Braid.

Visibility

I/O Braid builds on the physical affordances of cords, which may be grasped, tugged, and twisted. By adding fiber optic lighting, I/O Braid can display state. For example, the lighting may show the flow of data, which conductors are active, or how much current is flowing.

Discoverability

The fiber optic lighting can also suggest interactions. For example, as a user reaches to grasp a hoodie cord, it begins to light, hinting that the cord is an active interface (and revealing the cord in dim light). This capability should be used respecting social norms and cultural consideration [4].

Feedback

The I/O Braid can provide feedback for every interaction, allowing the user to monitor their performance and know that the system is operating as expected. Adding visual or auditory feedback helps the user understand which gesture is being detected, allowing the user to modify the gesture if needed. For example, while the cord brightens with proximity, it can change color with touch. Twisting or changing pressure maps to color or brightness changes as the user executes the gesture. The audio cord provides similar feedback through sound.

Scalability

I/O Braid scales well, independent of cord length. Calibration is required for hover, tap, and grasp, though the system could, in theory, self-calibrate based on its resting capacitance, its length, and its type of braid.

Non-destructive operations

Limiting gestures to nondestructive interactions encourages users to explore the interface and makes it more tolerant to false positives. In our work, we also use symmetrical gestures, where the user can undo by either repeating (Tap → Play/pause) or performing the opposite gesture (Rolling clockwise vs. counterclockwise).

Consistency

The affordances of a cord (tapping, grasping, twisting, etc.) help encourage consistency when creating an interface with I/O Braid. As the interface is intended for short interactions, complexity should be kept to a minimum. One can imagine creating a convention across devices where twists always control continuous inputs (such as lighting level or volume), taps toggle actions (with appropriate audio or visual feedback) and grasps map to global undo.

RELIABILITY AND ROBUSTNESS

To address issues such as drift, aging, and repeatability, our capacitive sensing boards provide auto leveling in hardware. This feature allows us to more reliably detect taps and grasps over time, as these gestures are relatively short compared to typical capacitance changes from the environment or drift. Auto leveling also improves sensing across scales, such as grasping the braid in the hand, followed by finer rolling motion between the fingers. The rotation gesture has advantages in that thresholds on the amount of twist needed before reacting reduces false positives. Rotation is particularly robust to drift, hysteresis, and aging as it can be detected by the change in the individual lines' signals relative to themselves and each other over time (increasing or decreasing).

Similar to existing wearable devices, multimodal sensing is advantageous to improve robustness. On-head detection sensors such as those used in modern earbuds can, for example, help inhibit accidental input for I/O Braid headphones when not actively worn. Cords may also repeatedly touch bare skin, such as the face or neck, during exercise, which may be challenging to distinguish from intended taps. These challenges highlight the importance of careful industrial design and adaptation to specific usage scenarios. For headphones, for example, one may want to reserve I/O Braid coverage for areas away from exposed skin.

I/O Braid was designed to be integrated into existing cords that already have a purpose. Cords designed to carry signals (e.g., data or power) are less susceptible to ambiguities, whereas we may need to more carefully design integrations with cords that also adjust or affect physical properties (e.g., garments). Is the user attempting to control music, or are they simply tightening the hood? Choosing an appropriate set of gestures from the available palette is critical to the user experience.

FUTURE WORK

We have created several interfaces that show the potential of I/O Braid, but we are also planning a number of additional directions in our future work.

Expressivity

We are interested in extending the I/O Braid gesture set. For example, we plan to investigate support for several of the popular gestures from the elicitation study, such as slide, as they should be possible to recognize using the current architecture. We are also interested in reflectometry [37] to sense the position of a touch on the cord. Combining I/O Braid with near field radio or bioimpedance [23, 24] may enable recognition of who is touching the cord. Also, ideas from CordUI could be useful to explore, such as sensing deformation [28].

Braids

The literature supplies many variants of braiding that might be used to apply the I/O Braid concept to new domains. Varying the number of threads and patterns can allow finer or more coarse sensing over larger and smaller diameter cords. Varying the braid and type of conductive thread can increase or decrease sensitivity with respect to proximity and touch. It can also improve tolerance to abrasion and fatigue, at the possible expense of flexibility. Establishing a set of options and experimental best practices could lead to better prototyping and more rapid adoption by industry.

New applications

Fashion power cords constructed of braided threads are common in the lighting industry. We would like to explore how I/O Braid could add interaction to these cords. Imagine a dark room where the power cord to a desk lamp begins to glow as the user reaches for it. A quick tap anywhere on the cord turns on the light, and twisting the cord modulates the hue for control of warmth. Power cords in an electrical facility might change color and brightness to show the amount and type (AC/DC) of current flowing through them. A squeeze turns them off. Data cables flash to indicate the speed and direction of data flow, and a sequence of gestures might be required as security before a cord allows connection. Braided covers on cords might also be used to detect and characterize wetness or wear.

User evaluation

We plan to follow up on our preliminary user evaluation with more formal studies to gather quantitative and qualitative data. We are also interested in experiments with larger sets of users to determine the best thresholds and algorithms for I/O Braid and to explore longitudinal use in-the-wild.

RELATED WORK

I/O Braid is a soft, touch-based textile interface that builds upon a significant body of literature in this space, such as the pioneering E-broidery work by Post et al. [17]. Pinstripe [8] utilizes conductive thread to create 1D textile interfaces that are manipulated by pinching the fabric. SkinMarks [35] and iSkin [34] are 1D compliant skin-worn sensors for touch input. Flexible touch matrices have been created through multi-layer resistive fabric [11, 19, 25], pressure-sensitive textile optical fibers [22], plastic film over sensing electrodes [21], a piezoresistive elastomer-based soft sensor using electrical impedance tomography [39], embroidery [6, 17, 40], fabric screen-printing [41]; metal foils [12], and weaving of conductive thread [14, 18].

In an exploration of interactive cords, Schoessler et al. [28] augment cords with a bend sensor to detect knots, conductive polymer sandwiched between two sheets of copper foil to detect pressure, piezo copolymer coaxial cable to detect kinks, and a resistive rubber to detect stretch. Most relevant to this work, they use resistance for touch and pressure in a headphone cord using conductive yarn woven into the fabric of braided cable sleeving. Schwarz et al. [27] augment cords by adding a SpectraSymbol Softpot sensor to detect touch and, at the cord's end, a linear potentiometer for pull and a rotary encoder for twist.

Wimmer and Baudisch [37] use Time Domain Reflectometry to detect the user's touch on a headphone cord and adjust the volume accordingly. Using resistance, Sousa and Oakley [29] sense the position of a conductive bead that slides along a cord. I/O Braid differs from these previous projects in that it can detect twist and other gestures leveraging the structure of the braid itself, and it can be created in any length using a commercial conductive yarn [18] and common textile braiding processes.

Interfaces have also been designed with retractable strings [3, 7, 16]. Detecting deployed cord length and angle relative to a base allows a 2D or 3D interaction space. Rope Revolution [38] used a tethered cord with motion sensing and force feedback to connected remote players. ShapeTape [2], while not textile-based, is a highly expressive cord-like interface with embedded sensors to track shape and orientation.

Textiles have been used for display using a wide range of technologies, such as LEDs [9], photonic bandgap fibers [1], thermochromics [4], and liquid crystal ink [33]. I/O Braid's scalable topology is particularly suitable for fiber optics, which enables large coverage with less light sources. Versalume [30], for example, sells USB charging cables that light and pulse using laser-powered fiber optics.

CONCLUSIONS

We introduce I/O Braid, an interactive textile cord with embedded sensing and visual feedback. We extend previous work in this space with an approach that is scalable based on a spiraling, repeating braiding topology, requiring only a few sensing lines to cover the whole length of a cord. With the same topology, we embed fiber optic strands to integrate co-located visual feedback. We provide an overview of the enabling braiding techniques and design considerations. These allow the derivation of a set of resulting interaction techniques, which we demonstrate with different applications, form factors, and capabilities.

We hope that other researchers will be inspired by I/O Braid's attempt at augmenting physical objects with a scalable technique, while preserving industrial design and aesthetics.

ACKNOWLEDGMENTS

We would like to thank the Google ATAP Jacquard team for our collaboration, and especially Shiho Fukuhara, Munehiko Sato, and Ivan Poupyrev. We thank the Google Wearables team, and Kenneth Albanowski, in particular, for engineering support. Finally, we would like to thank Mark Zarich for illustrations, Bryan Allen for videography, and Carolyn Priest-Dorman for advice on textile techniques.

REFERENCES

1. Joanna Berzowska and Maksim Skorobogatiy. 2010. Karma chameleon: bragg fiber jacquard-woven photonic textiles. In *Proceedings of the SIGCHI Conference on Tangible, Embedded, and Embodied Interaction* (TEI '10), 297-298. http://dx.doi.org/10.1145/1709886.1709950

2. Ravin Balakrishnan, George Fitzmaurice, Gordon Kurtenbach, and Karan Singh. 1999. Exploring interactive curve and surface manipulation using a bend and twist sensitive input strip. In *Proceedings of Interactive 3D Graphics* (I3D '99), 111-118. http://dx.doi.org/10.1145/300523.300536

3. Gabor Blasko, Chandra Narayanaswami, and Steven Feiner. 2006. Prototyping retractable string-based interaction techniques for dual-display mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '06), 369-372. http://dx.doi.org/10.1145/1124772.1124827

4. Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-Wei Gong, M. Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. I don't want to wear a screen: probing perceptions of and possibilities for dynamic displays on clothing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '16), 6028-6039. https://doi.org/10.1145/2858036.2858192

5. Sean Follmer, Daniel Leithinger, Alex Olwal, Nadia Cheng, and Hiroshi Ishii. 2012. Jamming user interfaces: programmable particle stiffness and sensing for malleable and shape-changing devices. In *Proceedings of the SIGCHI Symposium on User Interface Software and Technology* (UIST '12), 519-528. https://doi.org/10.1145/2380116.2380181

6. Scott Gilliland, Nicholas Komor, Thad Starner, and Clint Zeagler. 2010. The textile interface swatchbook: creating graphical user interface-like widgets with conductive embroidery. In *Proceedings of the IEEE International Symposium on Wearable Computers* (ISWC'10), 1-8. http://dx.doi.org/10.1109/ISWC.2010.5665876

7. Erik Koch and Hendrik Witt. 2008. Prototyping a chest-worn string-based wearable input device. In *Proceedings of the IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks*,1-6. https://doi.org/10.1109/WOWMOM.2008.4594882

8. Thorsten Karrer, Moritz Wittenhagen, Leonhard Lichtschlag, Florian Heller, and Jan Borchers. 2011. Pinstripe: eyes-free continuous input on interactive clothing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11), 1313-1322. https://doi.org/10.1145/1978942.1979137

9. Sunyoung Kim, Eric Paulos, and Mark D. Gross. 2010. WearAir: expressive t-shirts for air quality sensing. In *Proceedings of the SIGCHI Conference on Tangible, Embedded, and Embodied Interaction* (TEI '10), 295-296. http://dx.doi.org/10.1145/1709886.1709949

10. Yoran Kyosev. 2014. *Braiding Technology for Textiles: Principles, Design and Processes*. Elsevier. eBook ISBN: 9780857099211

11. 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 SIGCHI Symposium on User Interface Software and Technology* (UIST '16), 335-346. https://doi.org/10.1145/2984511.2984572

12. Diana Marculescu, Radu Marculescu, Nicholas H. Zamora, Phillip Stanley-Marbell, Pradeep K. Khosla, Sungmee Park, Sundaresan Jayaraman, Stefan Jung, Christl Lauterbach, Werner Weber, Tünde Kirstein, Didier Cottet, Janusz Grzyb, Gerhard Troster, Mark Jones, Tom Martin, Zahi Nakad. 2003. Electronic textiles: a platform for pervasive computing. *Proceedings of the IEEE*, 91, 12: 1995–2018.

13. Donald A. Norman and Jakob Nielsen. 2010. Gestural interfaces: a step backward in usability. *Interactions* 17, 5: 46-49. https://doi.org/10.1145/1836216.1836228

14. Patrick Parzer, Kathrin Probst, Teo Babic, Christian Rendl, Anita Vogl, Alex Olwal, and Michael Haller. 2016. FlexTiles: a flexible, stretchable, formable, pressure-sensitive, tactile input sensor. In *Extended Abstracts of the SIGCHI Conference on Human Factors in Computing Systems* (CHI EA '16), 3754-3757. https://doi.org/10.1145/2851581.2890253

15. 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 SIGCHI Symposium on User Interface Software and Technology* (UIST '17), 565-57. https://doi.org/10.1145/3126594.3126652

16. Norman Pohl, Steve Hodges, John Helmes, Nicolas Villar, and Tim Paek. 2013. An interactive belt-worn badge with a retractable string-based input mechanism. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '13), 1465-1468. https://doi.org/10.1145/2470654.2466194

17. E. R. Post, M. Orth, P. R. Russo and N. Gershenfeld. 2000. E-broidery: design and fabrication of textile-based computing. *IBM Systems Journal*, 39, 3-4: 840-860. http://dx.doi.org/10.1147/sj.393.0840

18. 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 SIGCHI Conference on Human Factors in Computing Systems* (CHI '16), 4216-4227. https://doi.org/10.1145/2858036.2858176

19. Cliff Randell, Ian Andersen, Henk Moore, Sharon Baurley. 2005. Sensor sleeve: sensing affective gestures. In *Proceedings of the IEEE International Symposium on Wearable Computers - Workshop on On-Body Sensing*, 117-123.

20. Michael L. Rivera, Melissa Moukperian, Daniel Ashbrook, Jennifer Mankoff, and Scott E. Hudson. 2017. Stretching the bounds of 3D printing with embedded textiles. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '17), 497-508. https://doi.org/10.1145/3025453.3025460

21. Jun Rekimoto. 2002. SmartSkin: an infrastructure for freehand manipulation on interactive surfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '02), 113-120. http://dx.doi.org/10.1145/503376.503397

22. Markus Rothmaier, Minh Phi Luong, and Frank Clemens. 2008. Textile pressure sensor made of flexible plastic optical fibers. *Sensors* 8, 7: 4318-4329. http://dx.doi.org/10.3390/s8074318

23. Munehiko Sato, Rohan S. Puri, Alex Olwal, Yosuke Ushigome, Lukas Franciszkiewicz, Deepak Chandra, Ivan Poupyrev, and Ramesh Raskar. 2017. Zensei: embedded, multi-electrode bioimpedance sensing for implicit, ubiquitous user recognition. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '17), 3972-3985. https://doi.org/10.1145/3025453.3025536

24. Munehiko Sato, Ivan Poupyrev, and Chris Harrison. 2012. Touché: enhancing touch interaction on humans, screens, liquids, and everyday objects. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12), 483-492. http://dx.doi.org/10.1145/2207676.2207743

25. Stefan Schneegass and Alexandra Voit. 2016. GestureSleeve: using touch sensitive fabrics for gestural input on the forearm for controlling smartwatches. In *Proceedings of the ACM International Symposium on Wearable Computers* (ISWC '16), 108-115. https://doi.org/10.1145/2971763.2971797

26. Thad Starner, Karissa Sawyer, Greg Priest-Dorman. Interactive Cord with Integrated Light Sources, U.S. Patent 9.807,852, Filed November 2, 2015, issued October 31, 2017.

27. Julia Schwarz, Chris Harrison, Scott Hudson, and Jennifer Mankoff. 2010. Cord input: an intuitive, high-accuracy, multi-degree-of-freedom input method for mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '10), 1657-1660. https://doi.org/10.1145/1753326.1753573

28. Philipp Schoessler, Sang-won Leigh, Krithika Jagannath, Patrick van Hoof, and Hiroshi Ishii. 2015. Cord UIs: controlling devices with augmented cables. In *Proceedings of the SIGCHI Conference on Tangible, Embedded, and Embodied Interaction* (TEI '15), 395-398. https://doi.org/10.1145/2677199.2680601

29. Cátia Sousa and Ian Oakley. 2011. Integrating feedback into wearable controls. In *Human-Computer Interaction* (INTERACT'11). Lecture Notes in Computer Science, vol 6949. Springer. https://doi.org/10.1007/978-3-642-23768-3_81

30. Versalume. 2018. Retrieved August 8, 2018 from http://versalume.com/

31. VOLT Smart Yarns. 2018. Retrieved August 8, 2018 from http://supremecorporation.com/

32. Anita Vogl, Patrick Parzer, Teo Babic, Joanne Leong, Alex Olwal, and Michael Haller. 2017. StretchEBand: enabling fabric-based interactions through rapid fabrication of textile stretch sensors. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '17), 2617-2627. https://doi.org/10.1145/3025453.3025938

33. Akira Wakita and Midori Shibutani. 2006. Mosaic textile: wearable ambient display with non-emissive color-changing modules. In *Proceedings of the SIGCHI Conference on Advances in Computer Entertainment Technology* (ACE '06), Article 48. https://doi.org/10.1145/1178823.1178880

34. Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. 2015. iSkin: flexible, stretchable and visually customizable on-body touch sensors for mobile computing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '15), 2991-3000. https://doi.org/10.1145/2702123.2702391

35. Martin Weigel, Aditya Shekhar Nittala, Alex Olwal, and Jürgen Steimle. 2017. SkinMarks: enabling interactions on body landmarks using conformal skin electronics. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '17), 3095-3105. https://doi.org/10.1145/3025453.3025704

36. Mark Weiser. 1999. The computer for the 21st century. *SIGMOBILE Mob Comput Commun Rev* 3, 3: 3-11. http://dx.doi.org/10.1145/329124.329126

37. Raphael Wimmer and Patrick Baudisch. 2011. Modular and deformable touch-sensitive surfaces based on time domain reflectometry. In *Proceedings of the SIGCHI Symposium on User Interface Software and Technology* (UIST '11), 517-526. https://doi.org/10.1145/2047196.2047264

38. Lining Yao, Sayamindu Dasgupta, Nadia Cheng, Jason Spingarn-Koff, Ostap Rudakevych, and Hiroshi Ishii. 2011. Rope revolution: tangible and gestural rope interface for collaborative play. In *Proceedings of the SIGCHI Conference on Advances in Computer Entertainment Technology* (ACE '11), Article 11, 8 pages. http://dx.doi.org/10.1145/2071423.2071437

39. Sang Ho Yoon, Ke Huo, Yunbo Zhang, Guiming Chen, Luis Paredes, Subramanian Chidambaram, and Karthik Ramani. 2017. iSoft: a customizable soft sensor with real-time continuous contact and stretching sensing. In *Proceedings of the SIGCHI Symposium on User Interface Software and Technology* (UIST '17), 665-678. https://doi.org/10.1145/3126594.3126654

40. Clint Zeagler, Scott Gilliland, Haley Profita, and Thad Starner. 2012. Textile interfaces: embroidered jog-wheel, beaded tilt sensor, twisted pair ribbon, and sound sequins. In *Proceedings of the IEEE International Symposium on Wearable Computers* (ISWC'12), 60-63.

41. Clint Zeagler, Scott Gilliland, Stephen Audy, and Thad Starner. 2013. Can i wash it?: the effect of washing conductive materials used in making textile based wearable electronic interfaces. In Proceedings of the ACM International Symposium on Wearable Computers (ISWC '13), 143-144. https://doi.org/10.1145/2493988.2494344

42. Yang Zhang, Gierad Laput, and Chris Harrison. 2017. Electrick: low-cost touch sensing using electric field tomography. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '17), 1-14. https://doi.org/10.1145/3025453.3025842