RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns

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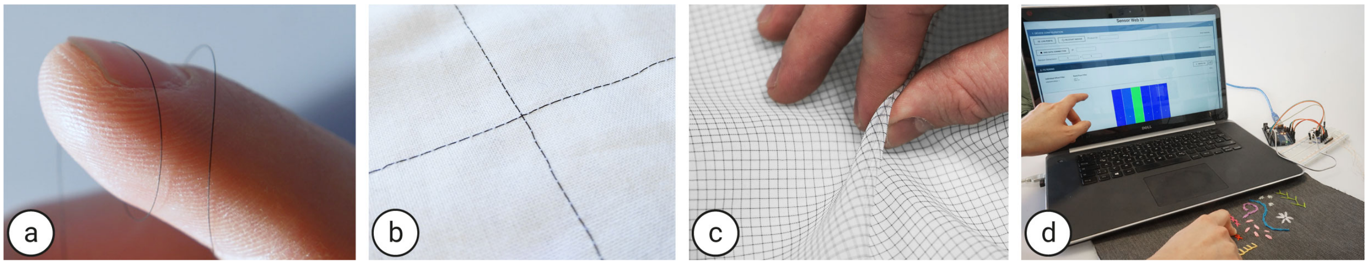

Figure 1: *RESi* is a resistive yarn-based textile pressure-sensing technology (a), which can be used in various textile manufacturing processes like sewing (b) or weaving (c). The sensing platform (d) enables a wide range of applications.

ABSTRACT

We present *RESi (Resistive tExtile Sensor Interfaces)*, a novel sensing approach enabling a new kind of yarn-based, resistive pressure sensing. The core of RESi builds on a newly designed yarn, which features conductive and resistive properties. We run a technical study to characterize the behaviour of the yarn and to determine the sensing principle. We demonstrate how the yarn can be used as a pressure sensor and discuss how specific issues, such as connecting the soft textile sensor with the rigid electronics can be solved. In addition, we present a platform-independent API that allows rapid prototyping. To show its versatility, we present applications developed with different textile manufacturing techniques, including hand sewing, machine sewing, and weaving. RESi is a novel technology, enabling textile pressure sensing to augment everyday objects with interactive capabilities.

Author Keywords

Wearable Computing, Interactive Textiles, Textile Sensor, Conductive Yarns, Manufacturing

ACM Classification Keywords

H.5.2.: [User Interfaces]: Input devices and strategies.

INTRODUCTION

Today, textiles make up an essential and indispensable part of our daily lives. Since they are generally lightweight and highly flexible, they are applicable in a wide range of applications. Beyond their traditional use in clothing, they are also used in furniture, vehicles, construction etc. In combination with electronic components, textiles can be enhanced with several additional capacities ranging from sensing and actuation to lighting and display information.

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In recent years, many computing technologies have been sewn, woven, or knitted into smart fabrics. Fabrics have been used for data storage [5, 16], for non-invasive measurement of pressure distribution on the human body [7, 19, 23, 36, 39, 41], as a display [1, 9, 21], or as an input device [18, 26, 29, 30, 35, 42, 13]. In this context there is also a significant body of work that aims to simplify the creation of interactive textiles [15, 34].

Overall, sensing approaches that were deployed in such interactive textiles can be divided into capacitive [23, 29], optical [19, 33], or resistive [7, 25, 31, 39, 41, 43] principles. Capacitive and optical sensing can be integrated easily into fabrics, as the required yarns are relatively simple. However, the required electronics to make it pressure-sensitive is more complex. The electronics for resistive sensing is comparably simple as it just requires a basic voltage divider. Until now, however, the drawback of resistive sensing approaches was their complex textile setup that required a multi-layer design [7, 25, 35, 39, 43]. This makes the approach suffer from mechanical issues, such as alignment shifts or wrinkles. However, inspired by the pressure sensing accuracy of these sensors, our vision was to develop a new kind of resistive textile sensor emphasizing the strengths and reducing the mechanical sources of errors.

In this paper, we present a pressure-sensitive textile sensor, where *the yarn itself* becomes the key component for sensing. This newly-designed and implemented yarn features a conductive core surrounded by a resistive, carbon-based coating. We introduce the yarn, describe its properties, and show how to create various interactive textile interfaces with little effort. We believe that such a sensor can be used in various DIY projects as well as in more industrial contexts and could be beneficial for many applications providing a significant additional contribution to the existing work of smart textiles. In summary, the main contributions of this paper are:

- The *presentation and technical evaluation of a novel yarn* consisting of a conductive core with a resistive coating, which can be used in various textile manufacturing processes like hand sewing, machine sewing, or weaving.

- The *design and implementation of a measurement principle* that enables the use of this novel yarn for pressure sensing.
- The *design and implementation of a sensing platform* that includes the necessary electronics as well as a platform-independent API to support a wide range of DIY projects and rapid prototyping.
- The *demonstration of different textile manufacturing techniques* in different applications, which highlight the versatility of the presented sensing technology.

RELATED WORK

Our work relates to many areas of HCI research, including work on *textile sensors* and the diverse underlying sensing approaches, as well as on *conductive yarns* that serve as the base material for the development of such textile sensors.

Textile Sensors

The process of integrating sensing capabilities into textiles in order to make them interactive has been studied for some time now. In doing so, researchers have developed diverse capacitive and resistive sensing approaches [4, 22, 38].

Capacitive Approaches are based on fabric capacitors that are constructed from conductive materials acting as electrode plates that are separated by a dielectric element. The electrodes can be woven, sewn, and embroidered into the fabric with conductive yarns, or can be painted and printed onto the fabric with conductive inks. The dielectrics used are typically synthetic foams, fabric spacers, or soft polymers. An early exploration of such capacitive textile sensors was the *Musical Jacket* developed at the MIT Media Lab, which integrated a touch-sensitive keypad made from stainless steel yarns embroidered onto the fabric [27]. A summary of early exploration of such capacitive textile sensors in textiles can be found in Post et al. [28]. Holleis et al. [17] used a similar principle to explore diverse applications of capacitive touch controls created from thin conductive wires embroidered onto various textile-based everyday objects. *Project Jacquard* [29] is a recent example of a textile sensing system, which is based on a newly-designed conductive yarn that enables capacitive sensing. It uses an insulated copper core that is over-braided with yarns, which is woven into interactive fabrics. Summarizing, such capacitive approaches can be achieved relatively easily from a yarn perspective, but require contact with a conductive surface (e.g., direct skin contact for touch sensing). In a more complex setup, Meyer et al. [23] presented a capacitive textile sensor that is based on a multi-layer design consisting of conductive and non-conductive fabrics in combination with a spacer fabric and foam. Compressing the foam or the spacer fabric varies the capacitor and can be measured. While such a capacitive sensing approach can be used to detect pressure more accurately, it requires more complex multi-layer design.

Resistive Approaches are typically based on fabric resistors that are constructed from textile materials acting as conductors, which are separated by a semiconductive, compressible textile material. For example, Rofouei et al. [31] implemented a smart textile surface composed of an array of pressure fabrics, each of which is a three-layer structure where a resistive textile is sandwiched between two conductive layers. Their sensor was based on a non-stretch, non-woven textile fleece that changes its resistance when compressed. Objects placed on this surface would produce variable resistances at different elements of this sensor array, from which information about object position, weight and shape were inferred. *eCushion* [41] used the same pressure-sensitive textile to implement a smart cushion that was used for sitting posture analysis. Shu et al. [36] presented a textile-based in-shoe pressure sensor that was fabricated by adhering a knitted, conductive-coated fabric with conductive yarns and a top-and-bottom conversion layer. Similarly, other researchers [7, 25, 35, 39, 43, 10] have developed resistive textile sensor arrays that are based on a similar multi-layer designs of woven fabric. For example, *Smart Mat* [39] describes a textile pressure sensor matrix that can be unobtrusively integrated into exercise mats to recognize and count exercises. *GestureSleeve* [35] is a novel input system for smartwatches using touch-enabled textile at the forearm. *FlexTiles* [25] introduced a stretchable three-layer approach, which has been used to augment prosthetic limbs [20], or to showcase interactive clothing [26]. Common among these designs is that they consist of a top and bottom textile layer with evenly-spaced alternating metallic conductive and non-conductive stripes, and an inner layer of a pressure-sensitive, semi-conductive fabric. In RESi, we reduce the layer stack of previous resistive pressure sensing systems, in order to overcome mechanical issues like sensor alignment shifts.

Conductive Yarns

At the core of most capacitive and resistive textile sensing approaches are conductive yarns. They have been used for many different industrial applications ranging from fashion and design elements, to heat-resistant fabric, for anti-static and electromagnetic shielding purpose and for antibacterial applications in health care. A closer examination of different types of conductive yarns as well as their properties can be found in [38]. In general, they can be divided into *intrinsically conductive* yarns and *specially treated* conductive fibres. Intrinsically conductive yarns are based on metal yarns or filaments which are produced by a wire drawing, bundle drawing or shaving process. Most often they consist of stainless steel, copper or other precious materials. Specially treated conductive fibres gain their conductivity through additional processing steps, such as coating the yarns or combining conductive and non conductive fibres. These yarns cannot be soldered and tear more easily. In RESi, we are using intrinsically conductive yarns due to the high conductivity and steadiness. Similar to the *Project Jacquard* [29], we use a metallic core, but instead of using twisted or braided yarns to create an isolation layer, we are using an organic polymer solution containing conductive carbon-based particles. This coating layer does not insulate the highly conductive core, but rather enhances it with pressure-sensitivity.

SENSING APPROACH

RESi enables *resistive*, pressure sensing on a yarn basis, which can be used in various textile manufacturing methods.

Anatomy of a Single Sensor

The underlying principle is similar to a *Force Sensing Resistor* (FSR) that has been used for over thirty years. A typical FSR device is a continuous electrical switch whose electric conductance gradually increases as external force is applied. In one common configuration, two conductors are placed into mutual contact via a semi-conductive material. Most of these sensors, though common, generally detect only a single touch. Resistive array-based multi-touch sensors have a flat form

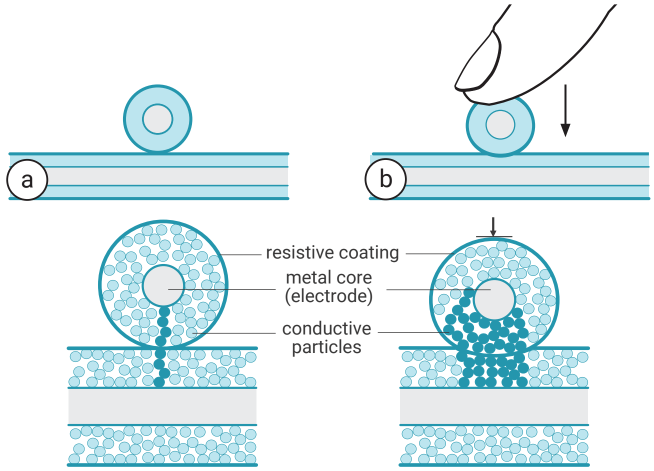

Figure 2: The cross-section of two resistive-coated yarns, which form a resistor (a) that can measure applied force (b).

factor, are inherently inexpensive, use little power, and can continuously measure applied force [24, 32, 37]. Researchers have transferred this basic principle into the field of pressure-sensitive fabrics in the form of textile materials that include an array of vertical and horizontal conductors separated by a semi-conductive layer [25, 41, 39]. RESi reduces the layer stack to one single layer by transferring the same pressure-sensing principle right into the yarn itself.

The novel yarn on which the RESi sensing technology is based, comprises a conductive metallic thread with a resistive coating consisting of an organic polymer solution containing conductive carbon-based particles (e.g., 80 μm yarn with 50 μm metallic core and 30 μm resistive coating). Once an external force is applied to the resistive yarn, the coating gets compressed, which increases the density of conductive particles in the coating (Figure 2) and corresponds to a change in resistance of the coating. In the case where two coated yarns overlap each other, the change in resistance can be measured by applying voltage to one yarn and measuring the voltage drop across the other one. The same principle can also be achieved by overlapping a resistive-coated yarn with an off-the-shelf conductive yarn. This simple principle opens up a wide array of possibilities for the design of interactive textiles. In the remainder of this paper, we refer to the *resistive yarn* as the conductive metallic thread with the resistive coating.

Our resistive yarn is created in an industrial production process, in close collaboration with the textile manufacturing company SEFAR AG. The technical details of the manufacturing process are as follows (cf. Figure 3): The yarn is composed of

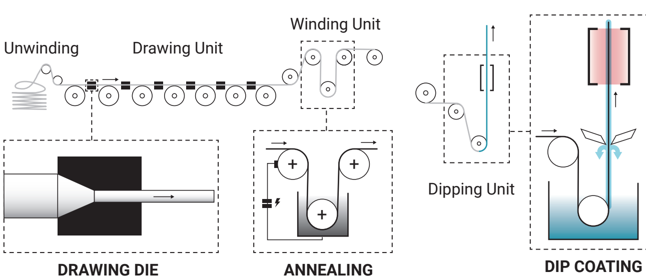

Figure 3: Schematic overview of the wire drawing and dipping process. The wire initially passes through several drawing steps to become thinner and longer. Next, the wire is annealed and quenched. Finally, the metallic thread is coated using the Dip Coating method.

a metallic thread, which is further coated. In RESi, we have implemented a copper fibre solution. Such wires can be produced by using different processes, which can be grouped into mechanical (e.g., wire drawing, bundle drawing) and thermal processes (e.g., Taylor process). In our case, the production was done through *Wire Drawing* [38], where the wire passes through several drawing steps to obtain a thinner and longer wire. The initial diameter of the wire was 8 mm. After drawing the wire to a minimum diameter of 50 μm, the wire gets annealed at high temperature (600°C-900°C), and then quenched. In the next step, the metallic thread was coated by using the so-called *Dip Coating* method [38], which is a simple and well-known technique that has been used for several decades in industry and laboratories. The dry metal fibre is dipped into a pre-treated solution, composed by polymers, elastomers (elastic polymers, thermoplastic elastomers), and carbon particles, dissolved in solvents. This ”glue”-like mix forms the coating of the wire. Finally, the solvent is evaporated (by heating and ultrasonic vibrations) creating a conductive yarn coated uniformly with polymer particles (with a thickness of 15 μm).

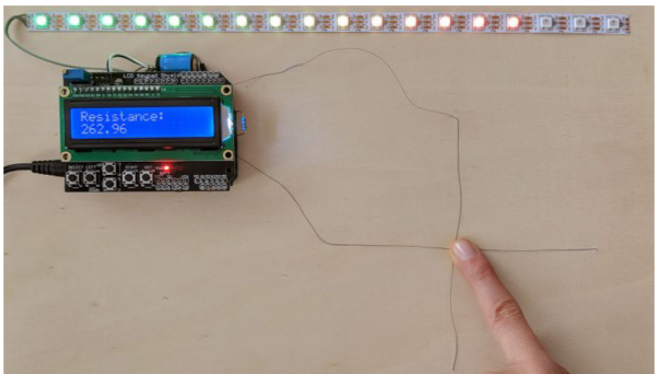

Figure 4: First prototype with a basic yarn crossing connected to a microcontroller measuring the resistance.

In a first prototype implementation (see Figure 4), we used two of the coated yarns placed over each other to form a pressure sensor, as the conductivity is only given via the resistive coating. This simple demonstrator showed impressive pressure-sensitive behaviour. Therefore, we conducted a technical evaluation to specify the characteristics of the yarns.

Resistive Yarns for Force Sensing

As with all yarn-based sensors, key features that make up for their quality include mechanical and electrical properties in terms of pressure-sensing, conductivity and tensile behaviour. To evaluate the behaviour of the resistive yarn with respect to these properties, comprehensive test measurements have been performed for yarns with different diameters (i.e, 80 μm, 114 μm, 167 μm, 355 μm, and a twisted yarn consisting of twelve twisted 80 μm yarns). The resulting characterization of the yarns indicates the necessary properties and requirements for their usage as textile sensors. For design engineers, this allows to predict the performance of a yarn-based pressure sensor based on its constituent parts. For application designers, this allows to evaluate the suitability of the different yarns for the envisioned applications of the resulting interactive textiles.

Pressure Sensing Behavior

To evaluate the pressure-sensitivity of the yarns, we performed an experiment that included pressing two yarns together and

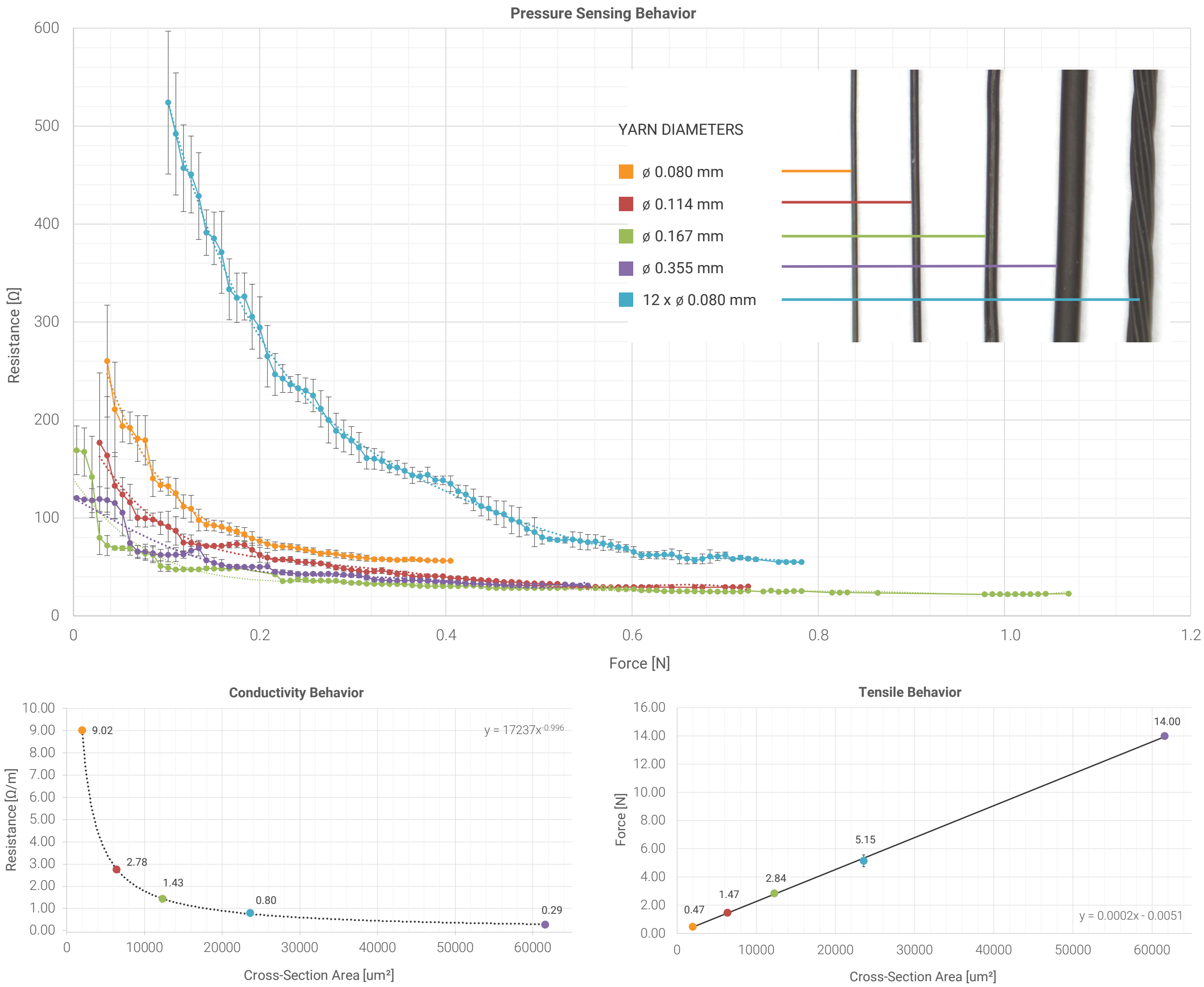

Figure 5: Pressure Sensing Behavior (top) of pairs of resistive yarns pressed perpendicular against each other. Conductivity Behavior (bottom left) shows that the resistance of the yarns correlates with the cross-section area of the metallic core. Tensile Behavior (bottom right) shows that the average fracture force correlates with the metal core cross-section area of the yarn.

measuring the corresponding resistance. The measurement setup consisted of an Alluris Force Gauge, a pickup holder for the yarns, a Keithley 2000 multimeter, and a Linos x.act linear slide. During the measurement, two yarns of identical diameter were pressed perpendicular against each other in between two curved ceramic plates. Thereby, the yarns only compressed in-between the two non-conductive ceramic plates, which had enough rigidity to not compress while testing.

Results confirmed that the resistance of the sensor changes proportionally to the applied mechanical stress, validating that pressure-sensitivity is given. The force-to-resistance characteristics of the individual yarn types are summarized in Figure 5 (top). As we can see from the graphs, thinner yarns achieved a higher resistance and showed a better pressure-resistance ratio. The best pressure-resistance ratio was achieved with the twisted yarn, as individual strands of the same thread can slightly elude each other, and the applied pressure does not influence the resulting resistance values so heavily.

Practically, the resistive behaviour of our yarns gets roughly linear when plotted force to conductivity ($1/R$). In addition, our yarn-based sensing approach offers the advantage that it can be integrated easily into textiles and curved surfaces in comparison to off-shelf FSR sensors. Hysteresis and settling effects were visible, however, negligibly small in comparison to the sensor readings. Furthermore, the technical evaluation has shown that the yarns are highly sensitive, but result in relatively low maximum forces of only 0.4–0.6 N. However, in relation to the actuating object (e.g., a human finger) the contact of two intersecting yarns is relatively small, so that it is affected only by a fraction of the overall applied force.

Conductivity Behavior

To evaluate the conductivity of the yarns, we performed another measurement experiment. The apparatus consisted of a Keithley 2000 multimeter that was soldered to the ends of the individual yarns in order to measure their conductivity. To minimize external influences, e.g., resistance of the connection

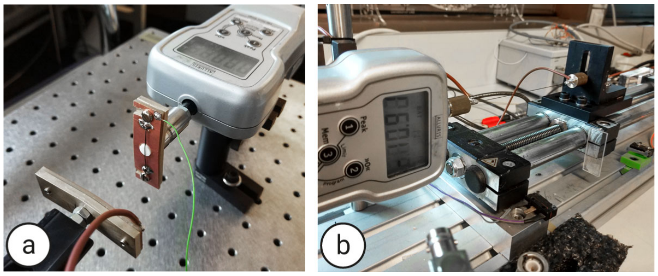

Figure 6: Apparatus for measurement of the pressure sensing behavior (a) and tensile behavior (b).

cables between the multimeter and the yarn, the setup was firstly analyzed without the test specimen.

The results show that the resistance of the yarn correlates with the cross-section area of the metal core (cf. Figure 5 bottom, left). Moreover, it shows that the resistance of the metallic filament cores in comparison to the resistance of the coating is negligible small. In contrast to the resistance per meter of commercially available conductive yarns, for instance 67 Ω (*SD* = 3.6%) with a *Conductive Thread - 60g* from Shieldex or 410 Ω (*SD* = 9%) with a *Nm 10/3 Conductive Yarn* from Plug and Wear [40], our yarns have a very low resistance per meter and are therefore good conductors. Given their high conductance, the yarns are suitable for creating textile sensors at large scale, and enables flexible placement of driver electronics not necessarily directly next to the sensor.

Tensile Behavior

To evaluate the tensile strength of the yarn, we developed a test setup with enough precision and strength to run ultimate tensile strength test (UTS) to define the loads the yarns withstands tending to elongate. The apparatus consisted of Alluris FMI Force Gauge, a pickup holder for the yarn, and a Rose+Krieger linear module to pull the yarn apart. During the measurement, the pickup holder was pushed in the opposite direction for each testing yarn sample and the resistance was measured accordingly. As soon as the resistance of the yarn was infinite, the yarn tore apart and the measurement was finished.

The results show great consistency throughout the tested samples. All yarns show similar elastic behaviour and tear apart under irreversible plastic deformation. The thinnest yarn with a diameter of 80 μm, fractures with 0.47 N (*SD* = 0.0424), while the yarn with 114 μm thickness fractures with 1.47 N (*SD* = 0.0578). The yarn with 167 μm diameter resist 2.84 N (*SD* = 0.0704), and the thickest yarn with 355 μm fractures at 14.00 N (*SD* = 0.0873). The twisted yarn fractures at an average force of 5.15 N (*SD* = 0.419), demonstrating the highest deviation. This is caused by the single yarns which tear apart individually, causing the whole strand to collapse. In comparison to the other yarns, which tear apart entirely from one step to the next, the twisted yarn tear apart step-wise. The results show that the thickness of the yarn correlates to the average fracture force (see Figure 5 bottom, right). Furthermore, the samples only show small deviations regarding the average fraction force, proving that the manufacturing process achieves consistent results. Moreover, these tensile tests prove that the soldering connection is a simple, yet robust connection between the yarn and electronics.

Summarizing, we achieved consistent results throughout the tested yarns. Nevertheless, there is always a trade-off between those qualities, e.g. while the thinnest yarn and twisted yarn show the best pressure sensing behavior, they are tearing more easily during machine sewing due to the additional frictions caused inside the machine. For this manufacturing process we recommend using the yarn with a diameter of 114μm, which cause less problems while sewing with the machine.

PROTOTYPING PIPELINE

RESi is a platform that makes it possible to quickly and easily prototype interactive textile interfaces based on resistive yarns. Three major steps are necessary for constructing an interactive textile interface: (1) *textile fabrication*, (2) *textile-to-electronic connection and read-out*, and (3) *signal processing and mapping*. Firstly, the yarn must either be sewn or woven to create sensing intersections. Secondly, the textile interface must be connected to an electronic circuit board that is able to read-out analog signals based on the resistance changes that occur at the different sensing intersections. Lastly, software is needed to refine and map the signals to one or multiple desired outputs. This sequence of steps is referred as the prototyping pipeline (see Figure 7). In the following each of these steps is explained in more detail.

(1) Textile Fabrication

The fabrication of interactive textiles using resistive yarns is fundamentally about creating sensing intersections. In principle intersections can be created using two different techniques:

a) Additive techniques such as sewing, seaming, or embroidery involve the resistive yarn being stitched onto regular, non-interactive fabrics in order to create interactive textiles out of them (see Figure 8a). Adding the resistive yarn does not require any specific equipment or technique, and can be done either manually via hand sewing, or with an off-the-shelf sewing machine. This enables all kinds of DIY approaches, where users can experiment with interactive textiles by using materials and techniques that they are already familiar with.

b) Constructive techniques such as weaving, knitting, or crocheting involve combining the resistive yarn with normal yarns into fabrics that serve as the basis for interactive textiles. For example, to produce a pressure-sensitive fabric, the resistive yarn can be used as weft and/or warp yarn to form a textile (see Figure 8b). This way, every single intersection builds a sensing point. The electrodes or metal threads of the yarn only contact each other through the pressure-sensitive coating in between. This enables the creation of high-resolution, large-scale, textile sensors with standard weaving technology and equipment.

(2) Textile-to-Electronic Connection and Read-Out

Electronic circuits are necessary to read-out the resistance changes of sensing intersections. Such circuits can range from a very simple voltage divider to a more complex measurement approach that can handle a high amount of sensors [14, 25, 32] simultaneously in real-time. Our approaches for single sensors as well as sensor matrices are based on a voltage divider principle and are described in detail in the following.

Single-Sensor Hardware Setup

In the simplest case of two yarns overlapping each other, a single voltage divider circuit is sufficient. One yarn is connected to the supply power and the other one to a pull-down resistor to ground potential. The connection between the yarn and the pull-down resistor is connected to an analog input of a microcontroller. With this circuit, the output voltage will increase whenever the resistance of the sensor decreases (e.g. by applying force).

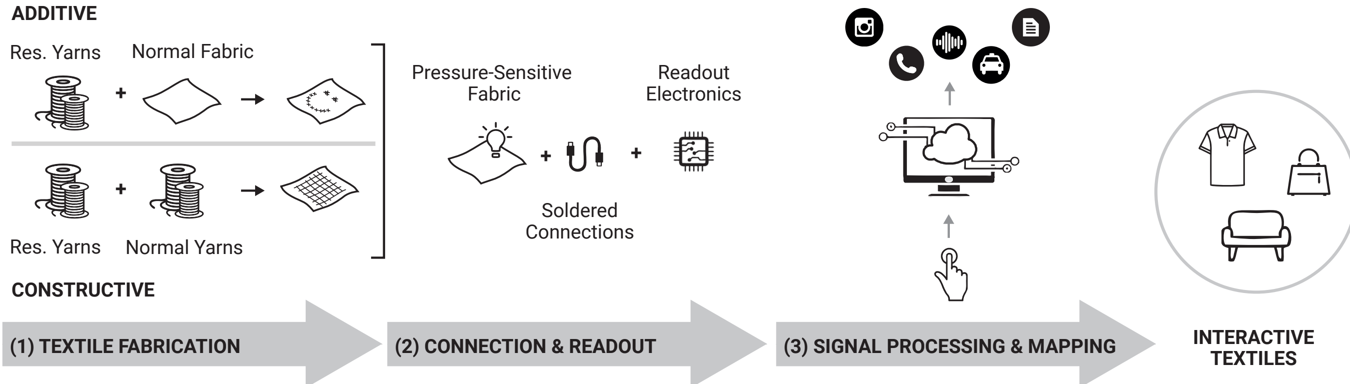

Figure 7: The RESi pipeline starts with a resistive yarn, which can be used to create pressure-sensitive fabrics (*constructive*), or enhance normal fabrics (*additive*) with pressure sensing capabilities. Next, the pressure-sensitive fabric gets connected to the readout electronics. Finally, a platform-independent API is provided for signal processing, gesture recognition, and their mapping to existing end-points. This enables textile pressure sensing to augment everyday objects with interactive capabilities.

Sensor-Matrix Hardware Setup

Once multiple resistive yarns in a grid arrangement should be sensed, the complexity of the read-out electronics increases. Our current prototype consists of eight analog matrix switches (*ADG1438BRUZ*), which are daisy-chained to reduce wiring efforts. Each of these includes eight analog switches, which can be triggered individually, connecting every single sensor input line to either reference voltage, ground potential or to the analog digital converter (ADC). With this simple setup, every single sensor of the matrix can be measured sequentially by connecting one electrode to the reference voltage and the other electrode to the ADC of an off-the-shelf microcontroller. While one sensor is measured all inactive sensor lines are connected to a ground potential to reduce crosstalk effects [8]. To further reduce crosstalk effects, we refer to Shu et al.'s comprehensive comparison of different methods [36].

Textile Connection

Connecting soft textiles to the rigid electronics is an ongoing challenge. Previous research introduced snap buttons, sewing, conductive epoxy, crimping, etc. [3, 26, 29, 35]. However, all of them struggle with connecting a high amount of yarns at a fine pitch. Furthermore, most of them are not scalable and not suitable for mass production. Most conductive yarns do not withstand the temperature used for soldering, which is caused by the way those yarns are produced [29, 38]. In contrast, RESi was designed to be solderable. This allows for high flexibility in design, since it allows for arbitrary, high-resolution pitches as used in modern connectors but also allows for an easy connection to off-the-shelve pin headers.

The coating of the resistive yarn can be easily removed by using a soldering iron at a temperature of approximately 350°C.

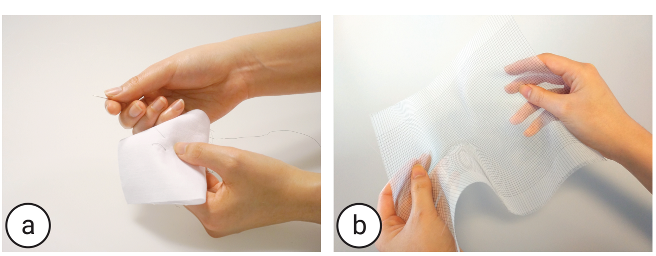

Figure 8: The resistive yarn can be processed using additive techniques, such as sewing (a), or constructive techniques, such as weaving (b).

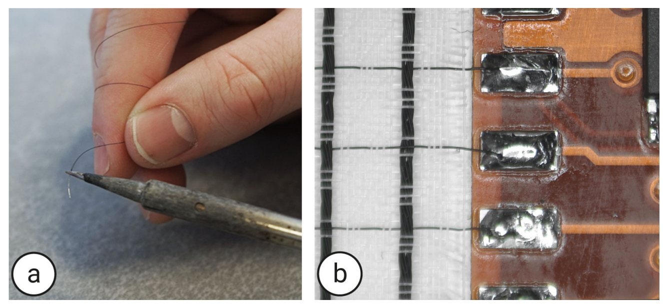

Figure 9: A resistive yarn with removed coating (a), and a woven textile prototype connected to a flexible PCB (b).

Figure 9a depicts the resistive yarn, where the coating was removed using high temperature, revealing the inner metal core. When multiple yarns should be connected to a PCB, the solder patches for the yarns are first filled with tin. When the yarn on the patch is heated during soldering, the coating vanishes and the metal core of the yarn automatically connects with the tin on the solder patch (see Figure 9b). This allows for quick connection of a large number of sensor yarns even on fine pitches.

(3) Signal Processing and Mapping

As RESi is an enabling technology for prototyping interactive fabrics, we worked to create an open web platform that would allow others to easily build on top of our technology*. The platform-independent application allows developers to visualize, process and utilize sensor data, is configurable and extendable, and incorporates a number of special features to support rapid prototyping.

System Architecture

Our application consists of a server and a client component that share a common database. They communicate via a REST API and web sockets. The server processes and distributes data (i.e. sensor data and recognized gestures), while the client hosts a user interface (UI) for data access and configuration (e.g. changing signal filters, capturing new samples, entering labels for classification). In the future, this architecture has the advantage that the server could run on a slim microcontroller, whereas the UI and performance-intensive visualizations could be offloaded to an external/mobile device. Several features

*https://github.com/MediaInteractionLab/RESi were incorporated into the application to help others to build upon our technology, as explained below.

Signal Filtering
The server can process raw sensor signals using a sequence of configurable signal filters. Examples include simple filters (e.g. scale, band-pass, or thresholding filters), and more complex filters (e.g. offset filters to eliminate zero-line sensor offsets). The application includes predefined filters but also allows developers to add custom filters via the extensible interface. The signal filtering pipeline can be edited via drag-and-drop on the client UI.

Signal Visualization
The processed signals are visualized in a grid arrangement on the client side, showing numeric values as well as colors for the different forces applied on the single sensors in the grid. Depending on the intended sensor application, the resolution of the grid can be adapted.

Basic Gesture Recognition
The application includes basic touch recognition that uses blob detection in a frame-based force image. Continuous touches, taps (single, double and triple), as well as slide gestures in the four main directions can be detected. When a gesture is recognized, the server sends the gesture via the web socket to all registered clients. Custom (more complex) gesture recognition algorithms can be uploaded to the server. Different gesture recognition implementations can be enabled or disabled via the client UI.

Classifier-Based Gesture Recognition
Discrete gestures can also be detected based on SVM classifiers. The approach is similar to [2, 26], where information of the most prominent blob in the force image of each frame (e.g. size, position, force) is used as classification features. Like before, recognized gestures are forwarded from server to client for visualization. The creation, capturing, and training of the classifiers can be done using the client UI. This is beneficial for rapid prototyping, since new sensor interfaces can be quickly linked to accompanying gestures without any development effort.

Action Triggers
Recognized gestures can be linked to existing endpoints of third-party REST APIs (e.g. Philips Hue, If-This-Then-That). Besides one-to-one mapping gestures to endpoints, developers can pass gesture properties as parameters in API calls. Continuous interaction (e.g. applied pressure to control zoom), and looping between pre-defined values (e.g. a slide gesture to switch between colors) are possible. The creation and management of the triggers can be done with the client UI.

CREATING INTERACTIVE TEXTILES USING RESi

In this section, we want to evaluate the suitability of our approach by prototyping a number of example applications using both the additive and constructive manufacturing techniques, including hand sewing, machine sewing, embroidery, and weaving.

Additive techniques, where the resistive yarn is *added* (stitched) into regular, non-interactive fabrics, are specifically interesting for DIY applications, as they do not require any specific equipment. Further, they are a means to augment existing, non-functional fabrics or fabric elements (e.g. embroidery) with interactivity at a later stage. Another option is to use the resistive yarn to *construct* entire functional fabrics by using constructive techniques. So far, resistive fabrics typically required a three-layer setup consisting of top and bottom electrodes and a resistive material in-between [7, 25, 35, 39, 43]. With RESi, we can reduce the three-layer setup to a single-layer, which eases the manufacturing process as well as reduces limitations such as alignment shifts or shorting caused by wrinkles. For constructive techniques, we focus on woven textiles, although there are also other manufacturing processes available that could potentially be used, such as knitting or crocheting.

In the following, we describe the manufacturing processes of our demonstrators as well as the created applications in depth. We further highlight some of the findings and takeaways we drew from the implementation of the demonstrators.

Hand Sewing

The simplest approach to achieve interactivity in textiles is to sew the resistive yarn into existing, non-functional fabrics. As discussed previously, the core concept is to create intersections between resistive yarns. During the design process, it is important to consider that the yarns should be mechanically able to come in close contact under pressure and release when relaxed. From our experience, very small, tense intersections can cause an initial drop in resistance that reduces the overall pressure-sensing range, but makes the intersections more sensitive to shear forces and forces applied to other sections of the textile due to tension. This is because the two yarns will be pressed against each other when the fabric is being stretched. However, if the intersections are sewn too loosely, there is the risk of a displacement and in the worst case tearing of the yarn during interaction. Thus, an ideal design of the intersection involves a trade-off between making the two yarns loose enough such that they barely touch each other in the relaxed state, and tight enough that minimal displacement occurs during interaction.

To keep wiring efforts manageable, it is possible to share a common yarn for multiple sensors. For instance, when multiple sensors are needed, one continuous yarn can be connected to the supply voltage of the microcontroller, whereas separated yarns are used for measuring each intersection. With this approach, it is possible to reduce the number of yarns that are needed (e.g. three sensors can be constructed with four instead of six yarns). In general, since the number of hand-sewn sensors is usually not that high, the voltage divider circuit as a hardware approach is well-suited.

Application: Light Control with an Interactive Couch
There is an abundance of different devices that are usually controlled in a living room environment, ranging from televisions and stereos, to lights, blinds, or even heating. Instead of having several remote controls for different purposes, we could think about embedding interactivity seamlessly into everyday objects in the living room - such as the couch. To demonstrate the applicability of hand sewing for RESi, we sewed three sensors into an existing couch and used it for controlling RGB light sources (cf. Figure 10). As described above, we used four resistive yarns with the horizontal yarn connected to the supply voltage and each of the three vertical yarns connected to a pull-down resistor and an analog input on the microcontroller. We further experimented with yarns in different diameters, with all of them resulting in a sufficient resistance/sensitivity range.

On an interaction level, we implemented a number of different gestures using the three sensors both individually as well as

Figure 10: Three hand-sewn pressure sensors on a couch are used to control different RGB lights.

in conjunction with one another. Tapping one of the sensors turns the associated lamp on. A double tap turns it off. Varying the pressure on the sensor controls the brightness of the lamp. In this way, three different sensors can be used to control up to three light sources individually. Swipe gestures over all three sensor points can be used to scroll through different predefined colors for all light sources. All these interactions can be carried out without any explicit mode switch.

Machine Sewing

For larger sensor patches that involve a higher amount of sensors, hand sewing may be impractical. Hence, a logical next step is to utilize machine sewing in such cases. First experiments with a Bernina B330 revealed that it is possible to use the resistive yarn for machine sewing directly. We used a straight stitch and the yarn effectively resisted the tensile stress caused by the sewing machine. However, further testing revealed that not each diameter of our yarns is equally well-suited for machine sewing. While the thinnest thread (80 μm) could not withstand the applied tension, the thickest (355 μm) was too stiff, and the twisted yarn was too thick to be used directly in the machine. For this reason, we recommend using the middle-diameters of yarn for machine sewing, ranging from 114 μm to 167 μm.

For the creation of machine-sewn patches, we recommend using the resistive thread as bobbin thread [11] and a normal yarn as a top thread. This fabrication technique has the advantage that the cover threads holds the underlying resistive yarns as well as the intersections in place, which greatly helps to avoid displacements of the resistive yarns during interaction. For the prototype, good results were achieved with a stitch length of about 2.4 mm for the resistive yarns.

Application: Wearable Music Controller

As a practical application area, we identified the upper leg area of a pants as a potential unobtrusive gesture-interaction space to control personal devices such as a smartphone. We used the Bernina B330 to sew a 6×6 matrix on a regular pair of pants with six vertical and six horizontal yarns (spacing: 8 mm) resulting in 36 intersections (stitch length: 2.4 mm). Both the horizontal and vertical resistive yarns were directly connected to two flexible multiplexing boards inside the pants. Figure 11 shows the pants with the integrated functional sensing patch. The resulting resistance range was 30 kΩ to 400 Ω, from a weak to a strong touch for every single sensor.

The sensor matrix was used to control the Spotify music player app on a smartphone. Therefore, we implemented the recognition of a set of common gestures (i.e. taps and swipes),

Figure 11: The machine-sewn sensor matrix acts as an interactive gesture pad. We used it to control the Spotify app on a smartphone.

which we integrated into our web platform. In our mapping, a tap is used for playing music, while a double tap is used for pausing. Swiping to the left or to the right is used to switch between songs in the playlist. Swiping up and down changes the volume in predefined steps. Currently, there is a lag of a few hundred milliseconds, due to the communication between the web platform and the Spotify service. We are convinced that this can be further improved, as the actual signal detection happens at decent framerates (100 Hz).

Augmenting Embroidery

Embroidery is a textile stitching technique, where strands of thread are stitched onto a fabric for embellishment. This can be done either manually or with specialized embroidery machines. In this paper, we focus on hand-crafted embroidery as this approach does not require specific equipment. Similar to the other manufacturing techniques, the main idea for interactive embroidery is to create intersections of resistive yarns. This can either be achieved by creating intersections with well-known embroidery stitches using resistive yarns or by augmenting existing embroidery with intersections in such areas where interactivity is needed. Figure 12 shows how stitches can be adapted to create intersections, which make the pattern interactive. However, one side-effect of our resistive yarns is that the carbon-based coating has a dark grey color and cannot be dyed.

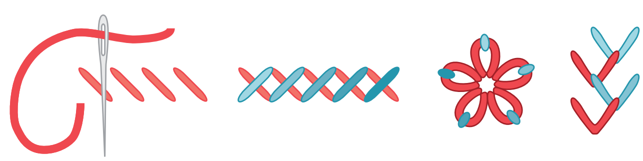

Figure 12: By using two overlapping yarns, we can produce different cross-stitch patterns. Even complex stitches like the Lazy Daisy stitch and feather stitch can be enhanced with interactive capabilities.

We were mostly intrigued by the possibility to enhance existing embroidery with resistive yarns. We focused on this approach as it does not limit the artistic freedom and it provides maximum flexibility for the creation of interactive embroidery. Doing this, it is important to position the intersections at spots where good force transmission is guaranteed. We had problems with weak sensor responses when the intersection with the thin resistive yarns was positioned right next to a cross stitch made with the thick embroidery yarns. This is because most of the force was applied on the thick yarns, which invalidated the sensor intersection. We also experimented with covering sensor intersections with normal, colored yarns. While this generally works, the sensor response is not ideal since the relatively soft embroidery yarns absorb some of the applied force. The best results were achieved when the intersections were placed on top of the embroidery stitches. Since our resistive yarns are very thin, they are almost invisible to the eye.

Application: Slider and Turning Knob

To experiment with the augmentation of embroidery, in a first step we started to create well-known embroidery patterns, such as *cross-stitch, feather, chain, blanket, herringbone, threaded running,* and *Lazy Daisy* stitches. In a second step, we then augmented these patterns with interactivity. Therefore, we positioned four resistive yarn intersections on top of the crossings of the cross-stitches, and six intersections on the outer edges of the Lazy Daisy flower. With this small augmentation, we achieved a fully functional horizontal slider with the cross-stitches as well as a rotational control with the interactive flower. We achieved a resistance range between 10 kΩ to 200 Ω from a weak to a strong touch for every single sensor. To show the functionality, we implemented a custom recognition algorithm using our web platform that tracks the slider and knob position and visualizes them accordingly.

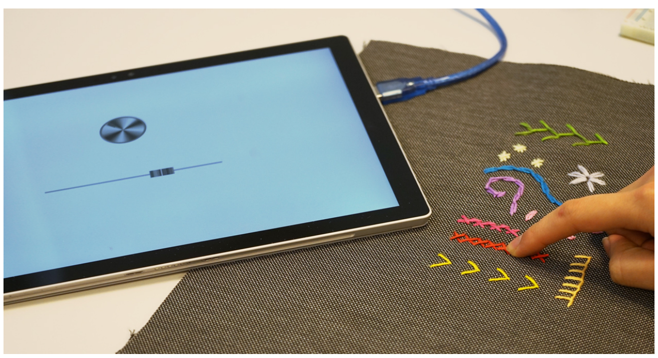

Figure 13: Different embroidery stitches were augmented them with pressure-sensitive yarn to create control elements consisting of different shapes, sizes and patterns.

Weaving

While the previous sections focused on adding intersections in a rather manual way, another possibility for creating pressure-sensitive textiles is to rely on industrial manufacturing techniques, such as weaving or knitting. In this paper, we focus on the exploration of the possibility of directly weaving flexible resistive yarns [12], resulting in a single-layer, interactive, and readily assembled textile. Woven textiles in general are widely used for clothing, home furnishing, and industrial applications. Thus, using this existing manufacturing process with our novel resistive yarn opens up new possibilities for the design of interactivity in these domains.

By varying the density of resistive yarns in the weft and warp direction, the resolution of the fabricated textile can be varied. As an example, a piece of fabric can comprise of a resistive yarn every 2.56 mm, with the rest being woven from non-functional yarns. Figure 14 shows examples of different weaving patterns that are described later. It would also be possible to produce an even higher-resolution woven textile by only using resistive yarns. With the current fabrication technique, a resolution of 31.612 sensors per square inch can theoretically be produced. The resolution could then be adjusted to suit the intended use case by bundling a number of weft or warp yarns.

A local weaving company produced two interactive woven prototypes utilizing different weaving patterns, namely canvas and panama weaving. For canvas weaving all warp and weft yarns are interlaced (cf. Figure 14a), while for panama weaving the warp and weft yarns are only interlaced in a defined interval (e.g. every three yarns, cf. Figure 14b). For both patterns, it was possible to weave the resistive yarns without adaptation of the current fabrication techniques. However, we discovered that the sensor response of the panama woven sample clearly outperforms the canvas pattern. Canvas weaving adds a high amount of initial tension to the yarns, because weft and warp yarns are constantly passing. This reduces the possible sensitivity range significantly, because the coating of the yarns is already compressed in the relaxed state given the internal structural tension. The panama weaving, in contrast, shows better sensitivity since the resistive yarns are not that tense in the relaxed state. Experiments applying high force revealed that the resistance changes two orders of magnitude for the panama weaving pattern, while for canvas weaving the resistance range is only a couple of Ohms. With the woven textile in its current state, a general challenge comes from localized tensions within the woven structure that appear when the textile is touched or deformed. This has to either be improved on a mechanical level in future work, or has to be counteracted by applying adaptive offset filtering to sensors that are triggered due to internal tension.

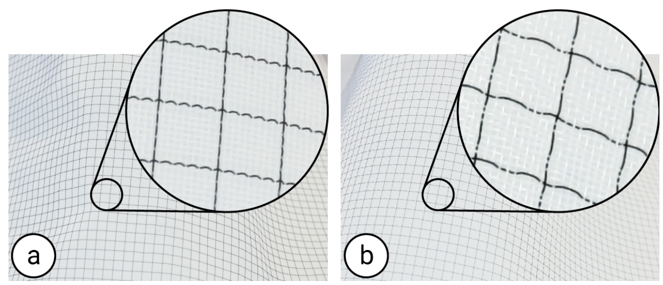

Figure 14: Woven prototypes using a 80 μm resistive yarn as weft and warp yarn in combination with 80 μm PET yarns: A canvas weave, where all warp and weft yarns are interlaced (a); A panama weave, where warp and weft yarns are only interlaced every third yarn (b).

Application: Interactive Handbag

As an application example using woven fabric, we decided to create an interactive patch on the flap of a handbag that can recognize gestures to control a smartphone, such that one does not need to search for and remove it from the bag. Therefore, we embedded a panama-woven fabric with a sensor resolution of 32 $\times$ 32 at the size of 82 $\times$ 82 mm. Using the panama weave, this results in a resistance range of 1 kΩ to 150 Ω, from a weak to a strong touch for every single sensor. The resistive yarns of the woven textile were soldered directly to two flexible multiplexing boards at a pitch of 2.54 mm. The textile including the flexible PCBs were integrated between the front leather coating and inner fabric. The boards are connected to an external microcontroller, which handles the multiplexing and measuring of the single sensor points in the matrix.

On an interaction level, the idea was to detect a number of different grip and deformation gestures, which can then be mapped to discrete actions on the smartphone (e.g. dismissing a call). To do this we used the previously presented SVM classifier. By using this feature set, we can distinguish between a *Corner Bend*, *Tap*, *Open*, and *Side Grip* , which are mapped to smartphone actions using If-This-Then-That (IFTTT). A simple tap on the bag mutes the phone, which can be handy when it starts ringing in an untimely moment. When the bag is opened the classifier detects the grip as well as the characteristic sensor pattern actuated by the bending of the flap and turns on the flashlight to make the phone easier to find in the bag. A *Corner Bend* sends an *"I'm on my way"* message to one's significant other, while the *Side Grip* opens the map application on the phone.

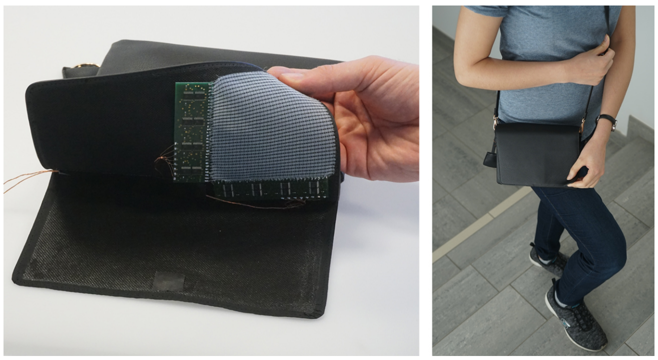

Figure 15: The interactive handbag allow interacting with the phone without taking it out of the bag.

DISCUSSION & LIMITATIONS

While our novel sensing approach goes beyond existing solutions, it also comes with a number of limitations. In the following, we will discuss both its advantages and limitations in greater detail.

Combination with Conductive Yarn

In this paper, we presented a pressure sensing yarn, which can be easily combined with any other conductive yarn. To prove the feasibilty of such a combination, we used our resistive twisted yarn (12×80 μm) in conjunction with a commercially available conductive thread (*Conductive Thread - 60g* Shieldex). This combination provided a sufficient change in resistance for pressure detection, ranging from approximately 500 Ω (light pressure) to 70 Ω (strong pressure). This is also in line with the pressure values reported in Figure 5. This combination however, was not the focus of this paper and will instead be investigated further in future work.

Connection Robustness

The connection between the soft textile and the driver electronics is clearly a challenge, since the connections can easily break. The technical evaluation of our resistive yarn revealed that the thinnest yarn can withstand an average fraction force of 0.47 N, which of course increases with the number of yarns connected to the read-out electronics. During the tests, we found that the connections of the textile to the PCB are more prone to tearing when users lift the textile unevenly, as it only applies tension on a few connections at a time. Therefore, we recommend placing the read-out electronics at positions where less tension is applied, for instance, by using longer yarns.

Interpolation

In comparison to existing resistive multi-layer approaches [6, 25, 32], we cannot detect pressure in-between two adjacent sensors. The main reason is because pressure can be only detected at yarn intersections. We can minimize this issue by increasing the number and density of resistive yarns. Another possibility is to use force-distribution layers on top of the sensor intersections as shown in [14]. However, this can be counterproductive for the flexibility and haptics of the textiles.

False Activations

In contrast to most capacitive sensors, sensors based on our resistive yarns do not require skin contact for interaction and simply react to mechanical stress. This can be beneficial for novel gestures that include deformation, but can also increase the occurrence of false activations. When introducing sensing on a yarn level, it is necessary to consider the textile's behavior in the design process in order to create gestures that are unlikely to be triggered by accident and to deploy adequate countermeasures when manufacturing the textile.

Tensions

During our experiments with our yarns, we observed that strong touches and deformations can change the tension in the textile's internal structure, leading to false activations in areas that are not activated at all. This problem becomes most apparent for the weaving technique, as the yarns are already quite taut in their relaxed state. We found that tension in the fabric usually triggers single sensors across the whole surface, while finger-touches and deformations usually trigger a greater number of sensors in a confined area. This finding could be used to eliminate single sensor noise from the signal. Another solution is to add a general activation threshold. However, this method decreases the sensitivity range of the sensors.

CONCLUSION & FUTURE WORK

We presented RESi, a novel sensing technology based on a resistive yarn, which features conductive and resistive properties. We ran a technical study to characterize the behaviour of the yarn and to determine the measurement principle. We demonstrated that our sensing technique can be used to create interactive textiles with state-of-the-art textile manufacturing techniques. In addition, we presented a platform-independent API that enables developers to rapidly prototype custom applications, such as those presented in the paper.

For future work, we want to gain further knowledge about the behavior of the yarn and the textile. In particular, we would like to conduct experiments in a temperature chamber to better understand the impact temperature may have on its force-sensitivity. Moreover, we would like to investigate the durability and robustness of the yarn in terms of washing cycles and with regards to shear forces in order to determine the use-cases for which it is most suitable. Finally, we would like to integrate this sensing approach into a knitted textile.

We hope that our work will inspire further researchers to implement their ideas based on our sensing yarn and corresponding hardware/software platform.

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