SensorSnaps: Integrating Wireless Sensor Nodes into Fabric Snap Fasteners for Textile Interfaces

Artem Dementyev
MIT Media Lab
Cambridge, MA
artemd@media.mit.edu

Tomás Vega Gálvez
MIT Media Lab
Cambridge, MA
tomasero@media.mit.edu

Alex Olwal
Google Inc.
Mountain View, CA
olwal@acm.org

ABSTRACT

Adding electronics to textiles can be time-consuming and requires technical expertise. We introduce SensorSnaps, low-power wireless sensor nodes that seamlessly integrate into caps of fabric snap fasteners. SensorSnaps provide a new technique to quickly and intuitively augment any location on the clothing with sensing capabilities. SensorSnaps securely attach and detach from ubiquitous commercial snap fasteners. Using inertial measurement units, the SensorSnaps detect tap and rotation gestures, as well as track body motion. We optimized the power consumption for SensorSnaps to work continuously for 45 minutes and up to 4 hours in capacitive touch standby mode. We present applications in which the SensorSnaps are used as gestural interfaces for a music player controller, cursor control, and motion tracking suit. The user study showed that SensorSnap could be attached in around 71 seconds, similar to attaching off-the-shelf snaps, and participants found the gestures easy to learn and perform. SensorSnaps could allow anyone to effortlessly add sophisticated sensing capacities to ubiquitous snap fasteners.

Author Keywords

Wireless sensor nodes, wearables, textile interfaces, ubiquitous computing, low-power

CCS Concepts

- Human-centered computing -> Interaction devices; Interaction techniques; User interface design

INTRODUCTION

Recent advances in materials and electronics have inspired a surge in the development of more seamless and ubiquitous wearable devices. In particular, the potential for integrating electronics and wearable interfaces into clothing has been shown to be particularly promising. It is, however, challenging to augment clothing with electronics, given that we need to consider the whole lifetime of a garment, which includes manufacturing constraints, end-user customization, and maintenance.

UIST'19, October 20–23, 2019, New Orleans, LA, USA

DOI: http://dx.doi.org/10.1145/3332165.3347913

Figure 1. SensorSnaps embed miniaturized electronics into generic snap fasteners, making it possible to augment garments with wireless electronics that enable on-device gesture recognition, wireless connectivity, motion tracking with sensor fusion, and touch sensing. A) SensorSnaps replace buttons on a shirt. B) SensorSnaps are used as cufflinks. C) The exploded CAD model of a SensorSnap. The electronics and the battery are contained inside the case. D) Integration with off-the-shelf plastic snap fasteners (in yellow).

Recent projects [29, 31] have contributed yarn-level innovations for integration at the manufacturing stage that are compatible with existing textile processes. These projects have the potential to enable interactive textiles with predefined capabilities in the garments at scale. The academic and maker communities complemented these efforts by leveraging traditional craft techniques for customization and modifications of existing textiles [37, 2, 28, 29]. These projects tend to integrate electronics through sewn connections, where adding and removing functionality may require time and specialized skills. Unfortunately, most electronic textiles also result in stiff areas due to the need to accommodate rigid components.

We observe that many garments consistently employ small, rigid parts for both functional and decorative purposes, such as buttons or fasteners in places where the fabric should support reconfigurability, for opening, closing, folding, or changing its length. *SensorSnaps* leverage advances in miniaturized electronics to augment such buttons with interactive capabilities without manufacturing dependencies. We specifically focus on one button category, snap fasteners, as they are widely available and allow integration into clothing with limited knowledge and tools. They also provide minimal constraints for attachment and removal, which is beneficial for flexibility in customization and maintenance.

We imagine that future SensorSnaps could be inexpensive and widely available interactive clothing fasteners for purchase from textile suppliers or in fabric stores. This could allow individuals, as well as manufacturers, to easily augment garments with wireless electronics and sensors. Thus, in addition to standalone operation, our approach can seamlessly co-exist with electronics for yarn-level integration, as well as craft-based techniques.

SensorSnaps enable many applications that could leverage touch and motion sensing, as well as ubiquitous sensor networks, since they can be added anywhere on clothing or textiles. For example, activity tracking or motion sensing during sports activities could be implicitly captured by SensorSnaps on the clothing, as an alternative to wearing smartwatches or Velcro-strapped sensor nodes. Instead of using separate remote controls or external sensors, SensorSnaps could be used to add gestural control on clothing, for example, on shirt cuffs to control heads-up displays, an in-car navigation system, or a slide presentation. Figure 1 shows SensorSnaps replacing the original buttons on a shirt.

In this paper, we demonstrate how the generic snap fastener can be augmented with miniaturized electronics that perform on-device gesture recognition, wireless connectivity, motion tracking with sensor fusion, and touch sensing, with the potential for all-day battery life under episodic use. We discuss how to design such devices in order to meet stringent power and size requirements, and conduct a technical evaluation to characterize our novel hardware. We develop multiple applications to show potential capabilities and discuss the results from a qualitative user study to evaluate the interactions and applications enabled by SensorSnaps.

The contributions of this paper are as follows:

- *Miniaturized wireless sensor node* implementation that integrates into snap button caps.
- *Technical evaluation and characterization* of power, cost and IMU performance.
- *SensorSnaps prototypes and interactions*, such as media player control, body motion tracking and alternative input for accessibility.
- *Qualitative user evaluation* that assesses the potential of our prototypes and interactions.
- *Low-power firmware* that uses IMU data to detect gestures, such as tapping and rotation. The SensorSnaps have a continuous battery life of 45 minutes or 4 hours in capacitive touch standby mode.

RELATED WORK

In this section, we review related work relevant to SensorSnaps. We are not familiar with any work that directly integrates electronics into snap fasteners. Most of the research looks into integrating electronics into the fabrics. Metal snap fasteners have, however, been used in smart fabrics as connectors from conductive fabric to circuit boards [5, 48] or as antennas [8], given great electrical conductivity when closed and support for soldering to the material.

Digital Jewelry, Wearables, and Accessories

In recent decades, there has been an increasing interest in combining electronic capabilities into objects that are worn, while respecting the aesthetics, style, and function of users and their garments. Researchers at IBM were particularly interested in exploring new wearable pervasive devices with an approach "that is based in jewelry design, not in technology" [26]. Versteeg et al.'s design exploration emphasizes the aesthetic importance of interactive jewelry [46] and Silina et al. [41] analyze 187 jewelry-like devices, particularly highlighting the opportunities with interchangeable modules that could be used in different locations and enclosures. These reviews identify a broad interest in consumer devices for communication, notification, and fitness, which are disguised as discrete neutral objects (Ditto [12], Smartstones [10]), jewelry (Misfit Shine [27], Ringly [34]) or clothing (Burton Mix Master Glove [7]), in form factors that are designed to blend into established fashion and social norms.

Inspired by this work, we created SensorSnaps, miniaturized modules that can be used in various form factors. In this paper, we focus on the novel capabilities enabled through our snap fastener integration, which opens up new possibilities for seamless integration with the most common clothing and accessories.

Motion-based interactions

Early work by Rekimoto [32, 33] and Hinckley at al. [20] showed various opportunities to leverage touch and accelerometers for expressiveness and context-detection for mobile interaction while being integrated inside devices or under garments. Whack Gestures, for example, proposes casual eyes-free accelerometer-based interaction with a phone in the user's pocket [21]. With more popularized head-worn displays, many such techniques have been implemented for wearable computing platforms, such as smart eyewear [22]. Most approaches emphasize self-contained sensing techniques, although examples exist where external passive objects with useful properties can enable new possibilities, for example by sensing changing electric fields caused by the motion of worn rings with embedded magnets[17, 3].

The use of accelerometers and gyroscopes is an attractive option for gesture sensing as they can be hidden, do not require direct physical contact for activation, can reduce mechanical complexity compared to physical switches, and can be configured to use minimal power in sleep modes. The use of IMUs for gesture sensing on mobile phones [19], tablets [40] and watches [25] is indeed well studied in the research community, especially in the Human Activity Recognition field [6, 24].

Recent miniaturization, cost reduction, and low-power improvements have popularized IMUs for gesture detection in many commercial products, such as Apple Airpods [1] and Google Pixel Buds [15], where tap gestures are used for media and device control. Other recent products include Samsung Gear IconX [36] and Sony Xperia Ear Duo [42]. Single and double tap detection is in fact built into many state-of-the-art IMUs such as BMX055 by Bosch [39] or LSM6DSOX by STMicroelectronics [43]

In this work, we want to extend the opportunities demonstrated through worn or held device form factors with the SensorSnaps approach, where motion-based sensing can be embedded at manufacturing time for discrete and direct integration on the garments themselves, through scalable augmentation of existing snap fastener components.

Body Sensor Networks

The early development of small and low power wireless sensors, such as the Berkeley Mote [16], enabled body sensor networks (BSN). A body sensor network is a wireless sensor network in or around the human body [50]. This field is concerned with connecting low power wireless sensors around the body, which could be wearable or part of smart garments. Most of the applications are in the physiological medical sensing domain [16] or activity sensing, such as human motion tracking. The XSens system [35], for example, uses up to 17 wireless inertial measurement units strapped to the body.

Similarly, SensorSnaps enables a body sensor network using Bluetooth communication to coordinate and collect data from a cluster of distributed modules. We particularly emphasize the importance in our work of being able to be flexible with location and placement, given our goal of following the existing style or design of the garment.

Electronic textiles

Smart fabrics became more accessible to larger audiences with the introduction of the LilyPad kit [5, 4]. Using off-the-shelf parts, the LilyPad simplified the interfacing of fabric and microcontroller by providing modules with different functionality that can be sewn together on fabric using conductive thread. This craft-based approach to smart textiles has been popular in many research projects that experiment with ways to integrate interfaces directly in clothing, in the spirit of Rekimoto's GesturePad [33]. FabriTouch [18] uses pants with conductive fabric for touch, whereas PinStripe leverages sewn patterns to track how the user interacts with rolled fabric. Sewing has also been used for multi-layer e-textiles [13], stretch-based interactions [47], and for detecting bends and fabric folds [14].

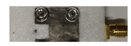
	Example	Textile compatibility (ease of integration)	Straightforward to attach/detach	Size
Woven or knitted sensors	 I/O Braid [28]	❌ No	❌ No (Soldered)	•
Sewn with conductive thread	 LilyPad [5]	❌ No	❌ No (Soldered + Sewn)	●
Attached with straps and velcro	 XSens [35]	❌ No	✅ Yes (Straps / Velcro)	⬤
Clothing buttons integrated	 Textile Antenna [8]	✅ Yes	❌ No (Sewn)	•
Embedded in snap fastener	 SensorSnaps	✅ Yes	✅ Yes (Screw)	•

Figure 2. Comparison of different wearable device attachment methods according to our design criteria.

For more advanced interactions, zebra fabric with alternating conductive/non-conductive strips has been employed in several projects. By using two orthogonally arranged layers, separated with piezo-resistive fabric, touch [38], pressure [23] and deformation [30] can be sensed to track movement, gestures and folding.

More recently, projects have also investigated how to enable interactive textiles at scale. RESi [29] and Project Jacquard [31] use yarn-based innovations to enable textiles that are compatible with existing manufacturing to produce garments with embedded resistive pressure-sensing or capacitive touch capabilities, respectively. I/O Braid [28] proposes a self-contained design that can be used to retrofit mass-produced garments with interactive capabilities, for example, by replacing drawstrings in sportswear (e.g, hoodies).

Inspired by these efforts to enable interactive textiles at scale, we envision SensorSnaps as a complementary approach where embedding miniaturized electronics in existing mass-producible snap fastener components provide additional options for interactive textiles to product designers and engineers.

SENSORSNAP DESIGN

In this section, we describe the design of SensorSnaps. The following principles guide the design:

- *Compatibility* with off-the-shelf clothing. Require minimum redesign of current technology to allow seamless integration and installation into existing clothing.
- *Quick attachment and detachment.* The SensorSnaps should be quick to add and remove from the clothing.
- *Low power*, as power is a constraint for small wearable devices. Have a battery life of at least a few hours and should be rechargeable.
- *Small and lightweight footprint*, so they are not obtrusive during everyday wear. Commercial snap fasteners are typically 9–15 mm in diameter. Furthermore, the SensorSnaps should not weight more than a few grams, which is comparable with off-the-shelf metal snaps (up to 1g).

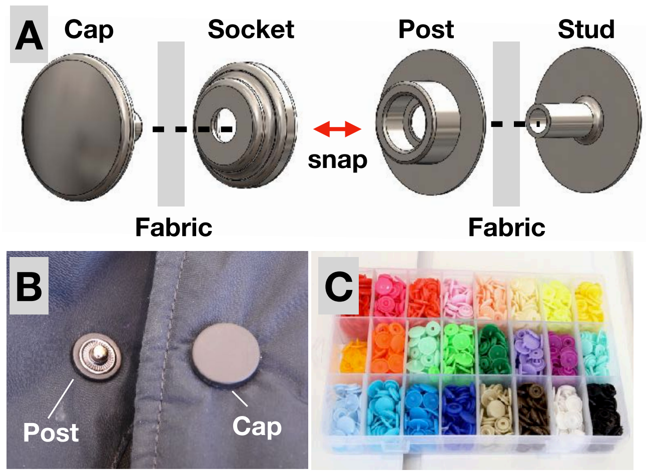


Figure 3. A) Parts of a standard snap fastener. One side of the fabric is sandwiched between the cap and socket. The other side is sandwiched between the post and stud. For attachment, post snaps into the socket. In this work, we modified the cap only. B) Example of metal snap fasteners on a winter jacket. C) Plastic snap fasteners of various sizes, shapes and colors.

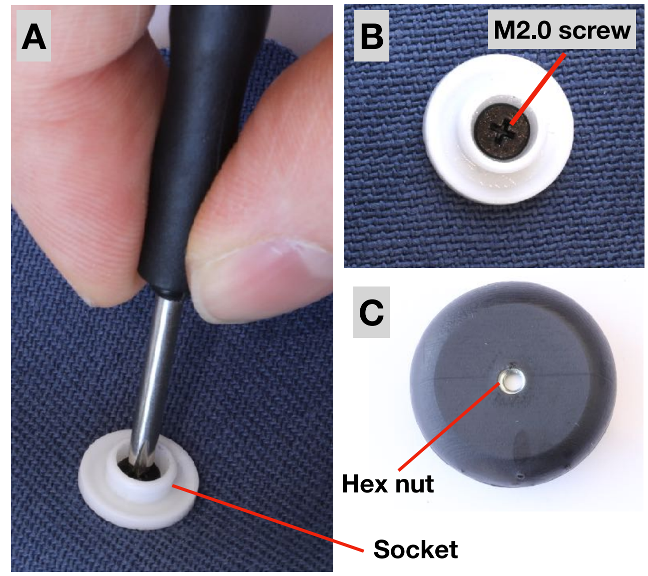


Figure 4. Attachment of SensorSnaps to the fabric. A) Using a screwdriver to attach the SensorSnap to the plastic socket (white, off-the-shelf component). SensorSnap is on the other side of the fabric. B) The white socket after it is attached to the SensorSnap. C) SensorSnap backside, showing the hex nut screw hole.

- *On-device sensing, computation and communication*. This allows multiple SensorSnaps to function independently, for easy integration and also as building blocks for complex and distributed wearable systems.

Methods to attach electronics to body

Guided by our design principles, in this section we review the advantages and disadvantages of potential body attachment methods. The potential methods are summarized in Figure 2. Integrating technology directly into textiles can enable more seamless designs, but is difficult to customize due to the challenges of bridging soft and hard components in the textile-electronics interface. Straps and velcro can be used to attach electronics to clothing or body quickly, but do not integrate into clothing. Buttons clothing fasteners with small electronics integrate well into clothing but need to be permanently sewn. Commonly, such buttons are thin so they can be pushed through a buttonhole and contain four holes for sewing. Their small size and thread holes in the middle makes it hard to include electronics. The Snap fastener method fits our design criteria best but has disadvantages as well. This method is not as quick as using straps. Also, it does not work aesthetically well for all types of clothing, especially if they lack fasteners. For example, SensorSnaps would look out of place on a t-shirt. SensorSnaps are designed towards dress shirts and jackets, as well as cardigans, blouses, and pants with snaps over the pockets.

Snap fasteners in fabrics

As shown in Figure 3, common snap-buttons contain four parts. They are typically made from plastic or metal. To connect two pieces of fabric, a cap and socket on one side of the fabric, snap into a post and stud, using a friction-based snap fit. In our design, we only modify the cap part of the fastener. The cap is the part facing the outside so that it can be used for gestures.

Our primary considerations for our snap fastener attachment was to avoid damage to the sensitive circuit during assembly, creating a removable connection, and enable easy and quick installation. We thus considered each of the three different methods to attach snap fasteners to the fabric.

1. *Sewn connection.* Snap fasteners can be sewn to the fabric. We did not use this method as sewing is time-consuming and creates a permanent connection. Removing the fastener requires cutting the threads.

2. *Crimping tool.* Another approach is to use a specially designed crimping tool. The fabric is sandwiched between two parts of the snap faster, and the crimping tool applies a force to deform a specially designed area of the snap to make a permanent connection. The crimping tool produces large forces on the snap fastener, which are challenging to withstand for electronics and 3D-printed parts. Also, it creates an undesirable permanent attachment, as buttons might need to be removed for reconfigurability or washing.

3. *Screw.* Another way is to secure the two parts with a screw, which fits our use cases well. The screw is removable and does not damage the electronics. We considered all three approaches, but using the screw was the most appropriate based on our criteria.

Attaching and detaching SensorSnaps

To attach the SensorSnaps to the fabric, the following steps are required (See Figure 4). First, a hole is punched in the fabric. This can be done by simply pushing the sharp end of an off-the-shelf cap through the fabric or with a die hole punch for thick fabric or leather. Second, the SensorSnap cap and off-the-shelf socket are placed on opposite sides of the hole.

A screw is added on the socket side to secure cap and socket. The post and stud side can be attached in a standard way using a fabric crimp tool.

Detaching commercial crimp snaps is difficult and requires destroying the snap with snippers (sewing scissors) or pliers. The SensorSnap can be quickly separated by removing the screw. The removal process leaves a small screw hole, but it becomes less noticeable over time. The hole is formed mainly by the displacement of the fibers, which over time tend to return to their original position.

Electronics

We designed and manufactured a 12mm diameter custom-made circuit board, as shown in Figure 5. We use the nRF52832 (Nordic Semiconductors) as the brain of each button, which contains an ARM Cortex M4F, as well as a wireless 2.4GHz radio. We employ the Bluetooth Low Energy (BLE) protocol, which can connect to a mobile phone or a computer and has low power consumption [11]. We chose the nRF52832 because of its small size and integrated BLE radio. Also, we added a 9-axis inertial measurement unit (IMU). Specifically, we use BNO055 (Bosch) as it contains onboard sensor fusion functionality for absolute orientation. We use a 10mAh lithium polymer battery (PGEB201212, General Electronics Battery Co.) to power the device. Lithium polymer batteries are currently the only batteries on the market that satisfy our energy density and size requirements. Also, the circuit board has a 20-pin connector for charging, programming and as an expansion port for additional functionality. We created an adapter that provides access to battery pins that are used to charge with an external charger and programming pins (Figure 5C). The PCB was too small to fit a standard port, such as micro USB.

Mechanical parts

We designed a custom enclosure for the electronics, that can replace the cap of the snap fastener. The enclosure is shown in Figure 6. All the parts were 3D printed using an SLA 3D printer (Form 2 and Black V4 resin, Formlabs). The designed enclosure had to fit with the standard snap fasteners and remain robust and small. The snap button interfaced with the socket using an M2.0 hex nut and a 4mm long screw. We used a flat head screw, so it does not interfere during snapping. The M2.0 screw was the largest size that could fit with the standard plastic snaps.

The total weight of the SensorSnap is 2.4 grams (electronics: 0.6g, battery: 0.6g, mechanical parts: 1.2g). The off-the-shelf plastic caps weight 0.1 grams and metal caps weight 0.8 grams.

Wireless Sensor Network

Multiple sensor snaps form a simple sensor network of Bluetooth nodes. We use a star topology with one central node and SensorSnaps as peripheral nodes, as shown in Figure 7. After turning on, SensorSnaps start advertising their name on the BLE network. The central node is continuously scanning for more SensorSnaps, even if some are already connected. The central node automatically attempts to connect to new SensorSnaps that are discovered.

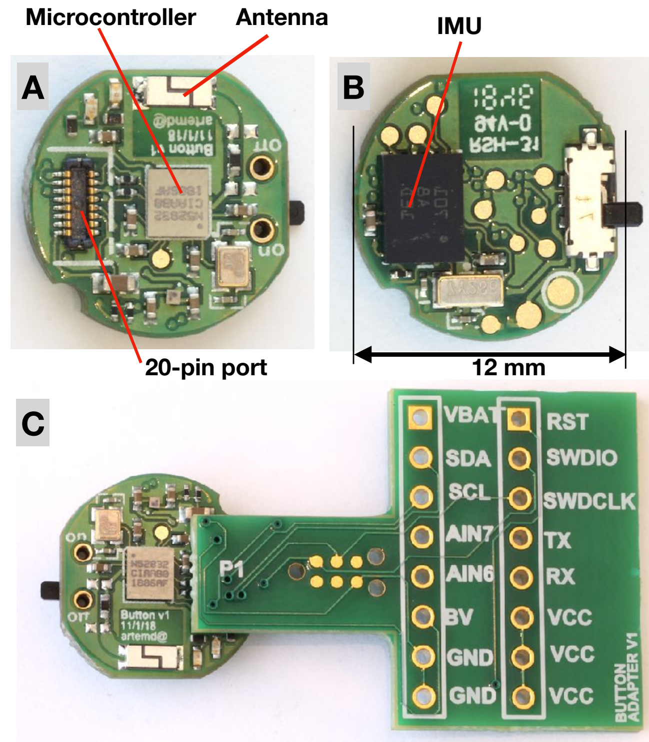


Figure 5. Printed circuit board (PCB). A) Top side with nRF52832 (Nordic Semiconductors) microcontroller, antenna and 20-pin port. B) Bottom side with BNO055 IMU (Bosch) and on/off switch. C) Programming and charging connector for 20-pin port.

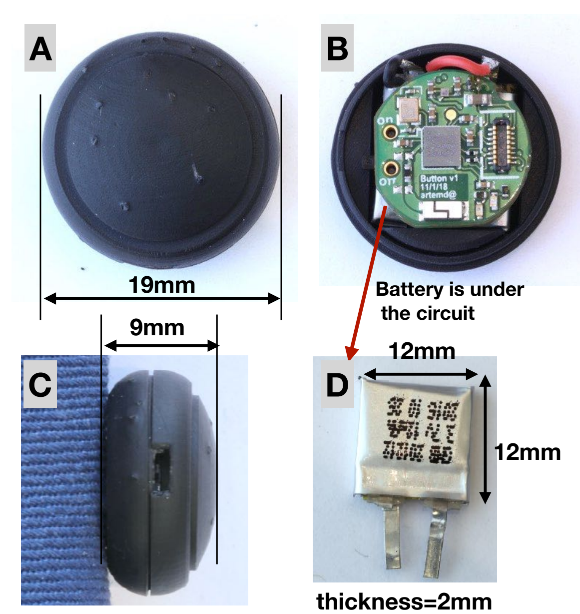


Figure 6. The 3D printed mechanical enclosure design. A) SensorSnap with the lid attached. B) SensorSnap without the lid, showing the PCB and the battery behind the PCB. C) The enclosure from the side. D) 10 mAh lithium polymer battery (PGEB201212, General Electronics Battery Co.) with a thickness of 2mm.

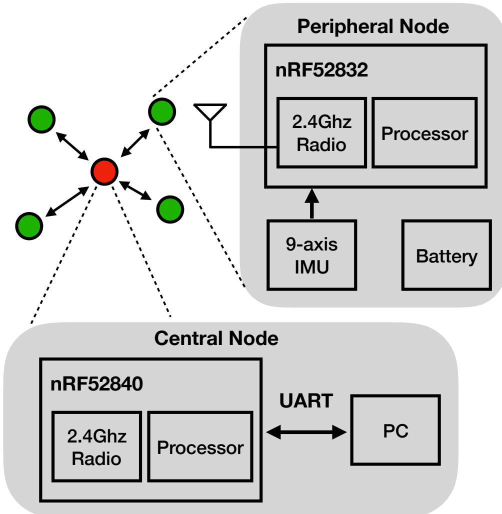


Figure 7. System diagram of the wireless network. SensorSnaps are the peripheral BLE nodes, which connect to one central node.

Our BLE network requires a central node to manage the connections. Many devices can act as a central node. We alternated between a MacBook Pro, an Android phone, and an NRF52840 development board (NRF52840 DK, Nordic) as central nodes. Technical evaluations and development were done with the NRF52840 dev board as a central node as it provided full chip-level access to BLE and debug interfaces, which were not as conveniently accessible when using the built-in Bluetooth in a MacBook or a phone. For our applications, we used an Android phone or the built-in Macbook Bluetooth as the central node.

To conserve energy, SensorSnaps only send data over Bluetooth when an event, such as a tap, is detected. The central node is always listening for new data. For continuous gestures, such as rotation, the SensorSnaps are capable of sending data continuously at a rate of 50Hz. The continuous mode is only used sporadically.

SENSING

The gesture detection is done on-board the SensorSnaps. Streaming raw data is not energy efficient as the wireless transmission is power intensive. The data is sent only when gestures are detected.

Tap gesture detection

The tap gesture uses the accelerometer to detect when the SensorSnap is tapped. The particular IMU that we used did not have built-in tap detection, so we implemented it in firmware. Our algorithm is based on a slope detection method, which is implemented in some IMUs (e.g., BMX055). The accelerometer's three axes are sampled at 33Hz. To subtract gravity, the slope of the accelerometer is calculated at every new data point. An example of the accelerometer data during a tap is shown in the Figure 8. When the slope reaches a threshold, a tap gesture is registered and transmitted over Bluetooth.

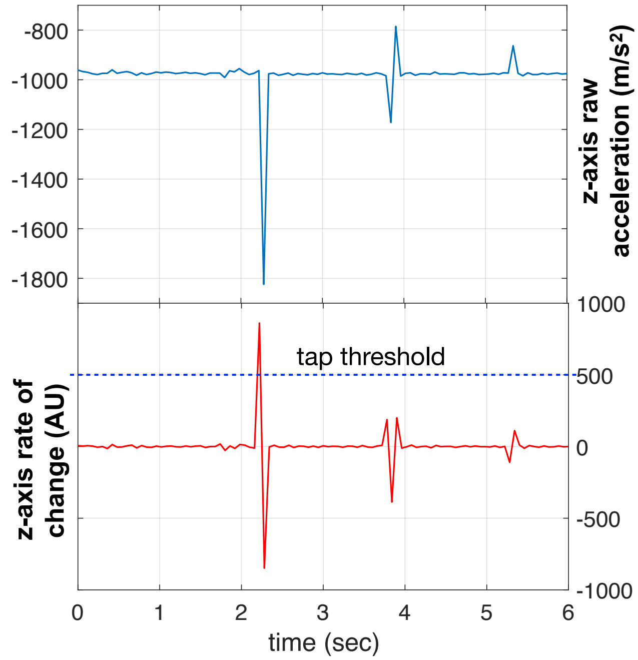


Figure 8. Example data from the accelerometer during a tap. Rate of change of the raw acceleration is used to detect taps.

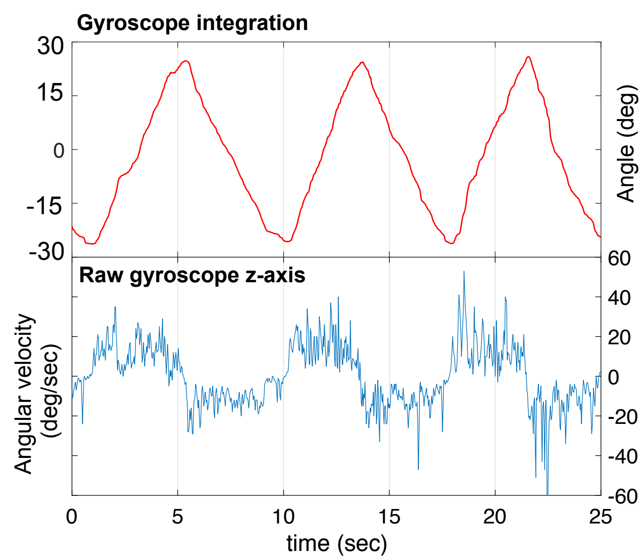


Figure 9. Example data from the gyroscope during left and right rotation. Raw angular velocity is integrated to obtain rotation angle.

Rotation gesture detection

The rotation gesture uses the gyroscope to detect the rotation of the SensorSnaps. To obtain the rotation angle, the z-axis of the gyroscope angular velocity is integrated at 33Hz. An example of the data is shown in Figure 9.

Capacitive touch sensing

The touch gesture detects when the SensorSnap is being touched. This gesture uses a capacitive sensing electrode

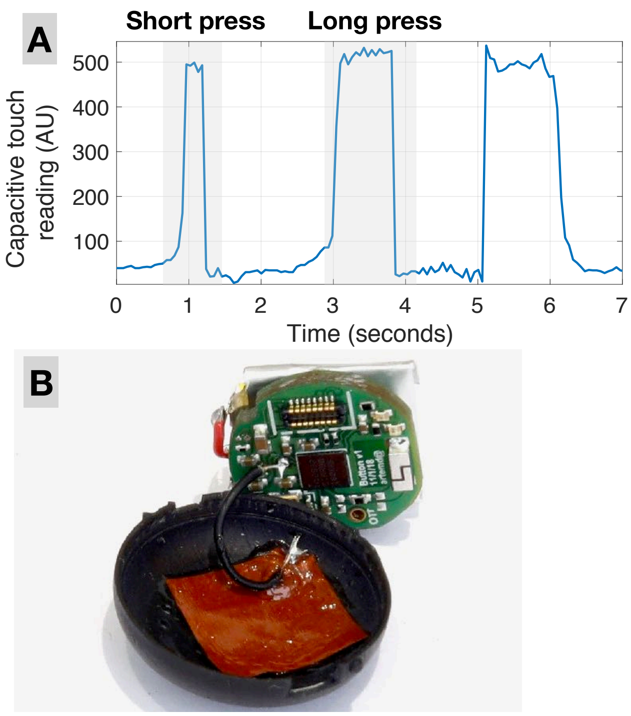


Figure 10. Capactive touch sensing. A) Example of capacitive touch raw data for long and short presses. B) The capactive touch electrode is shown on the back of the lid.

on the back of the SensorSnap's lid. The electrode is made out of plastic-backed copper foil (Pyralux AP, DuPont), cut by hand and attached with epoxy. The electrode is soldered to a pin of a microcontroller and uses the manufacturer's firmware driver [45].

We mainly employ capacitive touch gesture detection for wakeup. It is similar to tap detection but detects direct touch; therefore it is more robust to motion artifacts. Furthermore, the touch gesture only uses the microcontroller, so it can save power by leaving the IMU in sleep mode. As a drawback, capacitive touch requires adding an electrode to the device, which takes space and time. Raw data from the capacitive touch sensor is shown in Figure 10. A simple threshold is applied to detect touch events, which is determined experimentally after the SensorSnap is placed inside the enclosure. The electrode is sampled every 25ms. No additional calibration is required for capacitive touch gestures. IMU-based gestures do not require calibration.

Power optimization

The energy is extremely constrained on the SensorSnap. We employ multiple strategies to conserve the battery and the main strategy is to stay in standby mode as much as possible.

Standby mode. The standby mode is the lowest power mode. The SensorSnap performs two primary functions in the standby mode. First, to keep the BLE connection alive. BLE packets are sent at predetermined intervals to prevent the peripheral and central clocks from drifting apart. Synchronization requires the SensorSnap to respond to the central node every 500ms. Second, the capacitive touch sensor is periodically sampled for touches. If a touch is detected, the SensorSnap goes into gesture mode.

Gesture mode. This mode allows real-time interactions with minimum latency, at the expense of power consumption. In this mode, the BLE connection interval is 15ms, which means that packets are exchanged every 15ms. The gyroscope is turned on to sense the rotation gestures. Also, capacitive sensing is turned on. If no gestures are detected for 10 seconds, the device goes back to standby mode.

Motion sensing mode. This is the most power-expensive mode, allowing for 3D orientation tracking with the IMU. The power consumption is highest since the accelerometer, gyroscope, and magnetometer are turned on. Also, the BLE connection interval is 15ms, and 30-byte packets are used. The packets contain a unique 1-byte id, quaternions, and data deliminators.

TECHNICAL EVALUATION

In this section, we evaluate the SensorSnap in terms of technical performance and usability.

Power consumption

We measure the power consumption using a digital multimeter (34465A, Keysight) in the three power modes. To capture the transient current changes due to BLE transmissions, the current was sampled at 77 Hz, and the mean current over 5-minute intervals is reported elsewhere in the paper.

The power consumption in the standby mode was 2.45 mA (8.10 mW). The SensorSnap could last 4 hours in this mode. The current in this mode is mostly consumed by the capacitive touch sensing (1.78mA), and the rest (0.68mA) is used to keep the BLE connection and timers active. By periodically turning off the capacitive sensing, the power consumption could be reduced at the expense of missing touch events. By reducing touch sensing to one percent duty cycle, the battery life could be extended to a maximum of 15 hours.

The power consumption in was 13.72 mA (45.28 mW) in the gesture mode, and 16.06 mA (53.00 mW) in the motion tracking mode. In those two modes, most energy (around 9 to 11 mA) was consumed by the IMU.

Cost

Since we believe SensorSnaps should be ubiquitous, the cost is a vital factor. If SensorSnaps are manufactured on a scale of at least 1000 units, the material and PCB cost of each unit is around $20. Currently, the most expensive part is the battery ($7.94). If the battery and electronics is obtained on a mass scale, the cost can be potentially reduced to around $8.

IMU accuracy

We evaluated the accuracy of gyroscope angles in comparison to reference angles. The gyroscope was moved from 0 to 180 degrees in z-axis in ten-degree increments. The gyroscope integration mean error was 3.53 degrees (Standard deviation:$\pm$1.62). We tested for gyroscope drift, and no drift was measured over 10 minutes on a stationary device. See Figure 11.

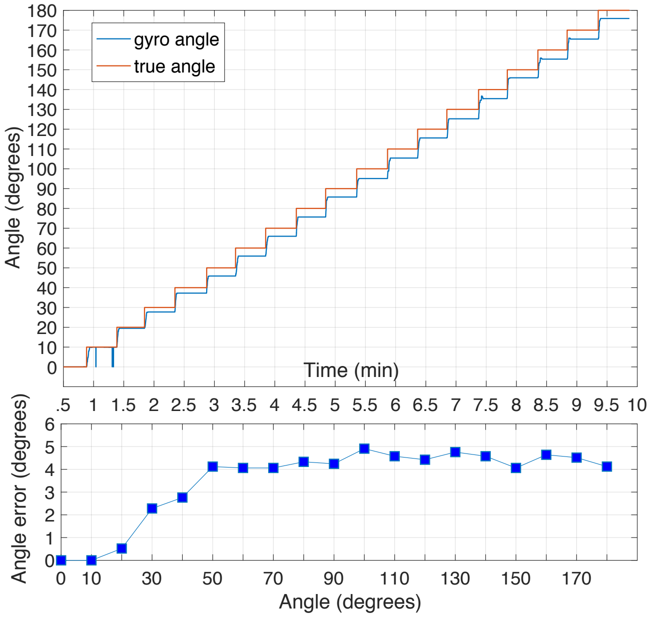


Figure 11. Gyroscope angle in comparison to the reference angle. The error between the gyro angle and the true angle is plotted on the bottom for each angle.

We did not quantify the tap gesture as it is based on the existing off-the-shelf implementations on a different version of the IMU from the same manufacturer (BMX055, Bosch). Also, as we used a standard capacitive touch library, we did not find it necessary to perform a detailed evaluation. In the simple test, the SensorSnap was able to wake up and transmit a packet over BLE in 142 out of 150 finger touch events (94.7%).

USER EVALUATION

In this section, we wanted to understand the usability of SensorSnaps as well as gain insight on how it will be used in the future. We conducted an informal user study with 10 participants, 22–35 years old (4 female). Each session took 20 minutes. As we imagine that people with different backgrounds and skills would use SensorSnaps, we recruited participants with diverse backgrounds: electrical engineers, mechanical engineering, designers, and artists. The user study was composed of three stages:

Usability. We introduced the participants to the functionality and purpose of SensorSnaps. Participants wore a shirt with a SensorSnap as one of the front buttons. They were asked to interact with the device and perform the tap and rotate gestures. The gesture data was visualized on a PC screen for real-time feedback. We did not collect quantitative data for the gestures. The rotate gesture was evaluated with reference angles.

Attaching to fabric. We wanted to gain an understanding of the effort required to add SensorSnaps in comparison to a standard fastener. The participants were thus first asked to connect the SensorSnap to a piece of cloth. In the second task, they connected off-the-shelf snap fasteners. Both tasks were timed and performed once.

Post-study questionnaire. The participants were asked to imagine potential applications of SensorSnaps as well as rank predetermined applications. The feedback was meant to inform the continued work and design of future applications.

Gestures

All the participants found the tap and rotate gestures to be easy to learn (mean:4.9, standard deviation:$\pm$0.31) and perform (4.7$\pm$0.48). The scale ranged from 1 (hard to learn) to 5 (easy to learn). Generally, the participants liked interacting using the gesture set. However, the participants did not find the gestures to be particularly subtle (2.7$\pm$1.41). One participant found the location on the shirt to be awkward and preferred the SensorSnap to be on the side of the hip or cufflinks. Another participant found that the overall torso movements has a large effect on rotation gesture, and hoped to remove this effect in the future. Four participants suggested adding other touch gestures such as rubbing, swiping, and pressure-sensitive touch. Two participants suggested pulling or tugging gestures. Also, two participants suggested detecting the snapping to be used as a switch.

Attachment

Attachment of the SensorSnaps took slightly longer (71sec$\pm$30) than off-the-shelf plastic snaps (63sec$\pm$32). In the survey results, the level of difficulty was the same for both (4.3). The crimp tool used for the commercial plastic snaps was difficult for some participants, and required multiple attempts, thus explaining higher standard deviation. One participant pointed out that SensorSnaps could attach with no screw, using a metal spike. Due to the learning curve, we believe that the tasks could be performed faster if done multiple times, such as in a factory setting.

Suggested application ideas by participants

The participants were asked to suggest application ideas. The most popular application theme was gestural control of other devices, as suggested by eight participants. Suggestions included using SensorSnaps to control a computer during a presentation, interact with a smartphone to reply to a call or a text, control of a music player, and navigate the contents of an audiobook.

The second application theme was sensing. SensorSnaps could be used for biosignal detection (heart and respiration rate), activity and movement logging or environmental sensing (UV exposure, temperature, humidity).

Ranking of previously defined application scenarios

The participants were then asked to rank our previously developed application ideas. They found the music controller to be the most compelling (4.4), followed by motion tracking (4.3), and augmentation of shirt cuffs (4.2) to enable subtle gestures.

APPLICATIONS

In this section, we introduce potential applications of SensorSnaps. The applications were based on the feedback from the user study.

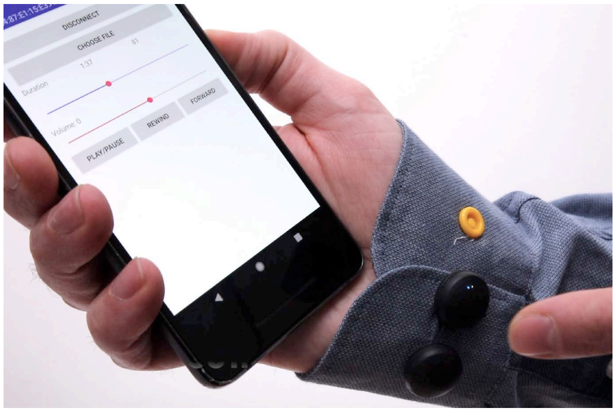


Figure 12. Music controller on the cuff buttons for a mobile device.

Snap cap music controller

As a basic functionality, SensorSnaps can replace snap fastener caps on off-the-shelf clothing. We replaced cufflinks on a dress shirt with SensorSnaps, as shown in Figure 12. The SensorSnap was connected to a music controller Android app running on a mobile phone (Google Pixel 2) through Bluetooth. The app permitted choosing an audio file (i.e., song, podcast, audiobook), and using the tap gesture to either play or pause the audio file. The rotation gesture allowed to change the volume of the audio being played. Direction of rotation increased or decreased the volume level. The angle controlled the magnitude of the volume change. Double-tapping allowed to change between volume and time modes. In the time mode, the rotation gesture is reused for either fast-forwarding or rewinding of the audio. Direction of rotation triggers fast-forward or rewind. The angle of the rotation controlled the speed of the fast-forwarding or rewinding.

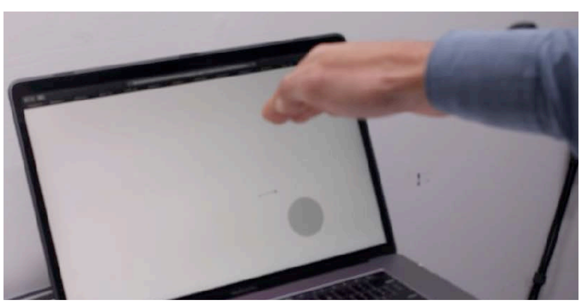


Figure 13. Cursor control using the gyroscope as an assistive input device. In this demonstration, the cursor is moved to a target on a laptop.

Assistive devices

The SensorSnaps could be potentially useful as interfaces for Augmentative and Alternative Communication. Users with motor impairment might have different capabilities from what standard interfaces allow [44, 49]. The SensorSnaps could be placed anywhere on the clothing. The number and the location of the SensorSnaps could be tailored to individuals' needs.

In this application we imagine an individual with limited or no finger control, making it hard to use standard hand-controlled input interfaces. We added a SensorSnap to the shirt's cuff. By supination and pronation of the forearm, and movement, flexion, and extension of the arm, the SensorSnap was used as a pointing device for a computer screen (Figure 13). The x-coordinate would move proportional to changes in the x-axis, while the y-coordinate to changes in the y-axis of the gyroscope.

Figure 14. Multiple SensorSnaps were attached to the arm and the torso for for motion tracking. The resulting 3D animation is shown on the computer screen.

Body motion tracking

Motion tracking can provide useful information for sports, medicine and gesture-controlled devices. Traditionally, optical motion tracking is done by tracking reflective markers with multiple cameras. Using 9-axis IMUs attached to different body parts, motion tracking can be done without external cameras. Currently, the IMU approach is still cumbersome and requires a special suit equipped with IMUs. The SensorSnaps could be added to off-the-shelf clothing to enable motion tracking on demand. We attached SensorSnaps to the arm, forearm and torso and quaternion orientation data is continuously sent to the computer. To visualize the data, the quaternions are received in Blender, and used to control the limbs of a virtual animated character. The animation was based on MotioSuit Python scripts [9]. See Figure 14.

LIMITATIONS AND FUTURE WORK

Charging: Contactless or magnetic connector. In the future, charging should be done without the need to remove the top part of the cap. This could allow the SensorSnap to be water sealed and washable. Potentially, inductive charging could be used to charge SensorSnap wirelessly. Currently, it is difficult to find a commercial inductive charging coil (Qi certified) that can fit inside the small cap. Alternatively, the snap connector could be made conductive so that it could snap to a charger. Such a design is difficult to achieve without sacrificing compatibility with off-the-shelf parts, as it requires a strong electrical contact. Furthermore, special pins could be added on the enclosure that dock to a charger using spring-loaded contacts. This solution is similar to what is implemented in many wearable devices such as smartwatches.

New form factors: jewelry, accessories, and attachables. In this work, the SensorSnaps are used as a replacement for caps of snap fasteners. As the fastener replacement, SensorSnaps only look appropriate with fastener-heavy clothing. In future

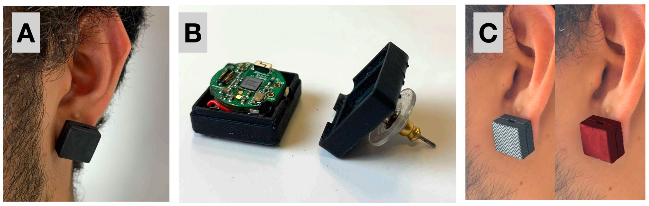


Figure 15. Alternative SensorSnaps form factors. A) SensorSnaps in an ear ring. B) The metal stud used to attach the ear ring to the ear. C) The casing could be designed in custom colors.

work, we plan to further explore the design space and interactions this technology opens. As suggested in the user study, some of the potential uses include jewelry such as earrings, bracelets, and necklaces. Potential use as an ear ring is shown in Figure 15. SensorSnaps could also be placed on belts, shoes, zippers, and backpack straps. Beyond wearables, SensorSnaps could be placed on objects and in the environment, for example, to add sensing capabilities to toys. Bluetooth RSSI (received signal strength indication) could be used to track the proximity of attachables, objects that have been attached with SensorSnaps.

Size and shape: further miniaturization. The current design is heavier and larger than most off-the-shelf snap fasters. This could make the SensorSnaps stand out in garments and reduce utility. In the future, we hope to reduce the SensorSnap to 15mm and 1g. The size of the electronics could be reduced with a more dense layout. Reducing the size of the battery is challenging and will require a custom designed round battery. Furthermore, in the future, the SensorSnaps could be integrated directly in buttons. In common 4-hole buttons, the fastening holes in the center of the buttons provide a battery integration challenge.

Software and usability. In the current implementation, there is only one type of SensorSnap. However, in the future, there might be various SensorSnaps with different sensors and actuators. To efficiently manage the multiple sensors, a scalable software layer on the PC or mobile phone will be required to configure, visualize, and control various SensorSnaps.

Power optimization. With hardware and firmware modifications, the battery should be optimized to last for at least a full day. First, the IMU should be replaced with a low power alternative. The state-of-the-art IMUs consume as little as 0.55 mA with 3D fusion (LSM6DSOX, STMicroelectronics). Second, the capacitive touch library could be further optimized for low power. Currently, it consumes 2mA, which could be lowered by disabling the timers and ADC between the samples.

CONCLUSIONS

In this work, we show that it is feasible to integrate a wireless sensor node into fabric snap buttons. We designed a screw mechanism that allows to attach and detach SensorSnaps from off-the-shelf plastic snaps quickly. We allowed participants with various backgrounds to try and attach SensorSnaps. Attachment took a similar time (71 vs. 63 seconds) and had the same degree of difficulty as commercial button snaps. We use capacitive touch to exit the standby mode and a 9-axis IMU to sense tap, rotation, and orientation. We investigate and introduce potential applications of SensorSnaps; cufflinks music controller that connects to a mobile phone. They allow to play/pause, volume control and rewind/fast-forward. In another application, we explore how clothing can be augmented for motion tracking and used as a mouse pointer in accessibility applications. One of the main design issues with SensorSnaps is the short battery life. With dynamic power optimization, SensorSnaps have a possible battery life of 4 hours in standby mode or 45-minute battery life in gesture mode.

SensorSnaps allows one to augment clothing with electronics and sensors quickly. SensorSnaps could be potentially manufactured on a large scale. We believe that SensorSnaps will pave the way for new interactive textiles that can be manipulated intuitively and integrate seamlessly, yet provide sophisticated sensing and communication capabilities.

ACKNOWLEDGEMENTS

We would like to thank the Google Bio Interfaces team, Interaction Lab, and Lego Labs for support.

REFERENCES

[1] Apple. 2019. Airpods. `https://www.apple.com/airpods/`. (2019). Accessed 2019-09-01.

[2] Jatin Arora, Kartik Mathur, Aryan Saini, and Aman Parnami. 2019. Gehna: Exploring the Design Space of Jewelry As an Input Modality. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 521, 12 pages. DOI: http://dx.doi.org/10.1145/3290605.3300751

[3] Daniel Ashbrook, Patrick Baudisch, and Sean White. 2011. Nenya: Subtle and Eyes-free Mobile Input with a Magnetically-tracked Finger Ring. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 2043–2046. DOI: http://dx.doi.org/10.1145/1978942.1979238

[4] Leah Buechley and Michael Eisenberg. 2008. The LilyPad Arduino: Toward wearable engineering for everyone. *IEEE Pervasive Computing* 7, 2 (2008), 12–15.

[5] Leah Buechley, Mike Eisenberg, Jaime Catchen, and Ali Crockett. 2008. The LilyPad Arduino: using computational textiles to investigate engagement, aesthetics, and diversity in computer science education. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. ACM, 423–432.

[6] Andreas Bulling, Ulf Blanke, and Bernt Schiele. 2014. A Tutorial on Human Activity Recognition Using Body-worn Inertial Sensors. *ACM Comput. Surv.* 46, 3, Article 33 (Jan. 2014), 33 pages. DOI: http://dx.doi.org/10.1145/2499621

[7] Casey Chan. 2011. Burton's Mix Master Gloves Can Wirelessly Control Your iPhone (Sort Of). (2011). Accessed 2019-09-01.

[8] Shengjian Jammy Chen, Thomas Kaufmann, Damith Chinthana Ranasinghe, and Christophe Fumeaux. 2016. A modular textile antenna design using snap-on buttons for wearable applications. *IEEE Transactions on Antennas and Propagation* 64, 3 (2016), 894–903.

[9] Alvaro Cifuentes. 2019. MotioSuit: An open-source, active motion capture suit. *HackaDay* (2019). https://hackaday.io/project/9266-motiosuit.

[10] Cognixion. 2015. Smart Stones. https://www.youtube.com/watch?v=2CNA2ucU5io. (2015). Accessed 2019-09-01.

[11] Artem Dementyev, Steve Hodges, Stuart Taylor, and Joshua Smith. 2013. Power consumption analysis of Bluetooth Low Energy, ZigBee and ANT sensor nodes in a cyclic sleep scenario. In *2013 IEEE International Wireless Symposium (IWS)*. IEEE, 1–4.

[12] Ditto. 2019. Ditto Wearable Technology. https://dittowearable.com/. (2019). Accessed 2019-09-01.

[13] Lucy E. Dunne, Kaila Bibeau, Lucie Mulligan, Ashton Frith, and Cory Simon. 2012. Multi-layer e-textile circuits. In *UbiComp*. 649. DOI: http://dx.doi.org/10.1145/2370216.2370348

[14] Guido Gioberto, James Coughlin, Kaila Bibeau, and Lucy E Dunne. 2013. Detecting Bends and Fabric Folds using Stitched Sensors. In *ISWC*. New York, New York, USA, 53–56. DOI: http://dx.doi.org/10.1145/2493988.2494355

[15] Google. 2019. Pixel Buds. https://store.google.com/us/product/google_pixel_buds/. (2019). Accessed 2019-09-01.

[16] Chris Guy. 2006. Wireless sensor networks. In *Sixth International Symposium on Instrumentation and Control Technology: Signal Analysis, Measurement Theory, Photo-Electronic Technology, and Artificial Intelligence*, Vol. 6357. International Society for Optics and Photonics, 63571I.

[17] Chris Harrison and Scott E. Hudson. 2009. Abracadabra: Wireless, High-precision, and Unpowered Finger Input for Very Small Mobile Devices. In *Proceedings of the 22Nd Annual ACM Symposium on User Interface Software and Technology (UIST '09)*. ACM, New York, NY, USA, 121–124. DOI: http://dx.doi.org/10.1145/1622176.1622199

[18] Florian Heller, Stefan Ivanov, Chat Wacharamanotham, and Jan Borchers. 2014. FabriTouch: exploring flexible touch input on textiles. In *ISWC*. ACM Press, New York, New York, USA, 59–62. DOI: http://dx.doi.org/10.1145/2634317.2634345

[19] Seongkook Heo and Geehyuk Lee. 2011. Forcetap: extending the input vocabulary of mobile touch screens by adding tap gestures. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services*. ACM, 113–122.

[20] Ken Hinckley, Jeff Pierce, Mike Sinclair, and Eric Horvitz. 2000. Sensing Techniques for Mobile Interaction. In *Proceedings of the 13th Annual ACM Symposium on User Interface Software and Technology (UIST '00)*. ACM, New York, NY, USA, 91–100. DOI: http://dx.doi.org/10.1145/354401.354417

[21] Scott E. Hudson, Chris Harrison, Beverly L. Harrison, and Anthony LaMarca. 2010. Whack Gestures: Inexact and Inattentive Interaction with Mobile Devices. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10)*. ACM, New York, NY, USA, 109–112. DOI: http://dx.doi.org/10.1145/1709886.1709906

[22] L. Lee and P. Hui. 2018. Interaction Methods for Smart Glasses: A Survey. *IEEE Access* 6 (2018), 28712–28732. DOI: http://dx.doi.org/10.1109/ACCESS.2018.2831081

[23] 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 *UIST*. 335–346. DOI: http://dx.doi.org/10.1145/2984511.2984572

[24] Jonathan Lester, Tanzeem Choudhury, Nicky Kern, Gaetano Borriello, and Blake Hannaford. 2005. A Hybrid Discriminative/Generative Approach for Modeling Human Activities. In *Proceedings of the 19th International Joint Conference on Artificial Intelligence (IJCAI'05)*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 766–772. http://dl.acm.org/citation.cfm?id=1642293.1642416

[25] Steven McGuckin, Soumyadeb Chowdhury, and Lewis Mackenzie. 2016. Tap'n'shake: gesture-based smartwatch-smartphone communications system. In *Proceedings of the 28th Australian Conference on Computer-Human Interaction*. ACM, 442–446.

[26] Cameron S. Miner, Denise M. Chan, and Christopher Campbell. 2001. Digital Jewelry: Wearable Technology for Everyday Life. In *CHI '01 Extended Abstracts on Human Factors in Computing Systems (CHI EA '01)*. ACM, New York, NY, USA, 45–46. DOI: http://dx.doi.org/10.1145/634067.634098

[27] Misfit. 2019. Misfit Smartwatches. https://misfit.com/. (2019). Accessed 2019-09-01.

[28] Alex Olwal, Jon Moeller, Greg Priest-Dorman, Thad Starner, and Ben Carroll. 2018. I/O Braid: Scalable Touch-Sensitive Lighted Cords Using Spiraling, Repeating Sensing Textiles and Fiber Optics. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings (UIST '18 Adjunct)*. ACM, New York, NY, USA, 203–207. DOI: http://dx.doi.org/10.1145/3266037.3271651

[29] Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner, Siegfried Bauer, and Michael Haller. 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 (UIST '18)*. ACM, New York, NY, USA, 745–756. DOI: http://dx.doi.org/10.1145/3242587.3242664

[30] 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 (UIST '17)*. ACM, New York, NY, USA, 565–577. DOI: http://dx.doi.org/10.1145/3126594.3126652

[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*. ACM, 4216–4227.

[32] Jun Rekimoto. 1996. Tilting Operations for Small Screen Interfaces. In *Proceedings of the 9th Annual ACM Symposium on User Interface Software and Technology (UIST '96)*. ACM, New York, NY, USA, 167–168. DOI: http://dx.doi.org/10.1145/237091.237115

[33] J. Rekimoto. 2001. GestureWrist and GesturePad: unobtrusive wearable interaction devices. In *Proceedings Fifth International Symposium on Wearable Computers*. 21–27. DOI: http://dx.doi.org/10.1109/ISWC.2001.962092

[34] Ringly. 2019. Smart Jewelery and Accesories. https://ringly.com/. (2019). Accessed 2019-09-01.

[35] Daniel Roetenberg, Henk Luinge, and Per Slycke. 2009. Xsens MVN: full 6DOF human motion tracking using miniature inertial sensors. *Xsens Motion Technologies BV, Tech. Rep* 1 (2009).

[36] Samsung. 2019. Gear iconX. https://www.samsung.com/global/galaxy/gear-iconx/. (2019). Accessed 2019-09-01.

[37] Mika Satomi and Hannah Perner-Wilson. 2019. HOW TO GET WHAT YOU WANT. (2019). https://www.kobakant.at/DIY/

[38] Stefan Schneegass and Alexandra Voit. 2016. GestureSleeve: using touch sensitive fabrics for gestural input on the forearm for controlling smartwatches. In *ISWC*. ACM Press, New York, New York, USA, 108–115. DOI: http://dx.doi.org/10.1145/2971763.2971797

[39] Bosch Sensortec. 2014. BMX055 Small, Versatile 9-Axis Sensor Module. *Bosch Sensortec, Baden-Württemberg, Germany* (2014).

[40] Marcos Serrano, Eric Lecolinet, and Yves Guiard. 2013. Bezel-Tap gestures: quick activation of commands from sleep mode on tablets. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 3027–3036.

[41] Yulia Silina and Hamed Haddadi. 2015. New Directions in Jewelry: A Close Look at Emerging Trends & Developments in Jewelry-like Wearable Devices. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers (ISWC '15)*. ACM, New York, NY, USA, 49–56. DOI: http://dx.doi.org/10.1145/2802083.2808410

[42] Sony. 2019. Eperia Ear Duo. https://www.sonymobile.com/us/products/smart-products/xperia-ear-duo/. (2019). Accessed 2019-09-01.

[43] STMicroelectronic. 2019. LSM6DSOX: iNEMO inertial module: always-on 3D accelerometer and 3D gyroscope. *STMicroelectronic Datasheet* (2019).

[44] Kelly Tai, Stefanie Blain, and Tom Chau. 2008. A review of emerging access technologies for individuals with severe motor impairments. *Assistive technology* 20, 4 (2008), 204–221.

[45] Einar Thorsrud. 2016. Capacitive Touch on the nRF52 series. *Nordic Semiconductor* (2016). https://devzone.nordicsemi.com/tutorials/b/design-examples/posts/capacitive-touch-on-the-nrf52-series.

[46] Maarten Versteeg, Elise van den Hoven, and Caroline Hummels. 2016. Interactive Jewellery: A Design Exploration. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16)*. ACM, New York, NY, USA, 44–52. DOI: http://dx.doi.org/10.1145/2839462.2839504

[47] 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 *CHI*. ACM, Denver, CO, USA, 2617–2627. DOI: http://dx.doi.org/10.1145/3025453.3025938

[48] Irmandy Wicaksono and Joseph A Paradiso. 2017. Fabrickeyboard: multimodal textile sensate media as an expressive and deformable musical interface.. In *NIME*. 348–353.

[49] Jacob O Wobbrock. 2019. Improving pointing in graphical user interfaces for people with motor impairments through ability-based design. In *Human Performance Technology: Concepts, Methodologies, Tools, and Applications*. IGI Global, 1193–1243.

[50] Guang-Zhong Yang. 2011. *Body Sensor Networks*. Springer Publishing Company, Incorporated.