E-broidery: Design and fabrication of textile-based computing

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Highly durable, flexible, and even washable multilayer electronic circuitry can be constructed on textile substrates, using conductive yarns and suitably packaged components. In this paper we describe the development of* e-broidery *(electronic embroidery, i.e., the patterning of conductive textiles by numerically controlled sewing or weaving processes) as a means of creating computationally active textiles. We compare textiles to existing flexible circuit substrates with regard to durability, conformability, and wearability. We also report on: some unique applications enabled by our work; the construction of sensors and user interface elements in textiles; and a complete process for creating flexible multilayer circuits on fabric substrates. This process maintains close compatibility with existing electronic components and design tools, while optimizing design techniques and component packages for use in textiles.

Everyone wears clothing. It conveys a sense of the wearer's identity, provides protection from the environment, and supplies a convenient way to carry all the paraphernalia of daily life. Of course, clothing is made from textiles, which are themselves among the first composite materials engineered by humans. Textiles have mechanical, aesthetic, and material advantages that make them ubiquitous in both society and industry. The woven structure of textiles and spun fibers makes them durable, washable, and conformal, while their composite nature affords tremendous variety in their texture, for both visual and tactile senses.

Sadly, not everyone wears a computer, although there is presently a great deal of interest in "wearable computing."[1] Wearable computing may be seen as the result of a design philosophy that integrates embedded computation and sensing into everyday life to give users continuous access to the capabilities of personal computing.

Ideally, computers would be as convenient, durable, and comfortable as clothing, but most wearable computers still take an awkward form that is dictated by the materials and processes traditionally used in electronic fabrication. The design principle of packaging electronics in hard plastic boxes (no matter how small) is pervasive, and alternatives are difficult to imagine. As a result, most wearable computing equipment is not truly wearable except in the sense that it fits into a pocket or straps onto the body. What is needed is a way to integrate technology directly into textiles and clothing. Furthermore, textile-based computing is not limited to applications in wearable computing; in fact, it is broadly applicable to ubiquitous computing, allowing the integration of interactive elements into furniture and decor in general.

In this paper we describe our efforts to meet this need in three main parts. First, we present examples of applications that can be realized only through the use of textile-based circuitry and sensing, including a piecework (or quilted) switch matrix, an electrical dress, a musical jacket incorporating an e-broidered

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keypad and fabric buses, a musical ball with e-broidered pressure sensors, and a flexible, multilayer "No-Soap Radio" built using textile-ready component packages. Next, we discuss the materials used in realizing these applications, both to report on our experience with them and to illustrate the range of presently available electronic textiles. Finally, we describe a process for making flexible multilayer circuits in fabric.[2] This is a detailed description of steps involved in fabricating the No-Soap Radio.

Throughout this work we hope to demonstrate that textile-based circuitry compares favorably with conventional printed circuitry when applied to user interfaces, and furthermore that its mechanical properties present several advantages over conventional flexible circuit substrates.

Overview of applications

Our research into textile circuits was driven not only by an interest in wearable computing, but also by a desire to create new sensor materials for physical computer interfaces. For example, commercially available electronic musical instruments, with their buttons, knobs, and sliders, are excellent examples of the physically limiting sensors available when creating physical interfaces for the computer. Textiles are typically soft, conformal, durable, and highly plastic. Turning them into computers and sensors was a compelling way to create better wearable computers and better physical computing interfaces. These applications reflect many of our motivations.

Row and column fabric keyboard. The row and column fabric keyboard (Figure 1) is a fabric switch matrix sewn from conducting and nonconducting fabric. The keyboard consists of two layers of highly conductive metallic organza with a resistance of approximately 10 Ω/m (ohm/meter) and nonconducting rows separated by an insulating layer of nylon netting (also known as tulle). When pressed at the right point, the two conducting layers make contact through spaces in the nylon netting and current flows from a row electrode to a column electrode. Commercial gripper snaps are used to connect wires from a microcontroller to the organza. The keyboard can be repeatedly rolled up, crushed, or washed without affecting its electrical properties.

Figure 1 Row and column fabric keyboard

The microcontroller used to read out the keyboard was programmed to generate standard MIDI (Musical Instrument Digital Interface) control information, allowing players to easily trigger different notes on an attached synthesizer. This keyboard did not measure pressure information (which is important for expressive control in music). Because there was no nonlinear element present at the switching intersections, false or "phantom" contacts were observed by the microcontroller when multiple keys were pressed. Finally, the piecework nature of the keyboard required more manual labor than was hoped for. For all its drawbacks, however, users found it very satisfying to make music by crushing and crumpling this keyboard.

Firefly Dress. The Firefly Dress (Figure 2) is a creative application that embellishes the wearer's motion with an ever-changing display of light. Its first part is a skirt, handmade from two layers of conducting organza (one supplying power and the other ground) separated by a layer of nylon netting. Light-emitting diodes (LEDs) with fuzzy conductive Velcro** ends for electrical contacts are placed throughout the netting. When both ends of an LED brush against the power and ground planes, the circuit is complete and the LED lights.

The bodice (with a conductive front panel) and the necklace form a second dynamic element. The necklace is a simple analog computer, powered when any of its conducting tassels brush against a plane of con-

Figure 2 Firefly Dress

ducting organza sewn to the front of the bodice. Each tassel has its own resistor network and provides a different color bias to the red, green, and blue LEDs on the face of the necklace.

The dress demonstrated the visual, tactile, and mechanical potential of sewing circuitry into clothing. The difficulty of adding ordinarily packaged LEDs to the skirt pointed out the need for more appropriate component packages. The time-consuming piecework involved in creating the dress also motivated our search for a better means of creating textile circuitry.

Musical Jacket with embroidered keypad. The Musical Jacket (Figure 3) turns an ordinary denim jacket into a wearable musical instrument, allowing the wearer to play notes, chords, rhythms, and accompaniment using any instrument available in the General MIDI scheme. It integrates directly into the jacket an embroidered fabric keypad, a MIDI sequencer/synthesizer, amplifying speakers, a fabric bus sewn from conductive organza, and batteries to power the above subsystems.

The embroidered keypad is flexible, durable, and highly responsive to touch. It was mass-produced using ordinary embroidery techniques and a mildly conductive stainless steel and polyester composite thread (Bekaert BK50/2, described later), and demonstrated for the first time that a textile keypad could be made by e-broidery on a single layer of fabric in one step. This process allowed us to precisely specify the circuit layout and stitch pattern in a computer-aided design (CAD) environment, from which any number of articles can be sewn under machine control.

The MIDI jacket keypad used a PIC** microcontroller from Microchip Technology Inc., to perform capacitive measurements of connections to sewn electrodes on a denim substrate. The measurement was implemented almost entirely in software as an exercise in developing electric field sensors with a minimum of hardware, but this minimalism also benefits the fabric circuit designer by reducing the number of components (and hence interconnections) required in a circuit. The electrode array was sewn in the pattern of a telephone keypad, with traces leading from the symbols to an array of connection pads intended to mate with a conventional circuit board.

The resistivity of the electrodes and their associated connecting traces is reduced by the precise placement of individual stitches. Each electrode is sewn from a single continuous thread that crosses itself many times, leading to a multiplicity of intersections that create parallel resistances and increase the overall conductivity of the sewn circuit element. By using this “e-broidery stitch” we obtain resistances per unit trace length that are dramatically lower (by more than an order of magnitude) and more consistent than those obtained with conventional embroidery stitches (e.g., satin or tatami stitches) that are chosen for their appearance or texture.

The embroidered keypad[3] uses a capacitive sensing technique[4] because of the high impedance of the sewn electrodes. The measurement algorithm is similar to that used in the Museum of Modern Art (MoMA) table described elsewhere in this issue,[5] but

Figure 3 On the left is the Musical Jacket, comprising a fabric keypad on one side, a MIDI synthesizer “boat” on the other side, speakers behind speaker grills in the pockets, and fabric buses visible inside the jacket. On the right is a composite image of both sides of the circuit board attached to the back of the fabric keypad.

here the measured capacitance is compared to a threshold to distinguish contact events. This measurement is implemented using a single bidirectional digital input/output (I/O) pin per electrode and a leakage resistor (which can be sewn in highly resistive yarn). Key contact events are output as a serial data stream by the microcontroller. The circuit board makes contact with the electrodes at the circular pads only at the bottom of the electrode pattern. A view of the component side of the circuit board has been superimposed to show its extent and its connections to the fabric. A flexible circuit board can be substituted for the rigid one used in this implementation.

Fifty denim jackets were embroidered with this pattern and outfitted with sewn fabric buses that carry power, ground, serial data and analog audio signals across the backs of the jackets. These jackets also provided an AC ground for the keypad, to ensure consistent capacitance measurements. In all 50 jackets, both the fabric keypad and bus worked reliably and held up to repeated mechanical stresses better than the more traditional wires and connectors also used. The interface between the sewn keypad and the electronics led into our work to do away with the circuit board entirely.

Musical Ball. The Musical Ball (Figure 4) is a plush stuffed toy that allows users to play music by applying pressure in any of eight regions as they squeeze the ball. There are ten electrodes made by e-broidery on its surface, eight of which capacitively sense pressure and two of which provide a ground reference for the capacitive sensing. The eight channels of pressure data are sent as serial data to a host running an application that uses these data to generate music through either external MIDI devices or an internal sound card. This application would have been impossible to realize using conventional pressure sensors. By using sensors made by e-broidery, we

Figure 4 Musical Balls

were able to create a light, hand-held, flexible, multichannel, continuous control instrument in a single manufacturing step. We were also able to directly tailor the sensor's size, shape, and appearance.

The impedance in the electrodes in the ball is dramatically reduced by using highly conductive thread in the machine bobbin during e-broidery. In contrast to the electrodes in the musical jacket, whose conductivity is improved and controlled through stitch pattern, the conductivity of the electrodes in the ball is limited by the conductivity of the bobbin thread.

Electronic Tablecloth. The Electronic Tablecloth (Figure 5) is a sensor surface that allows users to interact with a computer and with each other in the context of a social function. Attendees identified themselves to the system by setting their assigned "coaster tags" on the swirling pattern, above which are embroidered the words "Place your coaster here." The coaster is in turn a capacitively coupled radio frequency identification device (RFID) tag, and is read by the tag reader in the tablecloth when the user sets it on the swirling pattern and touches the fabric electrode on top of the coaster. The computer then enters a dialog with the user through the appropriate fluorescent display and keypad.

We combined five keypads and five capacitive tag readers all made by e-broidery to create a tablecloth (and centerpiece) that turns an ordinary table into interactive furniture. The electronics for this application are housed in the centerpiece. We encountered difficulty using our capacitive keys near the electrostatic tag reader electrodes, which in normal operation present a 50-volt rms (root-mean-square) sine wave at 125 kHz to power up and read out tags. By applying a shielding layer of metallic organza under and around the swirling electrodes, we were able to terminate most of the electric "field lines" before they reached the keypad electrodes.

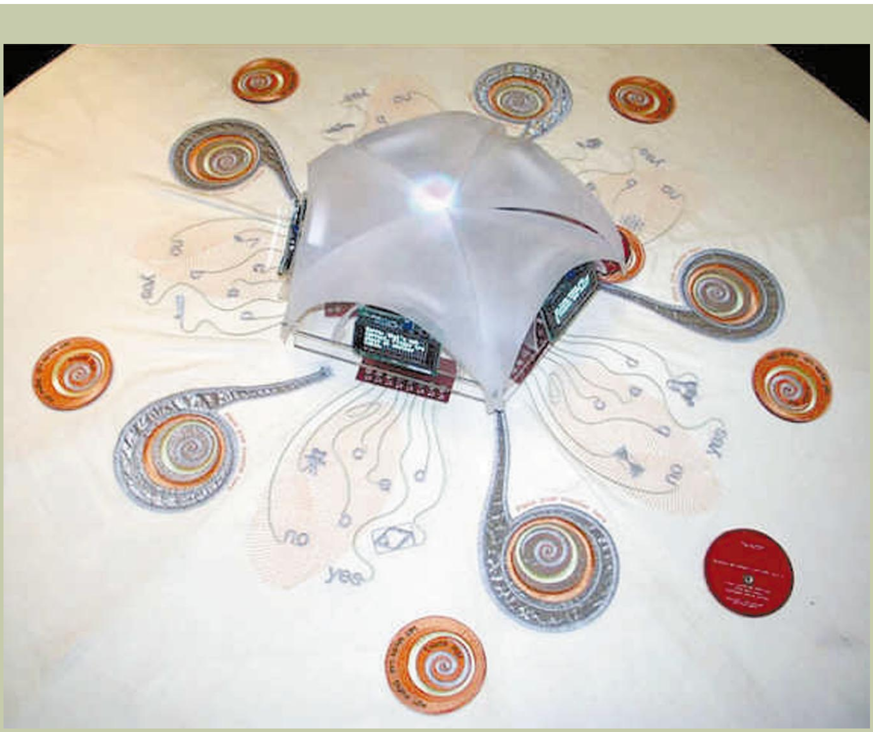
No-Soap Radio. This washable, crushable keypad made by e-broidery (Figure 6) is known as the No-Soap Radio, because it was designed to be dry-cleanable and to transmit data to a nearby AM/FM radio (via near-field electrostatic coupling). When the user touches a symbol on the keypad, the microcontroller capacitively senses the contact and then transmits a particular audible tone (depending on which symbol was touched) by FM-modulating a 455 kHz square-wave carrier in software and presenting the resulting signal on all of the keys connected to the circuit (Pad0 through Pad3). The user then acts as transmitting antenna for the No-Soap Radio. Two pins are reserved for intrasensor communications to allow the construction of larger keypads by networking several instances of the basic four-key sensor. Nodes can communicate with each other and a host processor over a serial bus on these two reserved pins.

The only external components used in this circuit are two 2MΩ resistors, which allow the charging time measurement to be done in software. These are used in lieu of resistors that could be included directly in the integrated circuit. The resistors are soldered onto the PIC12C509 leadframe after steel threads are microspotwelded onto the leads. The resistors are in surface-mount 0402 packages, with dimensions 0.040 inch × 0.020 inch × 0.010 inch. The fabrication of this and other, similar devices is discussed in detail below.

Textile circuit fabrication techniques

Our first step in manufacturing textile circuitry was to identify textiles and yarns suitable for use in fabric circuitry, and then to find a way to design and fabricate such circuitry. As piecework is time consuming and imprecise, our primary method of circuit patterning has been e-broidery, i.e., numerically controlled embroidery using conductive thread. We use e-broidery to stitch patterns that define circuit traces, component connection pads, or sensing sur-

Figure 5 Electronic Tablecloth



faces. By using commercial embroidery processes, we have built on prior art in the textile industry that permits precise control of the design, layout, and stitch pattern of the circuitry through CAD processes.

Yarns and threads usable in high-speed embroidery processes must make a trade-off between electrical and mechanical properties. These yarns must be conductive, but also strong and flexible enough to be sewn at high speeds without breaks in either the thread itself or in the electrical continuity. These yarns must also maintain their electrical properties when washed (we consider dry cleaning to be the target washing process, and exposure to water, alcohol, and sweat as an everyday occurrence).

These processes also allow control and integration of yarns with different electrical properties, for instance, different resistances. This level of stitch control and yarn variety brings up the possibility of replacing discrete components such as capacitors, resistors, and inductors with specific combinations of thread and stitch pattern. Such components might lead to reduced manufacturing cost and higher reliability from improved mechanical properties.

Figure 6 The No-Soap Radio. An AM broadcast receiver (right) is used to listen to the transmitted signal.

First, in order to work with available machine sewable threads we have chosen not to require low-impedance component interconnections, as is done in conventional printed circuit design. Instead, we choose circuit elements and design principles with low power consumption and high input impedances.

Second, our next step was to design packages optimized for use in fabric circuitry. In this report, we focus on the design of the "Plastic Threaded Chip Carrier" (PTCC), a package that resembles the Plastic Leadless Chip Carrier (PLCC). The PLCC is a well-known surface-mount integrated circuit (IC) package style, designed to be soldered onto printed copper circuit traces on a rigid or semi-rigid circuit board. Conversely, the PTCC is designed to be stitched or woven into a fabric circuit, and for this purpose has long, flexible conducting leads. Our primary goal was to demonstrate a durable interconnection and attachment scheme for electronic components used in circuits made by e-broidery.

The third step was to develop multilayer circuitry. Even if we can sew a circuit, its complexity will be limited if it is restricted to lie in a plane. By making multilayer e-broidery, we hope to demonstrate that textile-based circuitry compares favorably to printed circuit boards and conventional flexible substrates in terms of design complexity and reliability, particularly in user interface applications.

The first step in integrating electronic technology into textiles and clothing might be to simply remove the bulky and stiff housing of most electronic gear. We might also make the circuit board smaller and removable by redesigning it with components in smaller packages, and using conductive fasteners, like snaps, to connect the boards to the fabric. (This way the boards can be removed when a garment goes into the wash.) Unfortunately, circuit boards neither look nor feel good when they become part of clothing, nor does this approach scale well because of the many layers of packaging and connective elements that come between the silicon and the textiles.

To overcome these limitations, we have chosen to combine electronic components and conductive textile circuitry as directly as possible. We replace standard printed circuitry on rigid or flexible substrates with circuitry made by e-broidery and component packages optimized for use on fabric substrates. These packages can be washed without harm to either their internal electrical properties or their connections to the substrate and other components. Finally, we would like the interface between components and circuitry to withstand the flexing and stretching that clothing and textiles are prone to experience.

One goal of our work is to create electronic garments and textiles that exhibit integrity, that is, garments that look, feel, wash, and wear as well as ordinary clothing. In this context, system integration becomes the art of partitioning a digital system across several items of clothing. For example, most people have only a few pairs of shoes, a few more pairs of pants, several shirts, and a few outer garments. It makes sense to put the most expensive parts of a system in the shoes and outer garments, and the least expensive parts in the shirts, pants, and undergarments.

In this section, we discuss the properties of several textiles we have used. In the next section on component integration and packaging, we detail a strategy for making electronic circuitry disappear into clothing and textiles in several steps. First, we replace standard printed circuit boards with e-broidery (embroidered textile circuitry) designed with traditional CAD tools for circuit layout and rendered on numerically controlled embroidery machines using conducting and insulating threads. Second, we redesign electronic component packaging for use in circuitry made by e-broidery. Third, we combine layers of circuitry to form multilayer circuitry of arbitrary complexity.

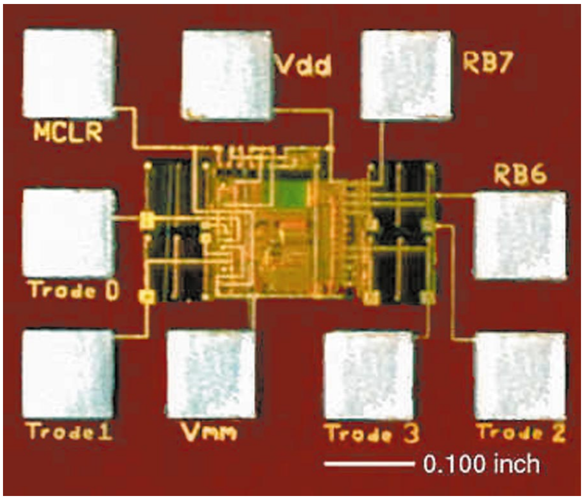
Existing flexible circuit substrates. Many methods already exist to fabricate circuits on flexible substrates. Most of these rely on the metallization of a flexible polymer substrate that can withstand the high temperatures of conventional soldering processes. Kapton** (polyimide) film, for example, is one of the most commonly used flexible substrates, typically finding applications in cameras (where circuitry must fit intimately into available space in a small package), printers and portable computers (where a number of connections must cross a hinge or other rotating joint), and nonplanar antennas (where the antenna elements must have accurate dimensions yet be shaped to fit on conical forms).

When circuitry is designed for such a substrate, care must be taken to ensure that in the final application mechanical stress will not be applied to the component-circuit solder joints. Because of this, the parameters of motion of the flexible substrate must be well understood at the time of design. That is, the motion of conventional flexible substrates must be constrained to ensure that they continue to work over their expected lifetime. In general, conventional flexible substrates are flexible only in regions where components are not attached.

Our dissatisfaction with conventional flexible substrates stems from the fact that they cannot be crumpled nondestructively in the way that cloth can be. To be clear, by "crumpling" we mean simultaneously folding the substrate along multiple nonparallel axes.

Flexible multichip modules. An interesting exception to our ruling against conventional flexible circuitry might be the flexible multichip module (MCM), an example of which is shown in Figure 7. This module is the result of collaboration with workers at the Charles Stark Draper Laboratory at MIT to produce small, semi-flexible circuit elements that may be embedded in textile products to form a sensor readout network. We make an exception in this case because of the module's small size.

Figure 7 Flexible MCM fabric keypad readout



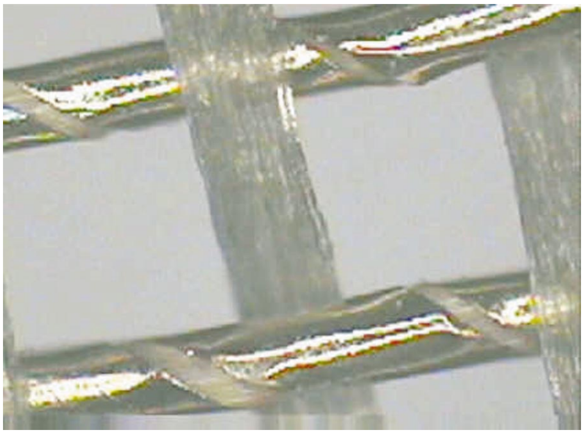
The major part of this readout element is a PIC16F84 microcontroller IC, visible underneath the titanium-copper interconnections. In addition to the PIC16F84 there are four 3MΩ chip resistors and a 16 pF (picofarad) chip capacitor. The schematic for the MCM is similar to the circuit used in the fabric keypad in its simplicity and choice of microcontroller. In this case, the host attaches to the RB7 and RB6 pins, which form a full-duplex (RS232) serial data link operating at 9600 baud. The connections are formed by drilling out the centers of the pads and inserting a small pin or rivet to pressure-fit each pad to a mating circuit trace made by e-broidery. Power for the circuit is supplied across the V_{dd} and V_{mm} pins, and electrodes are connected to the Trode[0–3] pins to be capacitively read out just as was done in the original fabric keypad.

The entire flexible MCM measures 0.600 inch × 0.300 inch, is 0.016 inch thick, and has a permissible bending radius of curvature of about 50 centimeters (cm). In a fabrication process similar to that developed by the General Electric MCM-E/F group,[6] the constituent components were thinned to 0.006 inch by mechanical grinding and lapping of the rear face of each component. The components were then placed on a rigid substrate, a laser-cut 0.006-inch Kapton mask was applied to planarize the top surface, and the Ti/Cu (titanium/copper) interconnect was deposited through a stencil mask. This process extends readily to multilayer circuitry by the addition of thin (0.001-inch) insulating layers. Finally, a protective Kapton cover was glued to the top of the circuit module. The module was then removed from the rigid substrate, and a Kapton cover glued to its bottom, resulting in a completely encapsulated element.

Previous work in conductive textiles. The state of the art in textile circuitry seems to be largely unpublished and proprietary. While a great deal of work has been done in the field of electrically active textiles, we have not been able to find (at the time of this writing) any published prior art relating to either the layout and sewing of active circuitry on textiles with conductive yarns, or to the integration and attachment of off-the-shelf or specially designed electronic components onto textile circuitry. However, there is related work which could enable the development of conductive textiles with active circuitry. A survey of the U.S. patent literature reveals much ongoing work focusing on the development of synthetic conductors compatible with existing textile production processes. For example,[7,8] there are conductive polymers that remain fairly conductive (~1 Ω/cm) after being spun into threads having the weight, strength, and appearance of ordinary nylon thread.

In other potentially enabling developments, for example, workers at Motorola have patented IC packages with hook-and-loop fasteners[9] as a means of attaching components to conventional flexible substrates.[10] Such packages—if successful—might do away with the complex art of surface-mount solder-

Figure 8 Micrograph of woven metallic organza. The two horizontal threads are wrapped with a metal foil.



ing and its associated environmental burdens. In another patent, workers at IBM proposed a zippered connector to simplify the assembly of wide backplane interconnections.[11]

Other researchers are embedding photonic conductors (optical fibers) into clothing to build architectures for sensing and data distribution. The sensate liner[12] is one such undergarment, in which a woven fiber optic matrix is used to sense disruptions of the weave (by measuring optical continuity) and to perform spectrographic analysis of the materials present at intrusions. Such analysis can be used to determine the type and severity of wounds suffered by the wearer of the liner. While this work is promising because of the variety of fiber optic sensors that can be made, drawbacks arise at the interfaces of the optical fibers to the conventional electronics that are required for signal origination and processing.

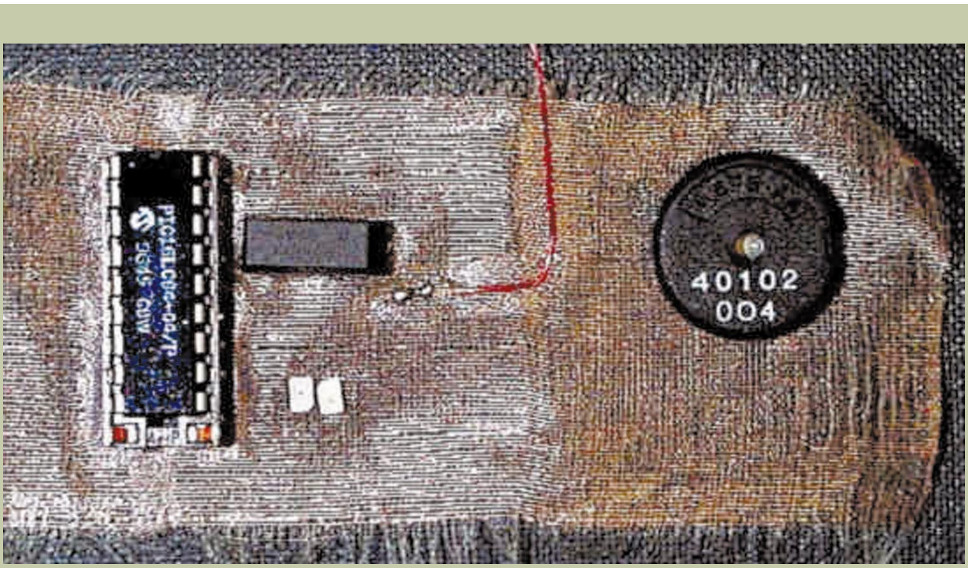
Conductive yarns, fibers, and textile substrates. The textile circuitry in this paper includes sewn or stitched textile circuit elements that function as conductive traces, sensor elements, electrodes, and discrete components (e.g., resistors and capacitors). Many textiles and yarns have properties that suggest their use in such fashion. There are also a number of manufacturing processes that could produce these fabric circuit elements.

An ideal yarn or textile for fabric circuits would have completely adjustable electrical properties and would maintain those properties while being sewn, flexed, and worn. In this section, we identify and describe the strengths and limitations of some of the materials that have been useful in our work. In outlining our practical knowledge of a variety of materials and processes for creating fabric circuits, we can at best hope to inspire the creation of new textile forms optimized for use in circuitry.

Metallic silk organza. In its primary form, this is a finely woven silk fabric with a thin gold helix wrapped around each thread that runs along the weft of the weave (Figure 8). Believed to have originated in India, this sort of fabric has been produced for centuries and appeared in Western fashion as early as the mid-18th century.[13] The warp of this fabric consists of parallel silk threads. Through this warp, the weft is woven with a silk thread that has been wrapped in a metal foil helix. This metallic thread is prepared just like cloth-core telephone wire, and is highly conductive ($\sim$0.1 Ω/cm). Because the conductors in this fabric only run in one direction, the fabric is anisotropically conductive. The spacing between these fibers also permits them to be individually addressed, so a strip of this fabric can function like a ribbon cable. If a section of organza is subjected to shear, the cells formed by the weave also shear to form parallelograms, keeping the conductive fibers parallel and separated at all times. The silk fiber core has a high tensile strength and can withstand high temperatures.

Circuits fabricated with components attached to organza only need to be protected from folding contact with themselves, which can be accomplished by coating, supporting, or backing the fabric with an insulating layer which can also be cloth. However, evidence shows that coating can disturb the conductivity of the fabric. Circuits formed in this fashion also have many degrees of flexibility (i.e., they can be wadded up), as compared to the single degree of flexibility that conventional substrates can provide. In the microcontroller circuit shown in Figure 9, a PIC16C84 microcontroller and its supporting components are soldered directly onto a patch of metallic organza. This circuit uses bidirectional I/O pins on the PIC to control LEDs and to sense touch along the length of the fabric, and uses audible feedback through a piezoelectric speaker to reinforce the sense of interaction. All of the components are soldered directly onto the surface of the metallic organza weave except for the microcontroller, which sits in a socket soldered to the organza.

Figure 9 Circuit fabricated on metallic organza



While the copper, gold, or silver foil wrap the silk thread, the foil's fragility makes it impossible to machine sew without damaging the wrap and breaking the electrical continuity. Consequently, this material was used to create labor-intensive piecework circuits, or as the substrate for component attachment. In piecework, many drawbacks of the material appeared. Because the material is anisotropically conductive, it was necessary to tie the conductors together either with a perpendicular conductive band or by folding the material over itself. All this was time consuming and labor-intensive. Finally, the standard copper and silver coatings on the material will corrode over time unless they are properly passivated.

Conductive yarns. The conductive stainless steel yarns outlined in this subsection were initially manufactured to make filters used in processing fine powders. Stainless steel presents some immediate advantages. It is inert and therefore not sensitive to washing or sweat. These stainless steel yarns vary in composition, from 100 percent continuous conductive steel fibers to feltings or composites of polyester and with short steel fibers interspersed throughout. Varying the ratio of the two constituent fibers leads to differences in resistivity. The conductivity of these yarns is also ultimately limited to the conductivity of the stainless steel fibers themselves. Their conductivity is limited by their manufacturing process, by cold working, and their fine diameter, which makes them sewable.

Bekaert Fibre Technologies[14] credits a 1936 U.S. Patent[15] with the original description of the process whereby a bundle of fine metal fibers may be drawn continuously and simultaneously from source metals. Bundle-drawn fibers can be produced in many different morphologies by translating the polymer-based methods of the synthetic textile industry into their metallurgical equivalents. Continuous and broken bundles, cut fibers, spun yarns, threads, etc., are all produced in this way.

The fibers themselves are available in diameters from 100 μm (micron) to 12 μm, and as small as 2 μm for very metallurgically clean (free of large inclusions) alloys. Alloys commonly used in these processes include stainless 316L steel, stainless 302 steel, Inconel** 601, NiCr (nickel-chromium) and FeCr (iron-chromium) alloys, and titanium.[14] These 100 percent metal fiber yarns are used in knitting, weaving, needlepunching, and braiding processes, with sewing and embroidery being notable omissions from the list.

Figure 10 Photomicrograph of BK 50/2. The dark, unruly fibers are stainless steel, in a polyester mesh.

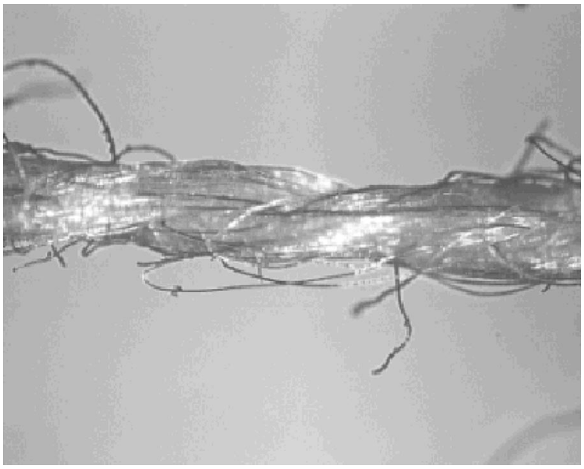


Figure 11 Photomicrograph of Bekintex single-ply continuous-drawn stainless steel fiber bundle

Bekaert Fibre Technologies[14] cites the primary applications for these materials as being filter media, antistatic textiles, heat-resistant textiles, burners, and conductive plastics. Their product range includes 100 percent metal fiber products as well as blends of metal fibers combined with natural or human-made fibers. Steel threads were chosen for their strength, resistance to corrosion, biological inertness, and ready availability in textile form at low cost. The major drawback of using steel and steel-composite threads is the difficulty involved in attaching them to existing electronic components.

Composite yarns of short steel fibers and polyester were chosen for machine embroidery because an all-steel continuous fiber thread (used to form component leads), cannot be sewn by machine. In a continuously drawn steel fiber bundle, individual fibers are meters (rather than centimeters) long. Stresses are no longer local to a small region of sewing, and tensions rapidly mount without resolution, resulting in bunching of the thread as it feeds through the sewing machine. Some of the bunched threads will eventually twist into an obstruction that will not pass through the sewing needle's eye, and the entire process will grind to a halt. In contrast, threads spun from short (staple) fibers are able to accommodate this variation in tension by stretching. Following is a list of fibers we have studied:

- BK 50/2 (~50 Ω/cm)—This composite thread, while being highly resistive, performs the best under machine sewing and passes through ordinary sewing needles better than any other conductive thread we have used. Both the magnitude and consistency of this thread's conductivity can be controlled by careful stitch placement, which determines the intrathread conductivity as a function of thread crossings as well as interthread conductivity as a function of thread tension. Use of this thread in both the needle and the bobbin dramatically increases the conductivity of stitched traces.

  The thread comprises a spun felt of short (~1-inch) steel and polyester fibers (see Figure 10). Because the steel fibers are short and extend from the body of the thread, short circuits can occur between sewn traces. This can be corrected after the traces have been sewn by brushing the fabric with a sponge-covered magnet. These same extending steel fibers provide an excellent contact surface. This is important for pads that make contact with circuit boards (as in the Musical Jacket), pads meant to contact skin for sensing, and contact between separate threads and traces (particularly in the case of vias in multilayer circuitry made by e-broidery).

- Bekintex 100 percent stainless steel continuous fibers (~1 Ω/cm)—These threads comprise bundles of continuous cold drawn stainless steel fibers (see Figure 11). The fibre is highly conductive, but cannot be machine sewn because of its low elasticity. The single-ply version of this thread will not hold a knot, but the two-ply version (BK 12/2 × 275/175S) will, because the plies are tightly twisted. These threads are suitable for microspotwelding to component leadframes and are used to repackage components with threaded connections. Although they are unsewable, these threads can be *couched* (attached to a substrate by a covering stitch); this is the technique used to attach component leads to e-broidered circuits.

- Bekintex 15/2 100 percent stainless steel spun fibers (~1 Ω/cm)—An alternative to the continuously drawn steel fiber bundle is an all-steel yarn spun from short steel fibers. This thread is machine-sewable and performs well in the bobbin of commercial embroidery machines. Its main drawbacks are due to its "untidiness"; although it contains a far larger number of short stainless steel fibers than its BK 50/2 counterpart, these fibers are not held in place by a polyester mesh. As a result, many more steel fibers free themselves from the thread body, causing short circuits between traces and irritation of the wearer's skin.

- VN 140 nyl/35 × 3 (~10 Ω/cm)—This thread is a nylon core wrapped with three continuous crossing stainless steel fibers. It is relatively sewable through needles and highly sewable in the bobbin of commercial embroidery machines. Electrodes sewn with this thread are limited by the conductivity of the steel fibers. Because it has no loose fibers, it creates fewer short circuits between traces. Electrodes sewn with this thread are highly durable and conductive. Because it has no loose fibers, it also presents less electrical contact area, making electrical connection difficult.

- Aracon** metal clad aramid fibers (MCAF) yarns (~0.001 ohm/cm)—Recently the DuPont company announced their Aracon MCAF yarns.[16] These yarns comprise anywhere from 24 to 200 conducting fibers, each approximately 15 μm wide. The aramid core of these fibers is usually Kevlar**, while the cladding metal is silver (Ag), nickel (Ni), copper (Cu), gold (Au), or tin (Sn). Ag and Ni cladding are preferred for the aerospace applications that DuPont has targeted as their initial market, where the benefit of a 40–60 percent mass reduction outweighs the added cost of what is presently a very expensive composite fiber.

  Aracon exhibits excellent mechanical and electrical stability over repeated flexures, radiation exposure, and changes in temperature. Because the aramid core can withstand high temperatures and has a thermal coefficient of expansion similar to that of the cladding metals, Aracon can be soldered like normal wire. Because of these properties, as Aracon comes to be mass-produced and its availability increases, it is likely to emerge as a material of choice for unexposed fabric circuitry.

Composites made by e-broidery. One technique we are developing is the stitching of composite traces. Suppose that a Bekintex 15/2 stitch is covered by a BK 50/2 overstitch. Segments of the trace that cover the steel bundle will exhibit much lower resistance per unit length than segments of BK 50/2 alone. As discussed above, the conductivity of the all-steel yarn is about 100 times greater than that of the composite yarn, which implies that low-precision resistor networks can be constructed simply by combining runs of stitches in the two materials. It also leads to the more general notion of a composite trace or sensor comprising materials combined by stitching.

This technique can also be used to build coaxial structures. One particularly useful example is that of covering a conductive trace with an insulating stitch to protect the former from coming into accidental contact with other conductors.

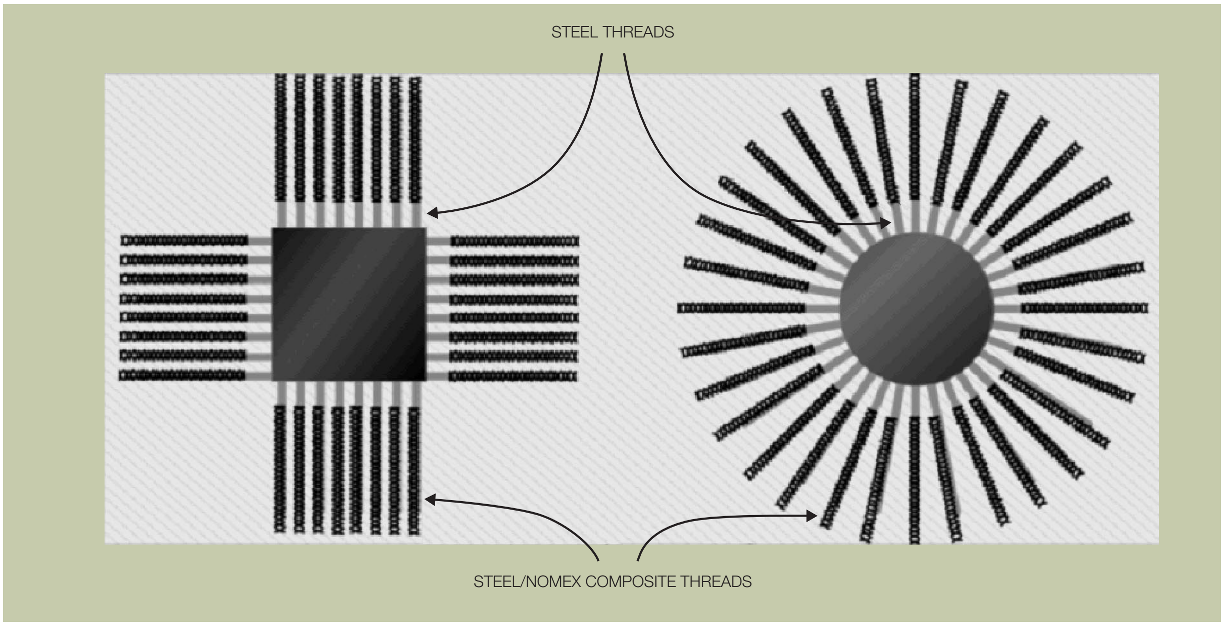
Component integration and package design in textile circuitry

As a consequence of the design principles mentioned above (i.e., distributed sensing and computation, thin interconnect, small packages with fully integrated circuitry), components destined for placement in fabric circuitry do not demand high connection densities. Most component packages are optimized for joining to printed circuit boards, so we instead optimize them to interface with textile circuitry. Ultimately, we hope this work will lead to an actual packaging standard used by the integrated circuit industry.

Fabrication techniques. There are several ways to embed electronic circuitry in fabric, depending on the choice of substrate. Some possibilities explored in the course of this work include:

- *Soldering* surface-mount components directly onto metallic organza
- *Bonding* components to a substrate using conductive adhesives
- *Stapling* components into a conductive stitched circuit (i.e., pressure-forming their leads to grip circuit pads)

Figure 12 Square and radial PTCC packages



- *Joining* a component's "threadframe" directly to a stitched fabric circuit (where components are formed with a single conductive thread per pin)

The last possibility is explored in some detail in the following section. We have ruled out the others for various reasons indicated below:

- Solders used with electronic components are soft alloys of lead (Pb), tin (Sn), and sometimes silver (Ag). Such compounds are not suitable for use in applications in which they could potentially be in constant contact with a user's body, because of their toxicity. Worse yet, while it is possible to solder components onto metallic organza and achieve (very) good electrical contact, the mechanical properties of the joint are unsuited to the flexure to which it will be subjected as an item of apparel.
- Conductive adhesives are better suited to this application than solder, because it is possible to envision adhesives that are nontoxic, highly conductive, highly durable, and moderately flexible to act as a "mechanical impedance match" between a flexible fabric substrate and a rigidly packaged component. They remain an open possibility and should be the subject of further study.
- Stapled components are an interesting compromise where a component lead grips a sewn conductive trace by being pressed into shape around it. When the substrate flexes, the trace is free to move within the clasp of the formed lead, forming a self-wiping contact at every junction between fabric circuitry and component pins. However, the dimensional rigidity of the component is a poor match for freedom of motion enjoyed by a fabric substrate, and the mismatch is likely to stretch open pins that have been formed into clasps and to accelerate wear and tear of the fabric substrate.

Gripper snaps make excellent connectors between fabric and electronics. When a two-piece gripper snap is placed on fabric, the first piece has several metallic "teeth" that pierce the substrate and any conductors, making a wiping contact that scrapes through surface contaminants (e.g., oxides) to make a metal-on-metal bond. They are already commonly used to connect circuit packages to fabric, but allow only a low connection density.

The case for round packages. Consider electronic components with threads leading out from the package rather than a rigid leadframe. These threads may be attached to the substrate by covering stitches that also form electrical connections to circuitry made by e-broidery. Alternatively, the threads emanating from a component may be punched or woven through the substrate on their way to connect to other components. In either case, these threads constrain the components to their location on the substrate. Because we would like to balance as evenly as possible the forces conveyed by these threads, we now consider round component packages. Figure 12 illustrates components in square and round packages stitched onto a fabric substrate, whereas Figure 13 shows an actual stitched prototype component couched onto a fabric substrate.

For a given lead spacing (s) at the periphery of a package and a given package diameter (d) or side length (l) the maximum number of threads coming out of each type of package is found to be

$$n_{square} = 4\left(\frac{l}{s} - 1\right)$$

$$n_{round} = \frac{\pi d}{s}$$

For a given thread spacing around the periphery of the package, it is clear that for a large number of pins the square package will have a smaller diameter than the round package. If the number of pins is less than 16 (or to be exact, $16\,(4 - \pi) - 4$), then the round package makes better use of the available space.

The finest practical thread spacing achieved in our work has been 0.050 inch (1.27 millimeter), which for 16 leads implies a package diameter of 0.254 inch (6.48 millimeter). It is practical to expect that a die of about half this width will fit into the package, which gives an upper bound of 10 mm^2 of single- or multichip real estate to work with in a typical sewable button package.

The plastic threaded chip carrier. Now we look to the practical aspects of building packages like those that have been described so far. To manufacture threaded packages, we would start with a bare die, add a "threadframe," and connect the near ends of the threadframe to the bondout pads of the die.

Figure 14 shows the possible construction of such a component package. Some details have been omitted for clarity, such as the metal base that helps to keep the die substrate at near-uniform temperature and electrical potential across its area.

Figure 13 Prototype PTCC package couched onto fabric substrate

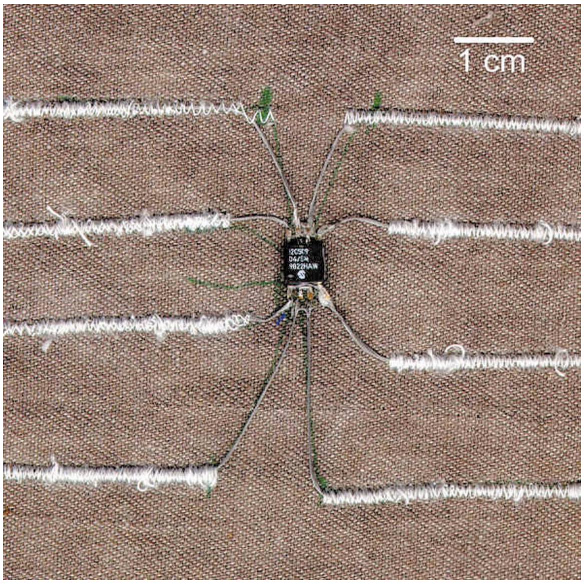
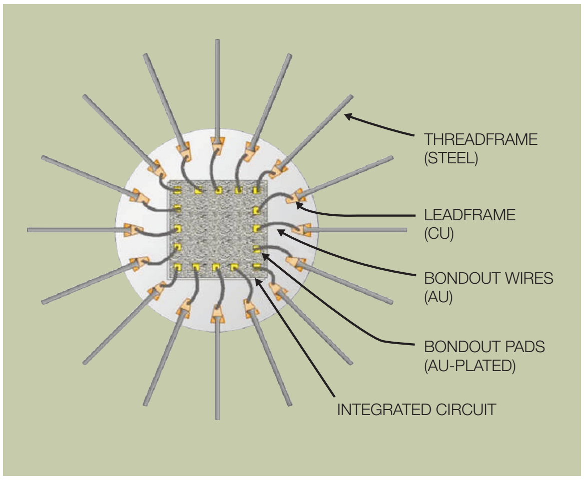


Figure 14 Details of round PTCC construction



Connections directly to the die are made in the usual way; fine gold wires are thermocompression-bonded on one side to the die's gold-plated "bondout pads" and on the other to the stubs of a conventional copper leadframe.

In most packages, the leadframe continues out of the plastic package and is ultimately soldered or cold-welded to external circuitry. Instead of having a solid external leadframe, the plastic threaded chip carrier (PTCC) has flexible, corrosion-resistant threads intended to connect to external circuitry.

In this case, the threads that leave the package are bundles of approximately 100 continuous steel fibers, each about 5 μm in diameter. These fiber bundles are microspotwelded to the leadframe stubs, and the entire structure is hermetically sealed in a plastic carrier.

Prototyping the PTCC. To test the proposition of a threaded chip carrier, prototypes were built to evaluate their electrical, mechanical, and sartorial performance.

Since part of the PTCC's assembly process is common to most IC packages, we can test the design principles behind the PTCC without building one completely from scratch. Leaded surface mount (SMT) IC packages already incorporate the die, the leadframe, and bonding wires in a sealed plastic carrier, and their electrical characteristics are well understood.

Prototypes have been built by starting with SMT packages, adding a few components directly to the leads, then microspotwelding steel fiber bundles to the leads. Finally, the threads are arranged in a radial pattern, and the entire assembly is encapsulated in an epoxy resin.

Packages made this way are larger than they need to be, but all of the new design principles involved are represented and open to refinement.

Spot welding. Elihu Thompson pioneered electrical or resistance welding in the late 19th century,[17] taking advantage of the fact that an electrical current passing through any resistive material evolves heat.

For constant-current welding the heat evolved per unit area ΔQ takes the form

$$\Delta Q = \frac{I_w^2 R}{A} \Delta t$$

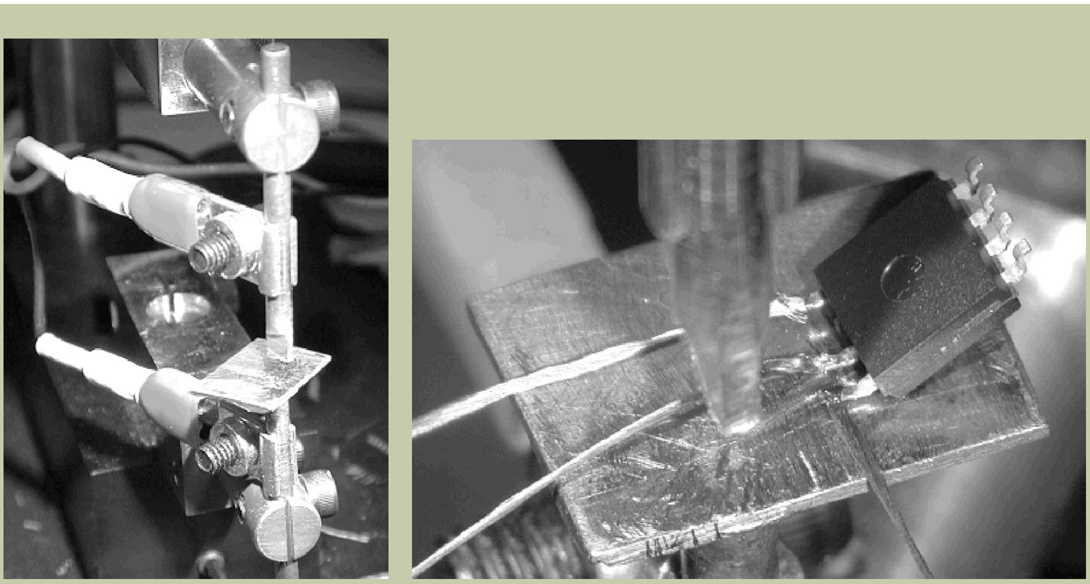
where I_w is the weld current, R is the weld junction resistance, A is the weld junction area, and Δt is the weld time.

The welding apparatus is arranged so that most of the weld power is dissipated at the faying interface, which is the junction of the materials to be welded. Inspection of the heat evolution equation reveals that for a given weld current and time, the weld heat increases directly in proportion to the junction resistance and inversely in proportion to the junction area. This suggests that the resistivity of the weld path should be concentrated at the weld junction, and that the junction area should be small. Resistive heating is only part of the story, however. Although a large area of contact is desirable between the electrodes and the workpiece to reduce heating at those points, a small electrode-workpiece junction area is preferred to reduce heat diffusion from the faying interface. When two uniform, smooth pieces are welded together, the heating will be greatest along the center axis of the applied current, and a weld will form between the pieces along this axis. The heating is greatest along the center of this axis, because at that point the weld is most surrounded by heated material. Different types of welds will arise from different levels of heating. The "coldest" welds form when the grain boundaries of the workpieces shift to form large interfaces. As heating increases, grain boundaries shift and dovetail, forming a complex interface. Still greater heating results in a breakdown of grain boundaries and a variable alloying of the materials making up the junction. The leadframe used in this case was copper (Cu) plated with a tin-lead (SnPb) alloy. Diffusion alloying takes place at the Cu-SnPb interface, and the result after several hours is a Cu-CuSn-SnPb interface. This chemistry is common to the process of soldering with SnPb alloys on Cu or CuSn surfaces.

It is worth noting that while the process described here was developed using Cu plated with SnPb, our goal is to produce component packages that expose only biocompatible materials (e.g., the stainless steel threads). Furthermore, the process is compatible with uncoated Cu leads, making SnPb altogether unnecessary.

Bondout metallurgy. Weld schedules are often difficult to optimize, and depend crucially on many factors including electrode geometry, contact area, and electrode-workpiece metallurgy. For instance, we might wish to attach steel threads directly to the bondout pads of an IC die without using an intermediate Cu/CuSnPb leadframe. This is impractical for many reasons.

Figure 15 Two views of microspotwelding rig



Steel threads are too strong to be thermocompression bonded to metallized pads on a crystalline silicon substrate without causing the substrate to crack.[18] More important, however, is the metallurgy of bondout pads on silicon chips.

Most ICs use Al (aluminum) metallization for on-chip interconnections, as well as for bondout pads. Nearly all pad-to-leadframe wirebonds take place using Au (gold) or Al wire (actually 99 percent Al + 1 percent Si). Au is used more frequently because it requires less preforming during the wirebonding procedure and because it forms less of a surface oxide layer than Al wire does. Bondout pads are also usually plated with Au (over the Al) to promote good wire-to-pad bonding.

The Au-Al interface does, however, represent a compromise between the need to achieve a strong wirebond and the need to develop a process insensitive to contamination. The most common reliability problem in wirebonding results from the formation of intermetallic compounds at the Au-Al interface, known by their color as "purple plague" ($AuAl_2$) or "white plague" (Au_5Al_2). These compounds are very brittle compared to the metallic Au and Al that surround them. Because of this brittleness, wire flexing (as a result of vibration or thermal cycling) more easily induces metal fatigue and stress cracks.[18] These and other intermetallic compounds and alloys deleterious to the strength of the Au-Al interface are known to form more readily in the presence of all of the metals that Bekaert produces in textile form. It is therefore essential to ensure the purity of the gold used in plating bondout pads, as well as the purity of gold wire used to bond to the gold-plated pad.

For the present work, weld schedules have been developed to maximize the pull strength of the thread-leadframe junction. To prevent interference that would be caused by fraying of the end of the fiber bundle, it is first welded by one or two weld operations. The tab is then cut in the middle and the excess length is discarded. To weld this tab to the leadframe, the tinned copper leadframe (Cu/SnPb) is placed on the lower electrode, the steel fiber bundle tab is placed on top of the lead, and the upper Cu electrode is brought down to weld the tab to the lead at an applied force of 16 pounds.

Other weld schedules, geometries, and electrode materials have been tried with varying degrees of success. To minimize the number of tool changes necessary during weld process development, an electrode geometry has been chosen to simultaneously provide a good mix of thermal, electrical, and mechanical properties, and is shown in Figure 15.

The upper electrode is formed from $\frac{1}{8}$-inch diameter copper rod stock, with the end ground down to a $\frac{1}{8}$-inch $\times$ $\frac{1}{16}$-inch rectangular cross section. The lower electrode is formed of $\frac{1}{8}$-inch copper rod with a 1-inch $\times \frac{3}{4}$-inch $\times \frac{1}{16}$-inch copper "anvil" soldered on top. The anvil provides a thermal sink that draws excess heat away from the weld, decreasing the tendency of the electrodes to stick to the weld and promoting even heating (and therefore, uniformity) of the weld joint. A representative weld joint of a stainless steel thread to Cu/CuSnPb lead is shown in Figure 16.

Weld evaluation. The mean shear strength of a weld formed by the above procedure is 36.8 N (standard deviation = 4.3 N, n = 9), determined by pull testing. Welds with a pull strength less than 10 N were discarded (3 out of 12 samples tested) as being the result of poor process control or weld contamination. During these tests, most failures occurred at the point where the leadframe entered the plastic package, not at the thread-leadframe weld itself. That is, the weld joint proved to be stronger than the leadframe itself.

A pull strength of 36.8 N (or equivalently, 8.25 pounds) is more than sufficient for the application described above, e.g., that of welding steel threads to leadframe stubs prior to encapsulation in a hermetically sealed plastic package. It also suffices for the purpose of prototyping such packages, where steel yarn is welded to the leads of an existing package and the resulting construction is encapsulated in epoxy. In both of these applications, the pull strength of the original weld is augmented by the adhesion of the thread to the package encapsulant.

Multilayer textile circuitry. The leap from single layers of e-broidery to multilayer circuitry is motivated not only by the desire to develop nontrivial interconnects and circuitry, but also by the need to control the outward appearance of fabric interfaces. Fabric-based user interfaces should at large display only devices and symbols relevant to user interaction, and not the underlying complexity of their implementation. In adopting the modular approach to circuit fabrication, we have so far developed circuit design techniques, component packages, and a method of "printing" an interconnect in fabric. All of this leads to the final step of stacking fabric layers with an insulating layer and adding an interlayer stitched interconnect. The way this is done with conventional circuit boards is to print each layer in copper on one side of a thin substrate, then to laminate the strata together, drilling holes as is appropriate, and to plate with copper to interconnect traces on different strata. The interlayer connections are commonly referred to as vias, and the metallurgy and chemistry of this process is messy and expensive.

Figure 16 Top view of a stainless steel thread welded to Cu/CuSnPb lead

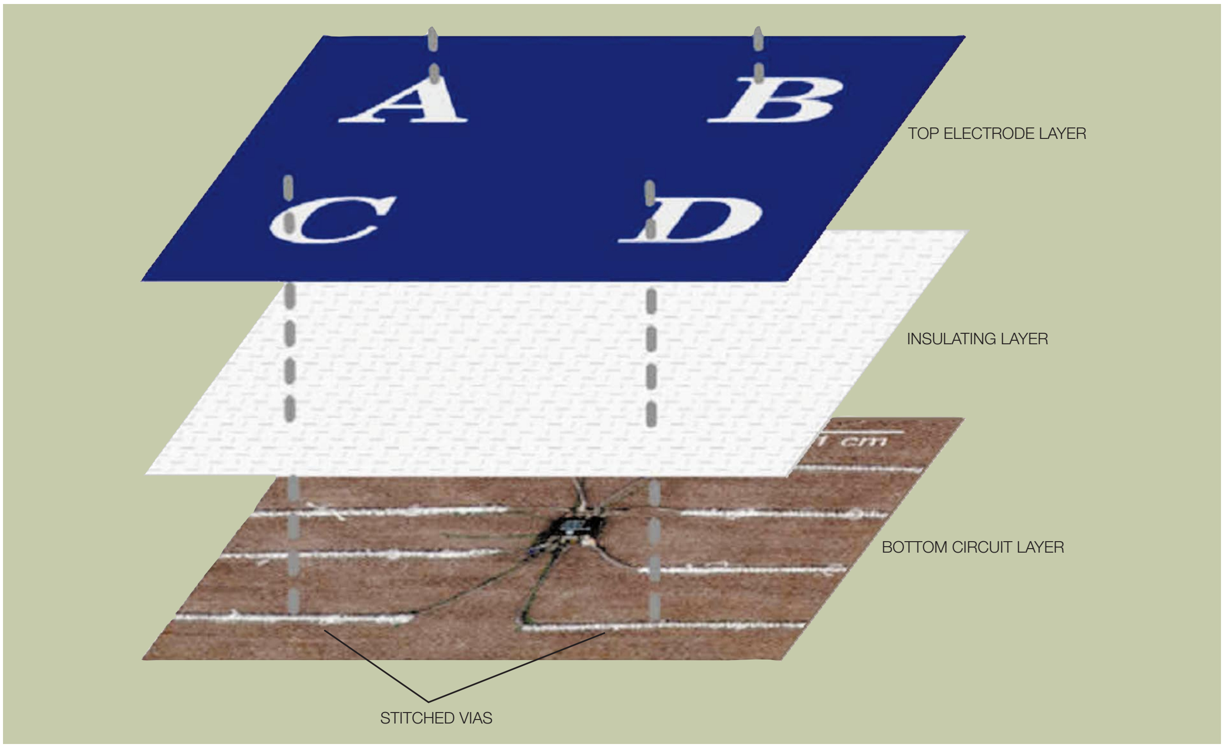
To do the same thing in fabric, however, we have an easier time. Each layer of the interconnect is made by e-broidery on its own fabric substrate. Then insulating fabric layers are placed between the layers with circuitry, and vias are stitched between layers using more conductive thread.

Suppose we want to build an interface that has only buttons on its top surface, such as the No-Soap Radio. How can this be done?

First, we make a plane by e-broidery with nothing but the interface objects sewn in. The next layer is simply a thin, sturdy insulating layer, followed by another layer with circuitry. This second layer of circuitry includes pads that line up with the interface symbols on the top layer. The next layer is again an insulator, and the last layer includes the components that have had their leads couched onto the fabric substrate connecting to traces, some of which include pads to connect with other layers. Finally, the layers are assembled and stitched together at points where signals must cross between layers.

To enhance the final appearance, the topmost layer is the last one to be quilted onto the remainder. This avoids sewing vias through the top layer for any con-

Figure 17 Exploded view of No-Soap Radio showing stitched vias

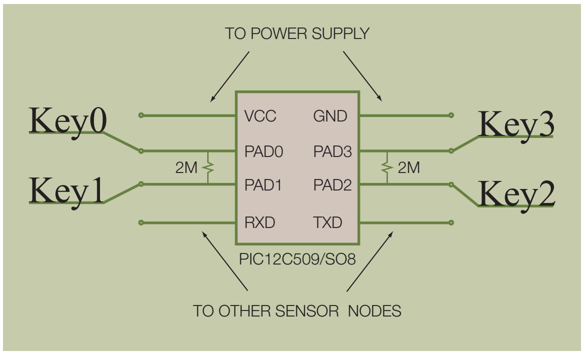


nections other than those required by the top layer. The principle is illustrated in Figure 17.

Capacitive contact and proximity sensing. Briefly, the increase in a sewn electrode's capacitance due to finger contact is measured in terms of the time taken to charge the electrode/finger capacitance from zero to the switching threshold voltage of a CMOS (complementary metal-oxide semiconductor) logic buffer (1/2 Vcc or supply voltage).

One form of the instrumentation for this measurement is illustrated in Figure 18. The main advantages of this technique are that it is a time-domain measurement, it provides a dynamic range of 10^4, and it can be implemented with little more than standard CMOS logic. Not only can direct contact be measured, but the dynamic range also permits noncontact sensing to occur over a distance roughly twice as far away from an electrode as the electrode is wide.

Figure 18 Schematic of No-Soap Radio



There are also a number of ways to refine the dynamic range of the measurement in software. For example, the measurement granularity of the charging interval is ultimately limited by the length of the software loop which performs the time count. Normally one might discharge the capacitors, then turn on the charging signal and count the number of iterations of a fast loop that elapse before the capacitor voltage exceeds the input high threshold.

Instead of letting the capacitor charge continuously, however, the software timing the charging curve can transfer small pulses of current on each iteration, meaning that each tick of the counter corresponds to a smaller portion of the charging curve.

For the MIDI jacket keypad, such careful measurements were not used. Instead, a simpler procedure was employed, with each electrode permanently connected to analog ground through a 1-MΩ resistor, to allow the measurement of the discharge curve of an electrode. For later systems, however (including the flexible MCM and the washable keypad), the technique described above was employed.

Future work

What remains to be done? The present work collects our observations and experience over three years of work with fabric circuitry in a desire to point the way toward scalable processes for the manufacture of washable computing systems. It is expected that the primary uses of such systems will be as interfaces to more commonplace devices, such as pagers, phones, and wearable computers.

Regarding washability, e-broidery will not currently function when wet, but works fine when dried again. Whether the wetting agent is water, isopropyl or ethyl alcohol, or one of the common dry-cleaning fluids, once the circuit is dry it functions as specified. Although rigorous testing remains to be done, the early indications are very promising. Even human sweat (a mildly corrosive saline condensate) does not appear to harm e-broidery over several cycles of exposure, while it does in fact corrode conventional tinned-copper printed circuitry.

The threadframe prototypes have been surprisingly robust, and further work should be done to characterize their integrity over many stress cycles. Since the stainless threads used in this work are composed of many long, thin fibers, we would like to know how likely an individual fiber is to break when the entire thread containing it is subjected to stress.

What if you want to change your clothes? This is an open research question that might best be addressed by ongoing efforts into building environments that support mobile agents in embedded applications. One vision of the washable computer of the near future is a jacket with many small computing elements distributed throughout, all interconnected by a stitched network. Each node would provide sensing in its physical locale, some storage for a distributed, redundant database, and a computing element capable of executing small mobile applications. A jacket or vest could easily host a hundred such small nodes (an added weight of about 50 grams or 2 ounces), and be powered all day by a battery slipped into a pocket. When you hang up your jacket, it joins the closet network and synchronizes itself with other articles of clothing and the network at large. The scenario is easy to construct given an embeddable substrate for mobile code.

Clothing is also interesting because it can augment intrabody signaling[19] and power transduction[20] techniques. The capacitive links to the human body that these depend on are limited by the total area of capacitive contact available at each link. By transmitting power harvested in the shoes through the body to a large receiving electrode in the jacket, efficiencies should be realized that are sufficient to replace the need for batteries.

Much work remains to be done in replacing Bekinox and Bekintex with other composite textiles designed to withstand corrosion, to allow easy welding and sewing, and to have higher conductivity. We also foresee a way to replace batteries, by collecting the triboelectric currents that cause charge migration and "static cling," but this will require careful attention to the topology and chemistry of weaves intended to generate power.

Many interesting proposals to make wearable information infrastructures suggest the application of highly redundant optical fiber networks in clothing. We do not see e-broidery as a replacement for optical fibers, but rather as a complement. E-broidery excels at certain things when compared to optical fiber, but fiber also has its fine points. Many successful systems are likely to stem from a clever combination of the two.

Apart from e-broidery, *electrospinning*[21] may also be a viable way to place electronic textiles on a substrate. It may turn out to be a good way to bond components to circuitry made by e-broidery, for example, by allowing one to deposit polymer meshes of different properties onto an existing cloth substrate. In electrospinning, the force of electrostatic repulsion is used to generate a fine, splaying jet of polymer (from a droplet of melt or solution) that forms a mesh at an electrically grounded collection surface. This may be better than spot-welding or applying conductive adhesives because electrospinning is guided by electric fields, so the spinning process will presumably extend previously deposited conducting paths and ensure their continuity.

Electrospinning is compatible with the needs of washable computing because it deposits a permeable mesh, rather than a solid, impermeable layer (as would silk-screening or printing). Materials spun into mesh form can have a better strength-to-weight ratio than in the solid form, as well as greater flexibility and breathability. By electrospinning with conductors, semiconductors, and insulators, one might effectively print and encapsulate multilayer electronic structures. Wearable displays could also be formed by combining electronic ink with an electronic textile substrate.[22] Large sensor surfaces are worth exploring. Textiles range in scale from small pieces of needlepoint (10^{-4} m^2) to tapestries and carpets (10^2 m^2), with a corresponding range of feature sizes. This indicates that textile processes may be well suited to the production of large, flexible sensing surfaces that conform to any underlying shape.

Finally, a large interesting area of work to follow will be in using these techniques to construct meaningful and compelling user interfaces and applications. Some of the more obvious applications include clothing that can use electric field measurements to determine its fit and shape, keyboards invisibly and comfortably stitched into sleeves, cuffs, and pockets, and hybrid structures that incorporate electronic ink into clothing to create highly interactive apparel.

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