Project Jacquard: Interactive Digital Textiles at Scale

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Figure 1. Project Jacquard envisions *seamless and fluid integration* of interactivity woven into everyday objects and environments.

ABSTRACT
Project Jacquard presents manufacturing technologies that enable deploying *invisible ubiquitous interactivity* at scale. We propose novel interactive textile materials that can be manufactured inexpensively using existing textile weaving technology and equipment.

The development of touch-sensitive textiles begins with the design and engineering of a new highly conductive yarn. The yarns and textiles can be produced by standard textile manufacturing processes and can be dyed to any color, made with a number of materials, and designed to a variety of thicknesses and textures to be consistent with garment designers' needs.

We describe the development of yarn, textiles, garments, and user interactivity; we present the opportunities and challenges of creating a manufacturable interactive textile for wearable computing.

Author Keywords
Wearable computing; digital textiles; conductive yarns; manufacturing; touch interaction;

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

INTRODUCTION
More than two decades ago Mark Weiser [19] envisioned future computers that disappear into everyday environments and "… weave themselves into the fabric of everyday life until they are indistinguishable from it." Since then, the body of research that explored and advanced this vision has grown. Wearable and ubiquitous computing [7, 41, 43, 44], Internet-of-Things [46, 47, 45], augmented reality [48, 49] and other advanced technologies aim to seamlessly merge the everyday physical world and digital computing. Despite great advances toward the vision of invisible, disappearing computing, significant challenges remain. These include:

- Designing technologies that allow *seamless and fluid integration* of interactivity into everyday objects and environments not meant to be interactive (e.g. socks, chairs, water faucets, and white boards [33, 34, 36]).
- Developing *effective, unobtrusive, and socially acceptable interfaces* for invisible, disappearing computers (e.g. interactive wearable cameras, on-skin interfaces or tattoos, and augmented reality interfaces dynamically projected on the environment [35, 37]).
- Creating novel materials and manufacturing technologies that enable deploying *invisible ubiquitous interac-*

*The work presented in this paper was conducted while the author had a research affiliation at the MIT Media Lab *tivity at scale* (for example, 3D-printed rapidly manufactured displays, programmable matter, interactive textiles, and robotic and self-reconfigurable environments [38, 39]).

This paper presents *Project Jacquard*, which contributes to and extends the previous body of work by proposing novel interactive textile materials that can be manufactured inexpensively and at scale with standard textile weaving technology and equipment. The resulting interactive textiles can be used to manufacture soft toys, furniture, apparel and bags, automotive or home interiors, and many other everyday objects made of textiles (Figure 1). Any object made using Jacquard textiles can be digitally interactive and computationally responsive. Consequently, for designers of those objects, digital sensing and computation become basic properties of the textile materials—like weight, color and elasticity.

Project Jacquard proposes next step toward Mark Weiser's vision. It makes the following contributions:

- Novel conductive yarns designed to be woven into textiles using standard looms, inexpensively and at scale.
- Woven textile structures that allow interactive multi-touch capacitive grids that can withstand the harsh and destructive processes of textile manufacturing.
- Novel, inexpensive techniques for connecting woven interactive textiles to electronics that can withstand home washing and drying cycles.
- Design and evaluation of interactive garments demonstrating that woven interactivity can be easy, intuitive, and reliable.

BACKGROUND AND RELATED WORK

Textiles are one of the most fundamental and universal ingredients used to build the world around us. The search for new materials to produce yarns and techniques to make textiles out of those yarns goes back to the late Stone Age [40] and impacted human civilization from the silk trade, to the crusades to the industrial revolution, and innovation did not stop there. New textile materials (for example, synthetics such as nylon) and new weaving and finishing processes (for example, Gore-Tex) have been an active area of research and development that today includes conductive yarns and textiles.Conductive Yarns

The core of the textile manufacturing is *yarn*. Conductive yarns have a number of industrial applications including construction of antistatic and heat-resistant textiles as well ornamental uses. They have been broadly used in designing interactive textiles and garments, primarily via embroidery and usually have one of the following structures (Figure 2):

Multifilament core yarns with metal coating (Figure 2a). For example, Dtex 117 [23] is 1-ply yarn that consists of 17 single filaments with a resistivity range of 10-500 Ohm/cm, break strength 1-8N, and elongation 25-40%. The metal coating is a thin film applied in a plasma process. These yarns often have inconsistent resistivity along the yarn's length, which also changes with wear and tear; they cannot be soldered.

Multifilament metal fiber yarns (Figure 2b). These usually use multifilament stainless steel, where the single filament can be as thin as 12 microns; a typical yarn would comprise of several hundreds filaments. The resistivity of these yarns is fairly low at ~0.07 Ohm/cm with a very high breaking strength of 75N and low 1% elongation, which creates a challenge during weaving. Stainless steel cannot be soldered and comes in a single grey color.

Multifilament yarn with wrapped metal fiber (Figure 2c). This yarn is used in the apparel industry to add sparkle to textiles [25]. The elongation depends on the material of the multifilament core; the twisted conductor has very low resistance but can be easily damaged during manufacturing or by wear and tear.

None of these yarns allows creating the variety of looks and tactile feels that is critical in textile design and the apparel industry, where aesthetic concerns such as colors and materials drive design decisions and ultimately consumer purchase decisions. Furthermore, existing yarns cannot be easily interfaced to electronics, because most cannot be soldered. We overcome these and other these challenges in designing Jacquard yarns.

E-textile Integration of Conductive Yarns

An early exploration of adding interactivity to clothing using conductive yarns was Musical Jacket developed in 1998 by Margaret Orth with collaborators at MIT Media Lab. They used stainless steel yarns to embroider a touch-sensitive keypad on denim [41], the keypad triggered musical notes when touched. Subsequently, stainless steel yarns have been used extensively to embroider interactive elements on textiles. The challenges of using stainless steel are the difficulty of interfacing reliably to electronics, because

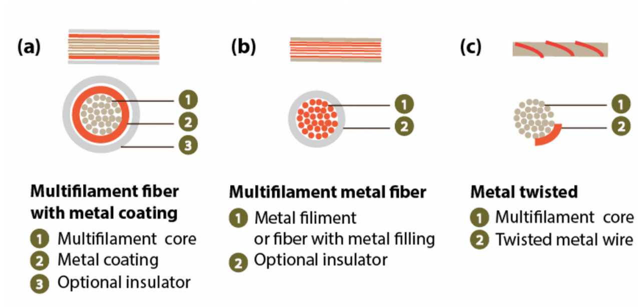


Figure 2. Conductive yarn structures: (a) multifilament fiber with metal coating (b) multifilament metal fiber (c) metal twisted on multifilament core.

stainless steel cannot be soldered; the slow speed and expense of embroidery; and the inability to make the technology truly disappear, as the embroidery is distinctive. Project Jacquard uses highly conductive custom-designed yarns that can be woven into textiles at scale using established industrial methods, can be dyed any color, and can be woven entirely invisibly without affecting the look and feel of the fabric.

Aesthetic, tactile, and visual qualities of a textile depends on the yarn it is made from, so yarn aesthetic is important. Conductive yarns were used in apparel for decorative purposes as long ago as the 1800s, when gold or silver-gilt copper metal threads became popular for decorative embroidery on clothing. Nowadays, novelty yarns that blend non-insulated metallic fiber and traditional yarn (Figure 2c) are readily available and often used in interactive design and the maker community to sew conductive elements and electronic components to clothes [1, 3, 12]. The distinct look and feel of the conductive yarns, however, inhibit their use in mainstream apparel.

The majority of current applications of conductive yarns for interactivity focus on *embroidery* and *stitching.* Project Jacquard focuses on *weaving* as the main approach for producing interactive textiles. Unlike embroidery, weaving can create large textile surfaces at high speed, e.g. a single industrial loom can fabricate more than 10 million square meters of textile per year. Furthermore, today's industrial weaving techniques allow production of an unbounded variety of textile colors, materials, patterns, and structures.

Industrial textile manufacturing uses aggressive and often destructive procedures that expose them to high stresses. For example, a common finishing procedure is singeing textiles with open fire to remove extra filament (Figure 3). We are not aware of previous work that attempts to design interactive conductive yarns for weaving into textiles at industrial scale, including withstanding finishing processes.

Figure 3. Singeing, i.e. burning with open flames, is a standard procedure that textiles are subjected to after weaving.

Electronics integration

Combining hard electronics and soft textiles is a challenge. No existing connector system can handle soft yarns at a fine pitch. Previous researchers used staples, sewing, snaps, conductive epoxy, crimping, etc. [16, 41, 26, 53]. These approaches are often not scalable for mass production and require re-thinking the design of yarns and textile integration, furthermore existing connector system can not handle fine pitch yarns. The Jacquard yarns are designed to be used with broad range of connection techniques, including soldering, crimping or conductive adhesives. We prefer soldering because it is a mature industrial process: techniques for reliable high-speed semi-automatic soldering are well-established. Soldering also affords very small, nearly invisible form factor and fine pitch connections common in consumer electronics. In comparison, crimping is challenging for any thin and soft conductors, e.g. copper alloys: the mechanical force has to be controlled very precisely or the wire easily breaks. Therefore, industrial-grade systems for crimping thin wires used for medical applications are very expensive. We have designed method for connecting conductive yarns to electronics that allows to avoid compromising the aesthetics of the garment. This process ultimately will be transparent, e.g. interactive textile will have manufactured “connector points” so that apparel designers could plugin the electronics to the textile or garment without any electrical modifications.

A variety of sensing and output devices have been connected to textiles using conductive fibers including touch sensitive buttons [41], pressure sensors [5], RFIDs, leads for EEG sensors in electronic socks and sports bras [32, 33] and others. Output devices used LED arrays, thermo chromic ink, vibration, and shape memory alloys [4]. The most common communication methods for interactive textiles are Wi-Fi and Bluetooth with a hybrid approach to power. Battery requirements are critical for interactive textiles: the power source must be either detachable from the textile or thin, flat, flexible, and able to survive washing, drying, ironing, and dry cleaning. Thin, flexible lithium ceramic batteries such as those made by Prologium [34] are good candidates.

Applications of Interactive Textiles

The majority of work on interactive garments *does not use interactive textiles*: the wearable devices are not integrated but simply attached to the garment. Examples include touch controllers, camera-based gesture interfaces, displays and voice input, and interfaces projected on the human body [9, 14, 17, 20]. The notable exceptions are Holleis et al. [9] who explored the locations of embroidered capacitive controls; Karrer et al. [10] who designed a novel sensing e-textile structure and explored the gestures it enables; and Lepinski et al. [13] who explored gestures derived from the natural affordances of cloth. Social implications of computing

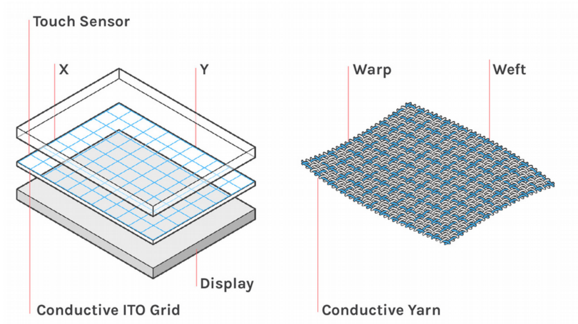


Figure 4. Textile structure is similar to that of multitouch capacitive panels used in tablets and mobile phones.

devices in clothing have also been explored [16, 18] as well as the effects of weight, size, and attachment method [6,11]. Sergio et al. demonstrated using conductive yarns as a textile based pressure sensor [61] and Berzowska et al. created bragg fiber jacquard-woven photonic textiles [60].

Significant research efforts focused on developing new tools and techniques for education and design. Do-it-yourself (DIY) toolkits (e.g., Lily Pads [1]) enable the DIY community to experiment with e-textiles and wearable computers by using materials and techniques (textiles and sewing) that they are familiar with [2]. Buechley et al. [1, 22] describe soft circuitry as a new language for electronics education and the STEM program, where yarns and buttons replace traces and connectors.

Despite more than two decades of development, interactive textile applications are still not widely available in the consumer products. The goal of Jacquard project is to develop an ecosystem capable to manufacture interactive textiles "at scale" and provide them to the general users. When we discuss developing digital textile "at-scale" we refer to "economy of scale", where the cost of production drastically decreases due to automatization.

PROJECT JACQUARD

In Project Jacquard we develop technology that enables weaving multitouch and gesturing interactivity into a broad range of textiles using standard, industrial looms and manufacturing processes. Project Jacquard was inspired by observing that the structure of woven textiles strongly resembles the structure of the multitouch sensor panels used in today's mobile phones and tablets with projected capacitive sensing: both are based on grid topology [42](Figure 4). Consequently, by replacing some of the yarns in warp and weft direction with conductive yarns (Figure 4), we can weave *flexible, textile multitouch panels* that have properties of both the touch screen and regular textiles: flexibility, lightness, multiple colors and textures, and low cost of textile production. The resulting textiles can be used like any other textile to produce clothing and household objects.

If the ultimate goal is manufacturing interactive objects using digital textiles, then developing interactive textiles is only a small part of the process of manufacturing products out of these textiles. Each step of production effects others down the production chain, which means that new yarns, textile structures, weaving and dying techniques, electronic interconnection and testing, and procedures for cutting and assembly must be developed to fit and support each other. Figure 5 illustrates the basic steps of producing an interactive garment, from Jacquard yarn to finished product. In the rest of the paper we present key elements of this process that we invented.

JACQUARD YARN

Conductive yarn is the core and the most fundamental technology for developing interactive textiles. The requirements for yarns depend on the application, in Project Jacquard they they were driven by the needs of the apparel and fashion industries. Here, we define the basic yarn requirements.

Jacquard yarn requirements

Conventional look and feel. The yarn must look and feel like normal yarn that designers are accustomed to working with.

Multiple colors, thicknesses, and materials. It must be possible to design the yarn in multiple colors and materials, such as wool, cotton, polyester, and silk. It must come in multiple thicknesses to accommodate the variety of user aesthetic choices, tastes and the types of textiles from organza to denim. Clothing is a seasonal product, and the same technology must accommodate interactive yarns for wool winter jackets and for lightweight summer dresses.

Electrical conductivity. The yarn must be highly conductive to support a high signal-to-noise ratio (SNR) in a capacitive sensor, for precise gesture and touch recognition. The conductivity must be uniform along the yarn, so that two pieces of yarn will have the same conductivity. The conductivity should not change with the use of the textile or from washing and drying.

Strength, temperature and chemical resistance. The yarn must withstand the high pulling forces that are applied during textile manufacturing. It must be resistant to the chemical agents used in color dying and textile finishing and those used in laundry and dry cleaning. Yarns should also withstand the high temperatures that textiles are subjected to during manufacturing (Figure 6) and use.

Reliability. The yarn must withstand aggressive wear and tear that is typical to normal yarn or textile use.

Electronics interconnectivity. It should be easy to connect the yarn to electronics, preferably by using existing techniques, such as soldering.

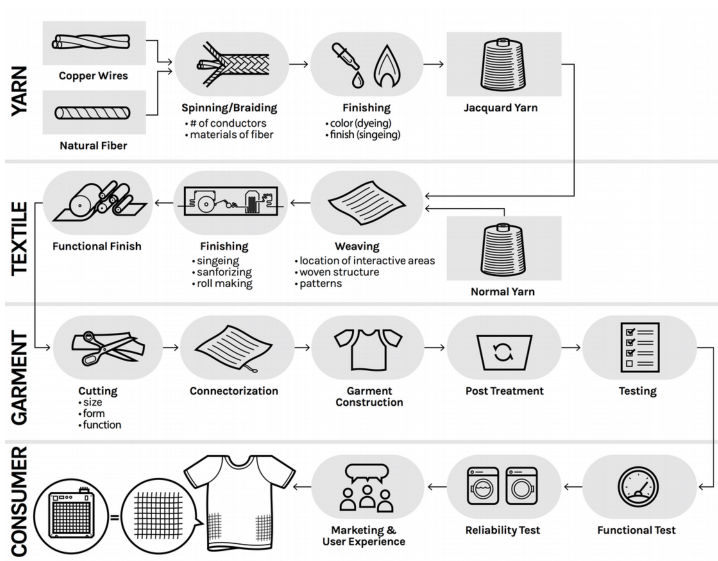


Figure 5. Project Jacquard manufacturing flow chart.

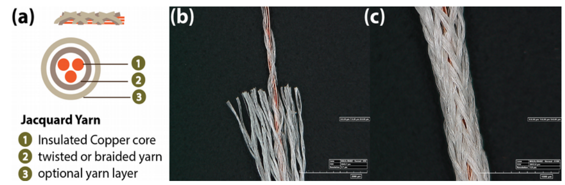


Figure 6. Jacquard yarn structure.

Figure 7. Jacquard yarns are indistinguishable from normal yarns

Safety. Yarn must be safe for people to wear and not introduce any health or safety hazards.

Cost and manufacturing at scale. Clothing can be a low margin business, so cost is a key consideration. We should be able to manufacture yarns at scale, which rules out rare and expensive materials and exotic manufacturing procedures and suggests use of materials that are readily available in global supply chains.

We were not aware of any existing yarns that could satisfy all these requirements and, therefore, we designed and implemented a manufacturing process for the new type of conductive yarns.

JACQUARD YARN ENGINEERING

Jacquard yarns are a multi-component yarn that consists of two structural elements (Figure 6). The core of the yarn is made of several strands of highly conductive thin metal wires, twisted at about five turns per meter and braided with two strands of silk that preserve structural integrity of the yarn during the manufacturing process. Furthermore, copper alloys can be easily soldered to electronic components using standard electronic manufacturing soldering techniques, such as hot-bar soldering.

This core structure is then over-braided to protect the thin metal core from external damage and abrasions, to strengthen the entire yarn in the tensile direction, prevent metal wires from coming into direct contact with human skin, and to give the yarn a natural look and feel.

Braiding is a standard manufacturing technique in producing yarns, ropes, and cables. By choosing different colors and materials for braiding we can produce yarn that looks and feels like any yarn made out of natural materials (Figure 7). Figure 6 demonstrates yarn over-braided with silk comparable to the #4-size cotton yarn standard in the textile industry.

The choice of metal core is defined by the use of the yarn and the envisioned applications of the resulting interactive textiles. Figure 6 shows Jacquard yarn that uses three alloy strands insulated with polyurethane. Polyurethane coating protects copper from harsh chemical environments, can withstand the high temperatures typical during ironing or textile production, and help ensure that metal does not touch human skin.

Table 1 shows how the physical properties of thin copper alloy wires compare with standard textile materials. The mechanical properties are comparable, which ensures natural look and feel of the yarn. The strength of Jacquard yarns that we tested (silk over-braided 3x50 micron copper lines) is more than sufficient for industrial textile manufacturing processes. Figure 8 shows the ultimate tensile strength (UTS) test. The graph of load vs time indicates that the breakage in conductive core occurs at 7.2 lb. This is much higher than required for industrial looms. For example, the maximum wrap tension of the Picanol OmniPlus 800 airjet weaving machine is less than 0.449 lb [29].

Project Jacquard introduces new design of conductive yarns that satisfy most of he requirements outlined at the beginning of this section. Developing these yarns is one of the key contributions of this project, because they enable production of interactive textiles reliably, inexpensively and at scale—opening up exciting opportunities for integrating digital interactivity and everyday objects.

JACQUARD WEAVING AND TEXTILES

The basic principles of weaving textiles are straightforward: yarns are interlaced in the horizontal (warp) and vertical (weft) directions, forming a tightly packed grid surface—

	Cotton	Silk	Wool	Copper
Fiber type	Cellulosic	Proteinic	Natural	N/A
Elongation %	5.9-6.7	20-25	25-40	>30%
Tensile strength (Kg/mm²)	28-84	25-35	13-20	25-28
Ironing limit (C)	180-220	140-165	215-240	>390

Table 1. Physical properties of 50 micrometers copper wire are comparable to cotton, silk and wool yarns which ensures natural look and feel of the Jacquard yarns.

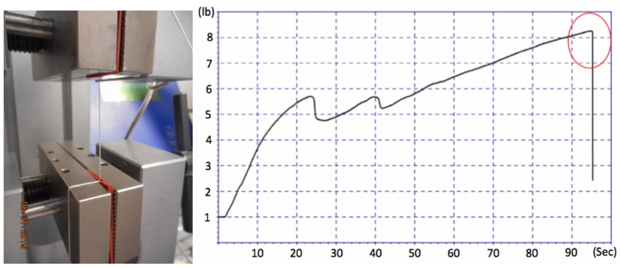


Figure 8. Tensile tests of Jacquard yarns

cloth. Choosing different configurations of warp and weft interlacing leads to a large range of textile structures.

Modern textile design and manufacturing allow for a practically boundless variety of woven textile structures and designs, including plain weave, twill, satin, and double and triple layer weaving. Practically any texture, image, or visual pattern can be woven. The textile can be rigid or stretchable, flat or woven with depth, bumpy, plush, or with ridges (like corduroy). Garment elements such as pockets and sleeves can be engineered into the weave of the fabric while it is still on the loom [42].

Design for Connectivity: 3D Woven Textile Structures

In the first design of Jacquard textiles the interactive grid was woven throughout the entire cloth as shown in Figure 9a. We used red conductive yarns to visualize the conductive grid. This textile design proved highly impractical in trying to design applications of Jacquard interactive textiles. Connecting individual yarns from textile required careful plucking of each yarn and soldering it to electronics, which was a laborious and error-prone process that could not scale to mass manufacturing.

We concluded that for interactive textiles to be useful, the interactivity of the textiles must reside in limited locations defined by the needs of the application. For example, a Teddy bear can have an interactive tummy, while a chair might have an interactive arm rest (Figure 1). In addition it was important for us to preserve the original vision of interactive textiles where interactivity is seamlessly woven into the fabric, rather than an external add-on.

Figure 9b presents the design of the interactive Jacquard textiles that solve these issues by using an advanced 3D weaving technique. This sample is woven as a two-layer textile, where the conductive (red) yarn forms a localized, square conductive area in the top layer, then passes through the fabric to the bottom layer, where it *floats.* There the yarns are free from the textile and can be addressed individually. We can easily bundle them together, strip them, and solder them to electronics without plucking them out of the cloth, which greatly simplifies connection to electronics and

a. b. c.
d. e. f.
g. h. i.

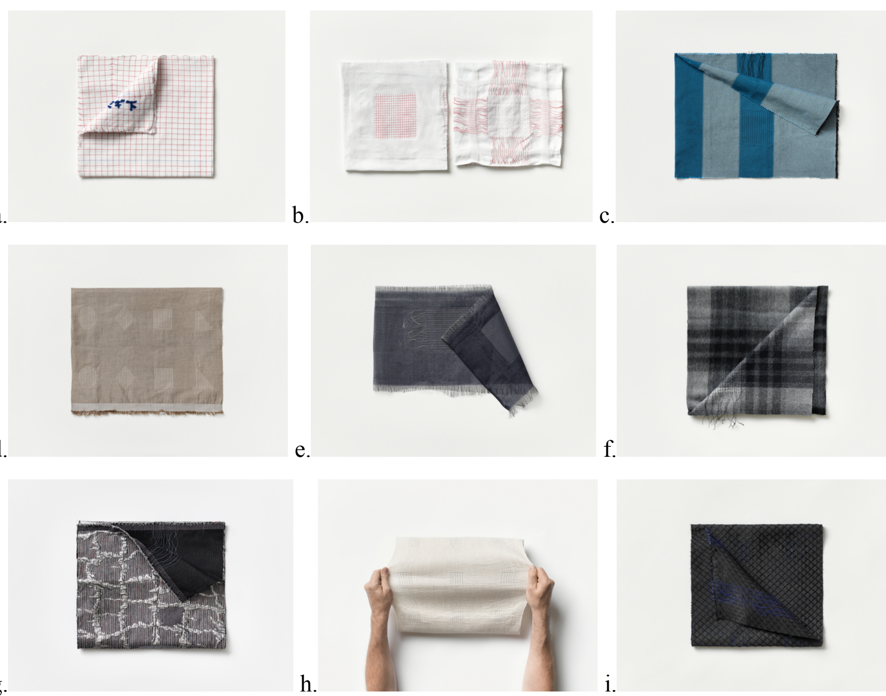


Figure 9. Jacquard Textiles: (a) Plain interactive (b) 3D Interactive patches and floats (c) Colors patterns (d) Shape of patches (e) Silk and translucent (f) Wool and invisible (g) Multiple materials (h) Stretchable (i) "Bumpy"

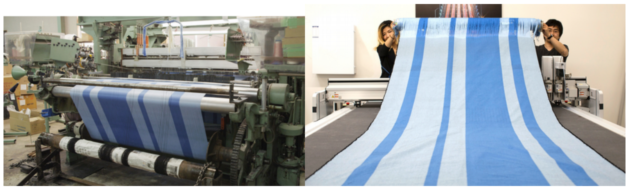
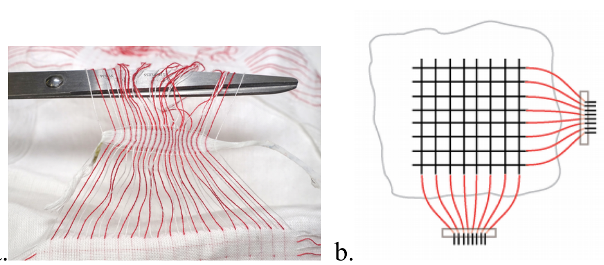


Figure 10. Left: Weaving interactive Jacquard textile Right: Interactive areas are in various locations

enables defining standard procedures scalable to manufacturing scale. What is important is that these interactive areas are woven seamlessly into the textile. Because they are an integrated part of the textile and not an external addition, they can be merged into the basic properties and visual designs of textile materials. Such an area can be easily woven anywhere on the textile that the designer desires and can be combined with visual color patterns (Figure 9c). The interactive areas can be either 2D grids or 1D arrays and take a broad variety of shapes such as triangles and circles (Figure 9d). They can be woven into translucent organza silk or thick wool textiles with classic patterns (Figures 9e,f). Interactive weave can be combined with any patterns, textures, and materials (Figure 9g) and can be stretchable (Figure 9h) or bumpy, where individual bumps form interactive areas, like buttons (Figure 9i).

Manufacturing

Jacquard textiles use novel conductive thread and standard textile manufacturing techniques to seamlessly weave touch and gesture interactivity into the textile touch surfaces of textiles of very large size and arbitrary color, material, and texture (Figure 10). The 3D weaving techniques used in Jacquard can precisely locate interactive areas and either completely hide them by making them invisible or make them prominent and tactile, by combining them with textile shapes like bumps. The creative and aesthetic freedom to create flexible, lightweight, and inexpensive textile touch and gesture sensors with Jacquard is virtually unlimited.



a. b.

Figure 11: a) floating yarns b) connecting to interposer

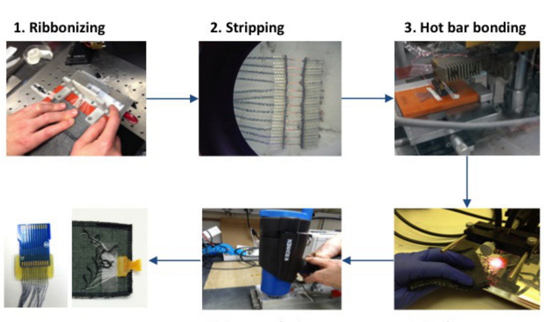


Figure 12: Connectorization process.

CONNECTIVITY AND ELECTRONICS

Some of the main challenges of designing and developing applications of digital textiles include *integration*, *power*, and *size*. The integration, i.e. connecting soft fabric and yarn with rigid electronics is especially difficult. In Project Jacquard we developed custom interconnection mechanism and connection procedures that makes it easy to create reliable connection between yarns and wearable electronics. We briefly describe them in this section.

Connecting Jacquard yarns to electronics

Compared to other conductive yarns described above, Jacquard yarns can be simply soldered to electronic components using traditional soldering techniques.

The purpose of the interconnection process is to connect floating Jacquard yarns (Figure 11a) to electrical interposers e.g. a flexible PCB (Figure 11b) with minimal electronics components. Once the yarns are connected to an interposer it is relatively trivial to connect the interposer to any other electronic device. The interposer can then be mechanically attached to the textile and sealed using such techniques as coating or over-molding. The overall connection process is presented on Figure 12. We break down the connection process into series of simple, distinct operational steps including a) arranging floating yarns to the pitch of the interposer, e.g. 1.2 mm pitch, b) thermal stripping, i.e. removing silk braid by heating it; c) soldering to a flex circuit board interposer using a hand tool or industrial equipment; d) sealing the yarn connection to stop water seeping through braiding into the electronics. The resulted encapsulation is on Figure 12.

Jacquard Electronics

The *sensing module* connects to interposer and includes capacitive sensing IC (Microchip, Figure 13) with 15 input channels that can operate as a slave over I2C bus to a main microprocessor. The capacitive sensing IC works on the principle of *self-capacitance*, which is an efficient gesture sensing scheme and has a built-in gesture recognition capability and can output gestures such as tap, hold, X-Y, distance between taps, and gesture click time. We can easily daisy chain multiple devices to expand the sensing lines.

The *processing module* houses the microprocessor and the communication between the sensing interposer and the outside world. Our main processor is a PIC18LF46K22l. It reads Jacquard sensor via I2C protocol from the capacitive sensing IC and sends gesture or touch location to the mobile phone using the Bluetooth 4.0 (nRF8001 IC).

Currently, the touch refresh performance is ~200 times per second with 12-bit resolution. The fully implemented sys-

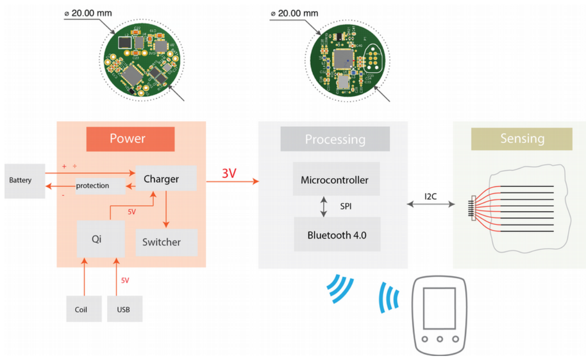


Figure 13: Electronics and system configuration

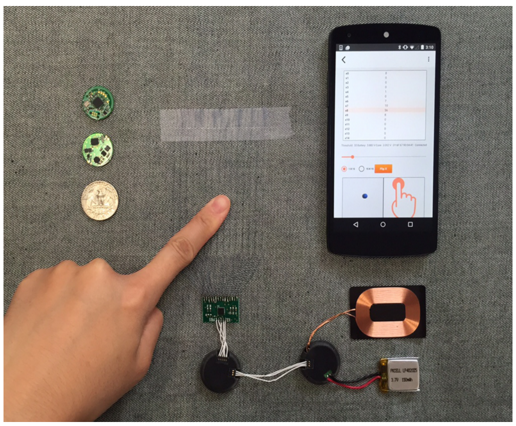


Figure 14: Electronics and application configuration Electronics are shown both inside of and without housings, and the interposer encapsulation is not shown.

tem is shown in Figure 14. A number of battery saving features, such an efficient sleep and wake up modes, have been implemented. Currently, we estimate that with regular usage, the time between re-charging can be ~7.35 days.

The Project Jacquard electronics system is modular, very small, simple, and power efficient; it provides sufficient functionality to allow us to build Project Jacquard textiles into various objects.

Low power design and implementation notes

One of the most critical aspects in the design of wearable device is power. The number of power modes depends on the advertising interval of the BLE, the frame rate setup, and the touch count of the touch IC (MTCH6102).

Initial power-up, reset, and/or BLE disconnect. In this mode, the average current consumption is 0.85 mA, the BLE is awake, not connected, but in advertising mode. The MCU is asleep, waiting for interrupts from BLE. The touch IC waits to be activated by the MCU.

Connected, no touch or gesture input. The average current consumption is 1.7 mA: the BLE is awake and connected. The MCU is in sleep mode, and interruptible by the BLE or touch IC.

Connected with constant touch and gesture input. The average current consumption is 3.3 mA. The BLE transmits data on touch and gesture. The MCU is asleep but wakes on interrupt when touch and gesture occur. The touch IC scans for input and send data over via I2C.
Connected with constant gesture. If we turn off the raw data streaming, we can lower the power with an average current consumption is 2.4 mA.

Capacitive sensing is powerful because it can be low power and with the use of a capacitive voltage divider technique, no external component is needed [27]. The background noise and the small difference between parasitic capacitance and electrode touch capacitance poses a challenge in a wearable applications where the environment constantly changes. Depending on sensor and system design, the parasitic capacitance between electrodes is normally around 100 pF. A strong touch could cause variation from 0.5 to 1.0 pF, and a weak touch, around 0.05 pF.

APPLICATIONS OF JACQUARD

Textiles are basic materials to develop a broad variety of objects and tools around us, including clothing, furniture, accessories and bags, toys, carpets, interior and automotive, etc. (Figure 1) We envision that interactive textiles can be used in all these application by replacing or enhancing the traditional textiles. In this section we present initial explorations of the applications of Project Jacquard and some of the basic uses cases that we implemented.

Garments represent possibly the most obvious personal use of interactive textiles. A certain area of the garment can become a touch sensitive, interactive area that allows users to initiate some functionality simply by touching a garment, for example a current location can be communicated on the Google Maps by pinching a color on the shirt (Figure 15).

We observed that interactive textiles allow adding interactivity to smart clothing invisibly and unobtrusively, without compromising the look and feel of clothes. However, it also raised several important issues: a) how the user would be able to find the interactive area b) when the user touches different parts of the garments, the gestures should be socially acceptable; indeed once the interface is hidden, the user can not indicate to others that he or she are interacting with the devices when they are touching the garment c) the technical aspects of the electronics integration could be challenging: even though our electronics components are very small integrating them in the garment seamlessly could be challenging.

To investigate these challenges we collaborated with independent fashion designer Camilia Skikos [50] and designed a series of garments with interactive areas woven into the garment sleeve (Figure 16). These included a silk and wool jackets, where in one case the interactive area was completely invisible (Figure 15, right) and in other case we used

Figure 15: Possible locations of the woven interactive areas

Figure 16: Interactive garments with Project Jacquard

a surface weave technique where the Jacquard yarns were raised over the surface of garment providing subtle visual and very distinct tactile feedback for interaction.

Through informal observations and evaluations we observed that tactile feedback was very effective and provided superior interactive experience. We also discovered that sleeve provides most natural, neutral and socially acceptable user experience. From the design point of view, the sleeve was designed separately from the rest of the jacket and could be open with a zipper to add electronics. Electronics, batteries, and battery charging pads were included in a pocket in specially-designed shoulder pads. The connection between the interactive area and the shoulder was carefully managed, using ribbon cable with strain relief on each end, to have minimal effect appearance, flow and motion of fabric on the wearer's body. The resulted interface was then connected to the mobile phones that implemented basic gestures recognition, such as swipe, hold and tap. These gestures were then mapped to the common tasks such as "answer a phone call", "or place a phone call to specified number", "call an Uber", etc. We observed that the interaction with garment was easy and intuitive and provided a direct interfaces to most important actions that user wanted to perform without accessing the phone internal interface. The garment formed a sort of interaction "bookmark", allowing immediate, fluent and seamless interaction with mobile functionality. These experiments represent very early and initial explorations of the design and interaction implications of the interactive textiles in wearable computing and smart garments. We believe that, as the technology develops and become accessible to growing number of researchers and practitioners, new applications will be developed.

Interactive environments and Internet of Things (IOT) represents another important application of interactive textiles. The Figure 17 demonstrates our explorations into use of

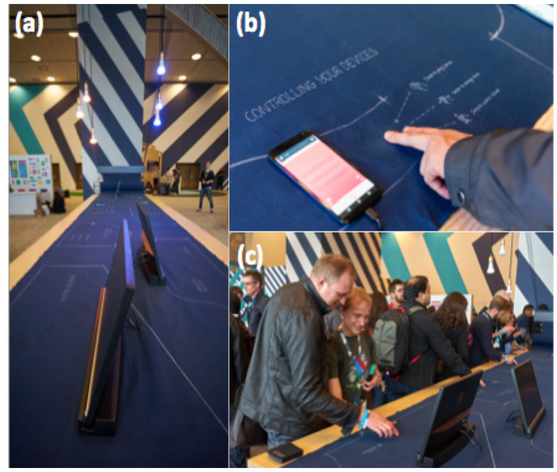


Figure 17: Interactive Environments designed with Project Jacquard's textile interface.

Project Jacquard interactive textiles as a control surface for connected devices, also known as the "internet of things". We developed a "living laboratory", an experimental set up where a single seamless 7 meters piece of fabric was woven with multiple interactive patches across the entire area and then connected to various devices. Instructions were printed on the textile to explain gestures required to control the devices. For example on Figure 17a, gestures allowed to control mobile player that would play music on connected Wi-Fi speakers. In another location on the same piece of textile, a swipe controlled the color of a LIFX light bulbs: the user was able to control lights, color, turn them on and off. We demonstrated our responsive environment in public demonstrations at the technical conference venue where over 4000 people explored the interaction with this technology. An informal, in-situ questionnaire was administrated to the visitors to collect feedback. Overall, The IOT application of interactive textiles was universally well accepted. Using smart fabrics embedded into the environment was supported by the visitors and delighted them. Several visitors commented that fabric invites touch and gesture; indeed in home environment touching fabric-covered surfaces, e.g. table clothes or furniture, are natural and regular activities. Enhancing the available textile surfaces with touch interactivity was perceived as an elegant, intuitive and easy to understand solutions to the challenges posed.

EXPERIMENTAL EVALUATIONS

We conducted a range of experiments to evaluate robustness and user experience in using interactive textiles. In order to do that we developed an experimental test bed running on the Android mobile phone, where gestures and interactions are recognized, time stamped and analyzed.

In these experiments we tested if repeated sliding on the interactive textile would affects gesture recognition because of the repeated deformations of textiles or the wear and tear on the interactive surface.

To evaluate this, we set up a KUKA LBR IIWA 14 R820 model robotic arm to simulate the wear and tear produced by the human touch over the lifetime of the interactive fabric (Figure 19). We used a 1x15 grid textile interactive rid, the product lifetime was estimated at 3 years, with 200 days of usage, and 20 swipes per day, that is, 12,000 swipes. We measured the number of swipes on the textile before breakage of the yarn as well as gesture recognition rate. Our testing application logs successful input from a swipe gesture in three input locations. Each swipe took 3 seconds and the total test took 10 hours. The fabric was set on flexible sponge foam to best simulate body flexibility. The average applied pressure was 2.037 N. After 12,000 swipes, the overall gesture recognition rate was 95.12% and there was no visible damage to the fabric. In the follow up experiments we performed 30,000 additional swipes on the same piece of fabric and the recognition rate remained over 95% consistent with the baseline recognition rate.

Usability evaluation of interactive textile

A preliminary usability evaluation of the interactive textile was performed to evaluate comfort and effectiveness of using different gestures on the clothes in different wearable conditions. We used Velcro to attach patches with small interactive areas to the sleeve of test jacket. Using experimental test bed (Figure 18) we measured recognition rate for 3 gestures: *swipe left*, *swipe right* and *hold* under 3 different conditions: *sitting*, *walking*, and *standing*. Within subject repeated measures experimental procedure was used with 12 participants, 28 to 43 years old 8 males and 4 females.

During the training phase of the experiments the participants used the phones to learn gestures, e.g. on Figure 18 the screen shows a swipe right gesture. After training the participants were asked to perform each type of gestures for 10 times without looking at the phone. The experimenter operated the phone and logged the data, by recording the recognition detection rates. Two outliers data set were removed due to sleeve with interactive area slipping off during the experimental session.

The overall recognition rate across all gestures and conditions was 76.8%. When we break down the recognition rate across the conditions we achieve 74.6%, 80.6% and 75.3% for sitting standing and walking respectively. The recognition rate across gestures was 71.3%, 71.0% and 88.3% for swipe right, swipe left and hold. We observe that recognition rate changes significantly depending on the activity that the user engages into (statistically significant at $p = 0.007$), which is to be expected and warrant further exploration in interaction design. Additional paired t-tests show that the swipe right gesture has the greatest difference in sit versus stand activity (p=0.001). This suggest that future work on the interactive clothes should take in account the user activity and correlate gesture design to types of activity the user is expected to perform. Post-experiment questionnaire with participants suggested that they enjoyed interaction and felt it was effective and natural.

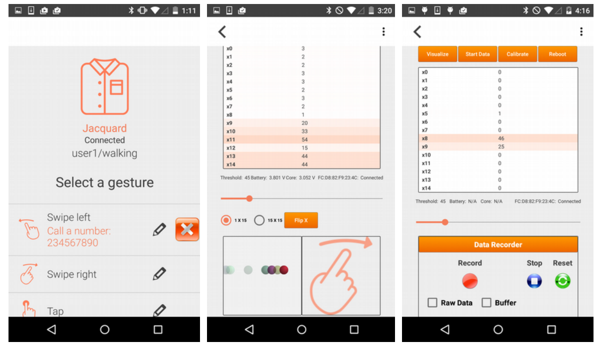


Figure 18. The Jacquard data-logging application including gesture/function matching; data visualization; data recording.

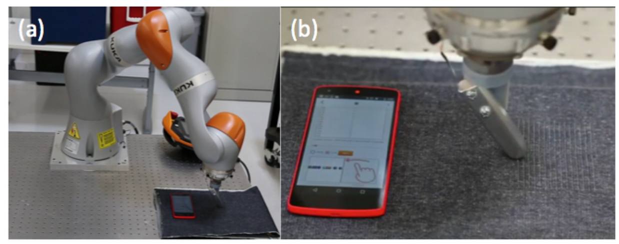


Figure 19. Gesture reliability, wear and tear test. The robotic arm scans interactive area with 2.037 N of pressure.

False-positive of the gesture recognition on soft substrate is indeed a challenge. Controlling the scenarios of the application where the triggering mode is obvious for the sensors is the key to increase the recognition rate. The reported experiments have preliminary nature and more follow up research is required to understand full implication of interactive clothes on user mobile and wearable interaction. Nevertheless, it is indicated that the interaction with textile based woven touch sensors can be effective and an important direction of designing future interactive experiences.

CONCLUSIONS

We presented Project Jacquard that allows weaving interactive textiles at scale. We presented underlying technology; procedures and materials used to develop this technology, provided early evaluation of possible use cases and developed sample applications. We hope that the current work will inspire research in new forms of materials and integration of computation into the everyday objects and environments, bringing the vision of invisible seamless computing one step closer to the reality. From the user study, we leant that effectiveness of wearable gesture sensors strongly correlated to the context of human activity. Further studies and gesture interaction design are needed to accommodate this new form of wearable input that project Jacquard presents.

ACKNOWLEDGMENT

We thank the help from Camelia Skikos, Ali Javidan, Mark Zarich, Norbert Tydingco, and Aaron Weiss.

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