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ORIGINAL ARTICLE

Fabric PCBs, electronic sequins, and socket buttons: techniques for e-textile craft

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Abstract The blossoming research field of electronic textiles (or *e-textiles*) seeks to integrate ubiquitous electronic and computational elements into fabric. This paper concerns one of the most challenging aspects of the design and construction of e-textile prototypes: namely, engineering the attachment of traditional hardware components to textiles. We present three new techniques for attaching off-the-shelf electrical hardware to e-textiles: (a) the design of *fabric PCBs* or *iron-on circuits* to attach electronics directly to a fabric substrate; (b) the use of *electronic sequins* to create wearable displays and other artifacts; and (c) the use of *socket buttons* to facilitate connecting pluggable devices to textiles. In this work we have focused on using easily obtained materials and developing user-friendly techniques; our aim is to develop methods that will make e-textile technology available to crafters, students, and hobbyists. This paper describes the techniques and employs them as a springboard for a wider-ranging discussion of “e-textile craft”.

Keywords Electronic textiles · E-textiles · Fabric PCBs · Iron-on circuits · Electronic sequins · Socket buttons · Do-it-yourself · E-textile craft

1 Introduction

The blossoming research field of electronic textiles (or *e-textiles*) focuses on ubiquitous computing as realized by a particular type of material: e-textile researchers seek to integrate pervasive electronic and computational elements into cloth. The ultimate goal of e-textiles is to develop technologies that are entirely fabric based and though terrific progress has been made (cf. [1–3]), this vision is still a ways off; at least for the present, researchers are forced to incorporate traditional electronics like microcontrollers and light emitting diodes (LEDs) into their designs.

This paper concerns one of the most challenging aspects of creating e-textile prototypes: namely, engineering the attachment of traditional hardware components to textiles. We present three new techniques for attaching off-the-shelf electrical hardware to e-textiles. In exploring this subject, we have tried to limit ourselves (if that is the right expression) to techniques that are accessible and materials that are easily obtained.

We aim to develop a set of methods that will make e-textile technology available to interested amateurs of all sorts. In the longer term, we hope to provide means for crafters and designers of a variety of ages and skill levels to create robust, affordable e-textile prototypes without postulating radically new hardware: to initiate a library of materials and techniques that form the foundation of “do-it-yourself” electronic textiles.

Our interest in this area originates in a desire to integrate research in ubiquitous or pervasive computing with the best traditions of educational computing—traditions that emphasize student creativity, empowerment, and self-expression. We believe that e-textiles offer an especially promising field for creating educational and expressive artifacts–artifacts that are at once intellectually challenging, aesthetically appealing, and personally meaningful. We will expand on these ideas in the fourth section of this paper.

We also argue that the techniques described in this paper will prove useful to the broader community of e-textile

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researchers. Indeed, in such a young discipline, it is especially helpful for researchers to draw on a wide range of techniques geared toward the creation of affordable, robust prototypes. Moreover, investigating new techniques of incorporating electronics into fabrics could conceivably inform the next generation of electronics package design, since it is likely that in the near future components will be manufactured specifically for wearable computing and e-textile applications.

In the remainder of this paper, we describe our techniques, situating them in the larger research areas of e-textiles and, more generally, ubiquitous computing. The following (second) section summarizes major trends in e-textile research as background to our work. In the third and central section we present our three techniques: (a) the design of *fabric PCBs* or *iron-on circuits* to attach electronics directly to a fabric substrate; (b) the use of *electronic sequins* to create wearable displays and other artifacts; and (c) the use of *socket buttons* to facilitate connecting pluggable devices to textiles. We will conclude the third section with a discussion of a variety of materials and techniques we use to insulate conductive materials in e-textile prototypes and a presentation of the results of preliminary washing studies for each of our techniques. In the fourth section, we use our techniques as the basis for a wider-ranging discussion on the opportunities for do-it-yourself e-textiles, and we argue that this is an especially important and fertile area for research. While the discussion in this section draws on our interests in educational computing, we maintain that the issues raised by do-it-yourself e-textiles are important to other areas of ubiquitous computing research as well. The fifth and final section discusses our ongoing work and outlines promising areas for future research.

2 Related work

Wearable computing explores technologies that are portable and attached to or carried on the body; head mounted displays, cell phones and PDAs, for example, are “wearable” computing devices. E-textile research is a closely related field, but has a slightly different focus: investigating electronic and computational technology that is embedded into textiles. E-textiles are often clothing, but can also be wall hangings, pillows, rugs and other pervasive fabric artifacts. Rather than focusing on existing (hard) electronic devices, e-textile researchers strive to build things that are as soft and flexible as traditional cloth. E-textiles can be beautiful examples of Weiser’s ideas put into practice; at their best, they truly, unobtrusively “weave themselves into the fabric of everyday life” [4]. The rest of this section will give a whirlwind overview of some of the work that has taken place in this young and vibrant field.

A good deal of e-textile research has been undertaken to advance the medical and military realms [5–10]. For example, in one groundbreaking early project, Jayaraman et al. [9, 10] built the “Georgia Tech Wearable Motherboard”. This vest-like garment utilized woven optical fibers and conductive yarns in conjunction with integrated electronics to detect bullet wounds and monitor physiological signs like heart rate and temperature. This and other similar early e-textile research efforts have since born fruit in the commercial arena. There are now several commercial devices—primarily in medicine and sports—that make use of e-textile research. One excellent example is the LifeShirt, developed by VivoMetrics [11]. This shirt, similar in many ways to the Georgia Tech Wearable Motherboard, continuously monitors and records the heart rate, respiration rate and posture of its wearer. This data can then be “downloaded” from the garment and analyzed by doctors and researchers, giving them a comprehensive portrait of the wearer’s physiological patterns.

Another genre of e-textiles research has focused less on applications of the technology and more on materials and techniques (cf. [1–3, 12–17]). In another example of groundbreaking early research, Post, Orth and their colleagues [16] developed both simple and sophisticated e-textile engineering methods including: the embroidery of conductive yarns to act as data and power busses, resistors and capacitors on fabric; the development of capacitive sensing cloth touch pads; and the use of gripper snaps in e-textile applications. Other innovations in e-textile techniques have focused on assessments of specific materials. For example, Edminson et al. [17] have described how to utilize piezoelectric materials in e-textiles, and—in conjunction with researching new transistor materials—several groups are researching techniques for embedding transistors in fabric, taking the first steps towards realizing entirely fabric-based computation [1–3].

Other practitioners have explored playful applications of e-textiles in fashion and other aesthetically driven applications (cf. [18–21]). Orth [16, 19] and Berzowska [20] are two of the more prominent researchers investigating this area. Orth became well known in part for using thermochromic materials and resistive heating techniques to weave beautiful, controllable, and non-emissive textile displays. Berzowska and her colleagues have embedded electronics like LEDs, sensors and speakers into fabric to create fanciful fashions and wall hangings. It is worth noting that the community of people developing artistic e-textiles includes individuals from outside technical academia, such as artists, designers and hobbyists of various stripes (cf. [21]).

Because we want to build artifacts that will spark the curiosity and interest of children and other novices, much of our work also falls into this last category. Our main interests are two-fold: we want to build artifacts that will capture people's imagination, and we want to develop tools and techniques that will allow them to experiment with e-textiles themselves—tools and techniques for a "do-it-yourself" e-textile community. In short, we want to bring e-textiles "to the people" by supporting and encouraging e-textile craft.

3 Three techniques for e-textile craft

This section will introduce our three techniques and analyze the potential of each as a do-it-yourself method, assessing every one in terms of the expense and availability of its required materials and how difficult it is to employ. We will conclude the section with a discussion of insulating techniques and a presentation of the results of preliminary washing tests for each of our techniques.

3.1 Fabric PCBs

Printed circuit boards (PCBs) allow for the precise placing of electrical components into small spaces. In prototyping and hobby contexts a circuit board pattern is first etched out of copper-clad board; then, holes for hardware are drilled into the board; and finally, components are soldered to the copper traces. This section will present an analogous technique for creating PCBs on cloth using conductive fabric and an iron-on adhesive. Section 3.1.1 will detail laser-cut fabric PCBs and Sect. 3.1.2 will focus on hand-cut fabric PCBs.

3.1.1 Laser-cut fabric PCBs

Laser cutters can cut a wide range of materials with astonishing precision and speed. The next few paragraphs will describe how one can make use of these wonderful devices to build complex circuits out of conductive cloth. There are several steps in this process, most of which are shown in Fig. 1. (It will be helpful to refer back to this figure throughout our discussion of the construction process.)

In the first step to creating a laser-cut fabric PCB (not shown in the figure), a heat activated adhesive is attached to a conductive fabric (we usually use a metalized fabric called "Zelt" [22], which has a Sn/Cu plating and a surface resistivity of less than 0.1 Ωs/sq). One is left with a piece of conductive fabric that has a layer of adhesive covered with a layer of paper on one side. This fabric is placed, paper side up, into a laser cutter where a circuit pattern is etched into the fabric. The settings on the laser cutter should be adjusted so that the adhesive and paper backing are cut, but the fabric is only scored. Figure 1a shows a laser cutter etching a circuit and Fig. 1b shows the completed etched circuit and its companion substrate of blue fabric.

Once the circuit is cut, the backing paper is removed from underneath the circuit—only where the conductive cloth should adhere to the baking fabric (Fig. 1c). The circuit is then carefully aligned on its fabric substrate and ironed into place (Fig. 1d). Finally, as is shown in Fig. 1e, the circuit is separated from the rest of the conductive fabric. Note how the laser cutter scored the conductive fabric so that it comes apart easily at this stage, but remained together beforehand so that the circuit could be accurately placed. Figure 1f shows the completed circuit.

Once created, a fabric PCB—with generous applications of flux—can be soldered like a traditional PCB. Figure 2 shows a close up of solder joints on a laser-cut iron-on circuit.

Fabric PCBs are subject to abuses that traditional PCBs are not—the twisting, folding and stretching of cloth—and solder joints inevitably break under this strain. To address this issue, each solder joint must be covered with an inflexible coating before the fabric PCB can be worn or washed.

We have experimented with a variety of materials to encapsulate solder joints on our fabric PCBs. Figure 3 shows joints encapsulated with an epoxy resin. This technique and others will be analyzed in Sect. 3.5. We have yet to find an easy way to protect solder joints using non-toxic materials, so we intend to keep investigating this topic. Many other researchers, including Linz et al. [14] and Kallmayer et al. [23], have developed encapsulation techniques to protect various types of circuitry on e-textiles. We find their work encouraging and hope that we will be able to invent similar, but more user-friendly, means of robust encapsulation.

As with traditional PCBs, fabric PCBs can be multilayered. Layers of conductive traces can be separated by layers of non-conducting fabric. Figure 4 shows an example of a multi-layered fabric PCB with two layers separated by purple insulating fabric. It is worth noting that a hobbyist who etches her own circuit boards cannot make multilayered circuits: she is restricted to etching the circuit out of, at most, two layers of copper, one on the bottom of the board and one on the top. Traditional multi-layered PCBs must be ordered from commercial PCB manufacturers. In this arena, fabric PCBs have a distinct advantage over the traditional PCBs made by hobbyists.

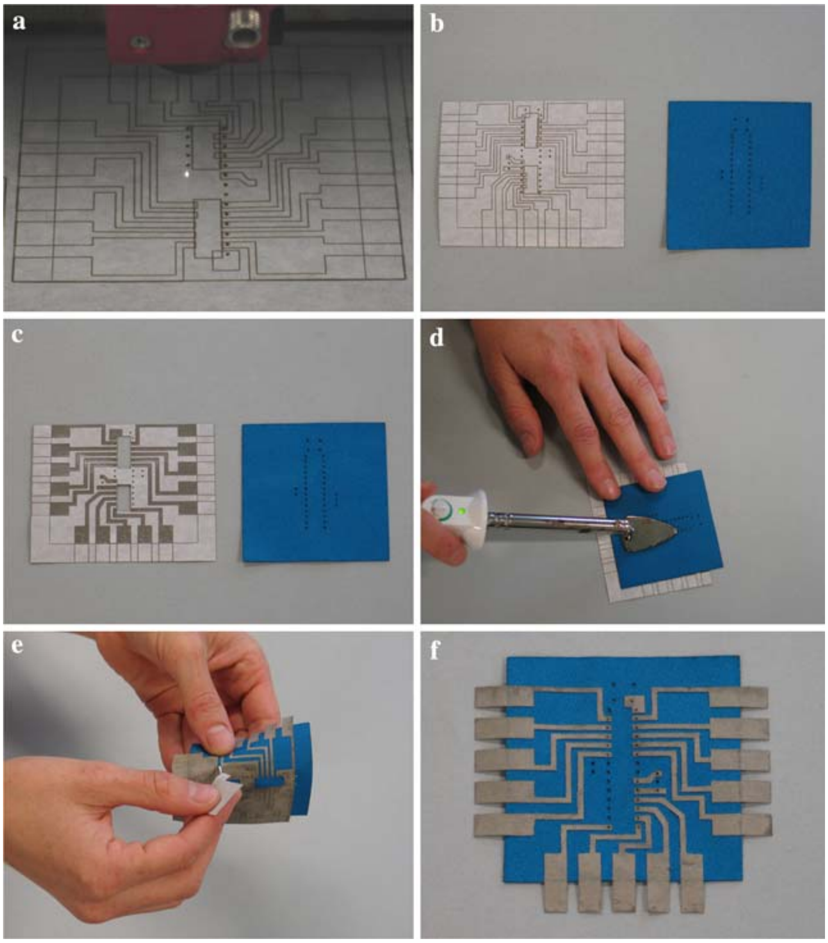

Fig. 1 Steps to building a laser-cut fabric PCB. **a** The circuit is cut by a laser cutter. **b** The cut circuit and its backing fabric. **c** The paper underneath the circuit is removed. **d** The circuit is ironed onto its backing fabric. **e** The conductive fabric that is not part of the circuit is removed. **f** The completed circuit

Fig. 2 *S*older joints on a fabric PCB

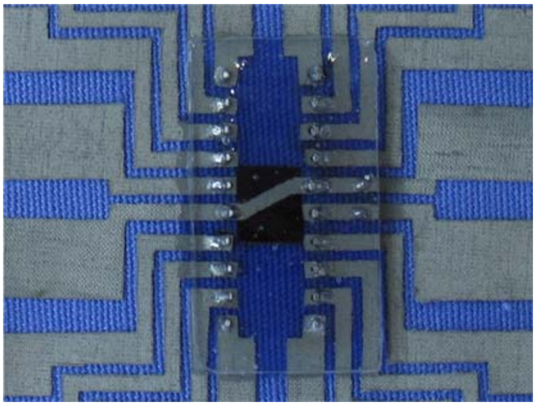

Fig. 3 Solder joints encapsulated in epoxy

Laser-cut fabric PCBs exhibit many of the advantages of traditional PCBs while preserving the essential qualities of cloth. As can be seen in Fig. 4, the traces are flexible and can be sewn as well as soldered. In a typical use of the technique in our lab, we solder IC sockets or microcontrollers to the traces and stitch other components.

3.1.2 Hand-cut fabric PCBs

Laser-cut fabric circuits are powerful e-textile tools, but they are challenging to build and require access to expensive equipment. How then, does this technique fit into the do-it-yourself or crafting category? In fact, iron-on traces

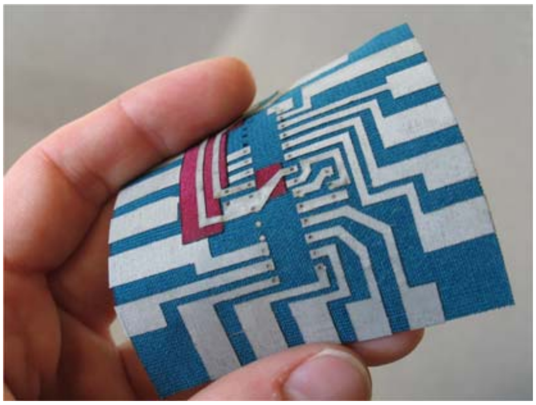

Fig. 4 A multi-layered fabric PCB

need not be etched by a laser cutter, they can be cut by hand.

The process to building hand-cut fabric PCBs is similar to that of building laser-cut circuits. One starts by attaching an iron-on adhesive to a piece of conductive fabric. Then, one can draw out a design on the adhesive's paper backing, cut the design out with scissors or a mat knife and iron it onto a backing fabric. Again, electrical components can be soldered or stitched to these traces. Figure 5 shows a hand-cut trace with an LED sewn to it. As is hinted at in the image, hand-cut traces (and laser-cut ones) can function as lovely decorative elements in e-textiles.

3.1.3 Accessibility and ease of use

The hand-cut iron-on circuit technique is very accessible. Though youngsters might need assistance working with irons, with help even they should be able to design and cut fabric PCBs by hand. We are hopeful that after familiarizing themselves with this basic technique, users will be comfortable with the possibility of employing the more sophisticated laser-cutting method. Laser cutters are expensive, "high-tech" machines, but they are becoming increasingly popular and are often available in places like high schools (the central high school in the small city where our research lab is located, for example, owns a laser cutter). We are optimistic that this trend will continue and we can envision laser-cut fabric PCBs being part of a high school course on e-textiles in a few years.

Fig. 5 A hand-cut iron-on circuit. The LED and power supply were stitched to the traces with stainless steel thread

Even with access to a laser cutter, there are challenges to working with fabric PCBs. In particular, they can be difficult to solder. Since most fabrics are flammable, heat is an obvious concern; the backing fabric for the circuit should thus be chosen for properties of heat resistance. (Thin polyesters, for example, are a bad choice for a backing fabric.) The encapsulation of solder joints is likely to present another challenge to novices. More research needs to be done to find user-friendly means of encapsulation before fabric PCBs can be easily used by novices. While these features of the medium present issues that users and researchers will have to grapple with, we do not believe that any of them present insurmountable barriers. Furthermore, iron-on circuits need not be soldered; they can also be employed in situations where all components are sewn.

Having examined the ease of use of iron-on circuits, let us now assess the technique in terms of our other accessibility constraints: how expensive and available are the materials one needs to build them? Conductive fabrics, though not well known outside of certain engineering fields, are widely available. The fabrics that we use were developed for electromagnetic field (EMF) shielding applications and can be purchased online from several different sites [22, 24]. Conductive fabric is expensive relative to other fabrics, but quite reasonable in the small quantities that are needed to make iron-on circuits. The other components of the technique, iron-on adhesives, are inexpensive and available in craft and fabric stores.

3.2 Electronic sequins

In our early experience designing e-textiles, we found ourselves frustrated by the lack of suitable electronic packages, wishing that LEDs and other components were available in form-factors that could be sewn to cloth, like sequins or beads. Electronic sequins evolved from our efforts to create such a package.

In our first crude attempt at realizing this goal, we twisted the leads of through-hole LEDs to create LEDs with looped leads that could be sewn down with conductive thread. Figure 6 shows one of these *stitchable LEDs*. We were interested in this "package" because, as it requires no soldering, it could be easily employed by novices. Still, as an LED package design, it left much to be desired: it was bulky and ugly, and the leads were prone to breaking off during twisting.

Our second attempt to create a sewable LED package was considerably more successful. We attached silver crimping beads to the leads of surface mount LEDs with lead free solder. The resulting "LED sequins" could be stitched to fabric with conductive thread in much the same manner as traditional beads. Figure 6 shows LED sequins before and after being stitched.

This sequin package is stable because almost all of the stress of flexing fabric is allowed and forgiven by the thread moving inside the bead. Very little strain is forced onto the solder joints and these joints remain intact as they are used. (Section 3.4 will present the results of preliminary washing tests for LED sequins.)

The sequin package can be used for other electrical components in addition to LEDs. Almost any two-lead component can be attached to beads or devices that achieve the same effect. Since the initial LED sequin realization, we have created switch, capacitor, resistor, sensor and battery sequins. Figure 7 shows a picture of switch and battery sequins.

We have used electronic sequins in a number of e-textile prototypes. Figure 8 shows one application of the LED sequin, a wearable display in which 140 LED sequins were stitched into a shirt to create a wearable display that is capable of displaying low-resolution animations like scrolling text and cellular automata.

LED sequins have proven to be useful, robust and—most importantly—fertile in the way that they suggest a wide variety of (initially unanticipated) designs. Figure 9 shows an example of one such unforeseen design, a beaded bracelet woven out of LED sequins. In this case, we were prompted to use the LED sequins just as one might traditional beads, weaving the bracelet from glass beads, LED sequins, standard thread, and conductive thread on a bead loom. Much like the shirt in Fig. 8, the bracelet can also be used to display scrolling text, cellular automata and other low-resolution animations.

It is worth noting that much of the electrical wiring for the bracelet was built out of a multi-layered fabric PCB. One can get a sense of this layout by referring to Fig. 10. This highlights yet another aspect of the techniques described here—namely, that they are complementary in their functions. That is, while LED sequins and fabric PCBs are separable techniques for e-textile craft, they can be profitably used in conjunction.

Having presented the electronic sequin and a couple of its applications, we can now turn to an assessment of it in terms of expense, availability of materials and ease of use. The materials required to build electronic sequins are easy to acquire and inexpensive. LEDs and other electrical components are sold by a variety of electrical supply retailers, and crimping beads are stocked in most craft stores. A variety of conductive threads are increasingly available: metalized (metal coated) threads and spun stainless steel threads are the most common and these can be purchased from online stores at reasonable prices [24].

Electronic sequins should be easy for an experienced solderer to make, and they are not as time consuming to build as one might imagine; we have found that 100 LEDs can be attached to beads in about an hour. However, soldering irons are dangerous and intimidating, and children or electronics novices would most likely be incapable of delicate soldering. This does present a drawback, but we think the lead-twisted "stitchable" components mentioned earlier could introduce novices to the electronic sequin. These stitchable components are easy to build, requiring only the component one wishes to transform and a pair of pliers, and they provide most of the functionality that the sequins do. We imagine that as a person becomes more experienced with e-textiles, she will learn skills like soldering and will then be able to make her own sequins.

Furthermore, we are optimistic that in a few years, we may see component-ready e-textile sequins available at craft shops or in electronics catalogues in much the same way that standard beads or electrical components are available now.

3.3 Socket buttons

The iron-on circuits described in Sect. 3.1, while extremely handy, do not have universal applicability. In particular, not all users will be able to cut out the precision circuits

Fig. 6 *Left* A stitchable LED. *Center* An LED sequin. *Right* An LED sequin stitched into fabric

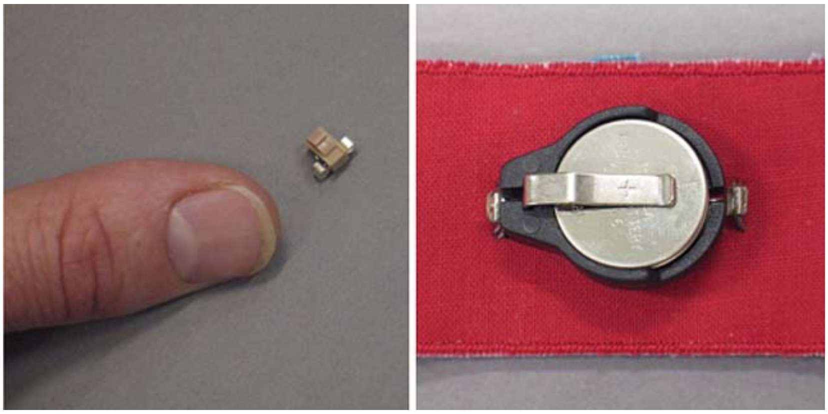

Fig. 7 Switch and battery sequins

Fig. 8 A wearable LED display matrix: a shirt embellished with LED sequins

that are required to attach components like microcontrollers to fabric or to solder iron-on circuits. When attempting to attach a microcontroller or other device requiring densely packed traces to fabric, a user may encounter other problems as well. Sometimes, for instance, the stiffness of solder joints is undesirable; or a user may be working with a fabric that needs to stretch. For these situations, we have developed another means to attach IC sockets, and thus microcontrollers and other "pluggable" components, to fabric.

Sockets with through holes can be sewn onto fabric like buttons to create what we have dubbed *socket buttons*. Each hole in a socket can be stitched onto a fabric backing with conductive thread. (We prefer to use a metalized, silver-coated thread for this purpose because it is more flexible and less prone to fraying than stainless steel threads.) One can use this thread to continue a trace across the fabric, or simply to make a connection between the socket and an existing trace on the fabric. When a microcontroller or other device is plugged into the socket, it makes contact with the traces on the textile via the stitching on the socket.

An example of a socket button is shown in Fig. 11. Here, the same thread was used to stitch out traces on the garment (the shirt shown above in Fig. 8) and sew on the IC socket. The socket can hold a 40-pin microcontroller; the result is that complex programs can be plugged into (or unplugged from) the shirt; one can effectively reprogram the display by inserting a new microcontroller into its socket button. Socket buttons might also serve as different types of plugs, facilitating connections to devices like power-supplies and computers.

While the socket button technique has the disadvantage of being time-consuming, it provides a powerful and

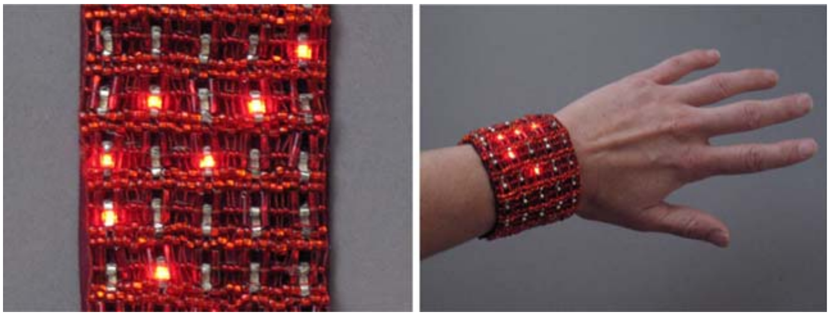

Fig. 9 A wearable LED display matrix: a bracelet woven out of LED sequins and glass beads

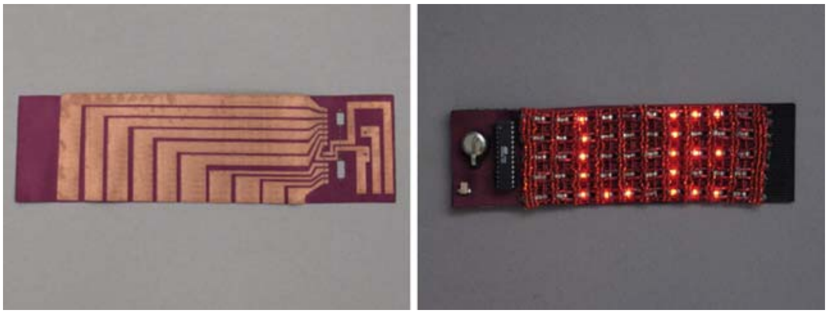

Fig. 10 *Left* the first layer of the fabric PCB that powers the bracelet. *Right* a flat view of the bracelet

Fig. 11 The socket button used to hold the microcontroller that powers the shirt shown in Fig. 3. *Left* Stitching the socket. *Right* The finished button

important benefit: it allows users to build sophisticated e-textile prototypes using only a needle and thread. A circuit can be sewn in conductive thread; stitchable electronics can be stitched to these traces for decorative or other purposes; and finally, socket buttons allow designers to attach controlling computer chips to their textiles.

That the socket button technique is quite accessible, requiring only IC sockets and conductive thread. IC sockets are cheap and available from electronics retailers and, as was mentioned earlier, conductive thread is also easily obtainable for reasonable prices. The delicate stitching that the technique requires may be difficult for young people or those lacking fine motor skills, but most patient teenagers and adults should have no problem employing it.

3.4 Insulators

Textiles bend and fold during use. This presents a challenge for e-textile design—electrical traces may come in contact with one another as a fabric flexes. Exposed traces are acceptable on circuit boards that are not only stiff, but also usually encased in hard protective boxes. Traces on textiles, however, must be insulated and protected to prevent shorts. Furthermore, the insulation must preserve the qualities of the textile; it should be soft, flexible and even stretchy if necessary. The remainder of this section will detail our experiments with a variety of readily available materials that can be used as insulators on fabric. We will focus on three techniques in turn: the use of stitching, the use of iron-on patches and the use of fabric paints.

A "couching" embroidery stitch can be used to insulate traces sewn in conductive thread. The couching stitch is a stitch that covers what is underneath it with a densely packed, zigzagging layer of thread. Figure 12 shows a picture of two traces—one exposed and one covered with a couching stitch. The couching method allows the insulator to become part of the fabric with the advantages that that implies: stitches wear wonderfully, and they simply look like natural parts of a textile. A designer can choose to camouflage the stitches, by matching thread color to background fabric, or to employ them as decorative elements in his e-textile.

However, there are also disadvantages to the couching technique. Most importantly, the stitch does not provide a fail-safe insulator—when pressure is applied to it, the insulating threads can part away from the conductor underneath. Thus, while it serves as a good means to protect against accidental shorts that occur when one region of fabric brushes against another, it cannot be used to insulate two traces that will come into frequent contact. Furthermore, the stitch occupies space—it is at least 3–4 mm wide—and thus cannot be used to insulate tightly packed traces. Finally, while the method is basically

Fig. 12 An exposed trace sewn in stainless steel thread, and a similar trace covered with a couching stitch

accessible—the materials are cheap and easily obtained and sewing machines are widely available—there are some limitations to ease of use: the technique requires a sewing machine and thus cannot be used in certain contexts (most classrooms, for example, are unlikely to have sewing machines) and what's more, not all sewing machines can produce a good couching stitch.

The second insulating technique we examined is the use of non-conducting iron-on fabric patches. To employ this technique, one simply follows the procedures outlined in Sect. 3.2, substituting a traditional fabric for the conductive cloth. Figure 13 shows an example of how this technique can be fruitfully employed: a simple hand-cut iron-on circuit is applied to cloth and then a matching iron-on insulator is applied over it. If additional support is desired, the iron-on insulator can be stitched down with non-conducting thread after it is ironed.

Iron-on insulators do not interfere with the conductivity of the materials to which they are applied. We tested the conductivity of sewn traces and iron-on circuits before and after iron-on insulators were applied, and detected no increase in the resistance of the traces. It should be noted that we employed a commercial digital multi-meter for these tests—it may be the case that the iron-on adhesive does interfere with the conductivity of yarns and fabrics very slightly but the meter we used was incapable of detecting the change. A justification for our measuring technique is detailed in the next section.

As is suggested by Fig. 13, the iron-on insulator method can be used particularly successfully in conjunction with iron-on circuits. Section 3.1 touched on the fact that one can create multi-tiered circuits by alternating a layer of non-conducting material with an iron-on circuit, each layer attached to the previous one with an iron-on adhesive. Fabric insulators can be cut to custom fit and cover any iron-on trace, using a laser cutter or scissors. These covers not only insulate the trace, but protect it from corrosion and wear. (We will return to this issue a bit later in the paper.) Iron-on insulators can also be used for decorative purposes.

A disadvantage of these insulators is that they stiffen the area to which they are applied. Though the patches will soften with use, they will always remain less flexible than the rest of the textile, and multi-layered areas will stay particularly stiff. Also, like the iron-on circuits, they cannot be applied to stretch fabric.

The iron-on patch technique is quite easy to employ. One needs only adhesive, an iron and a piece of fabric to make use of it. As we discussed above, these materials are cheap and easy to find, and we are confident that novice e-textile practitioners could make use of iron-on insulators.

Perhaps the most useful and robust class of insulators we have investigated is paint-on materials. We have experimented with a variety of paint-on substances including latex, acrylic gel mediums and an assortment of fabric paints. The most robust insulators we have found so far are "puffy" fabric paints. Latex rubber also works well, but because latex allergies are not uncommon, we will focus on fabric paint in this discussion. Figure 14 shows a picture of two traces covered with puffy fabric paint. The image illustrates how effective fabric paints are as insulators. One trace was sewn out and painted, then a second traces was stitched over the first and painted. The fabric paint separates the first trace from the second one, providing a robust insulation. We utilized fabric paint to insulate many of the traces on the shirt shown in Fig. 8 and have utilized it in other garments. Fabric paint can also be used to cover electronic components like electronic sequins and socket buttons with protective coatings.

Fabric paint does not interfere with the conductivity of yarns and fabrics. Again, we tested the conductivity of traces with a digital multi-meter before and after paint was applied, and detected no change in the resistance of the traces.

There are some noteworthy drawbacks to using fabric paint as an insulator. Fabric paint can change the look and feel of a textile. To get good insulating coverage, the thread or fabric must be completely covered, and this necessitates a raised area of paint. Also, the paint does not provide as elegant a covering as couching stitches or iron-on patches, being a conspicuously non-fabric material. Furthermore, it can be difficult to match the color of the paint to the color of the background cloth and thus difficult to camouflage painted traces. And finally, paint stiffens fabric—while bendable, painted areas are slightly hardened.

Though fabric paints aren't the ideal insulator, they have several benefits. In particular, they are non-toxic, familiar to many hobbyists, and quite easy to obtain and use. They're cheap and come in a variety of colors. What's

Fig. 13 *Left* a hand-cut iron-on circuit consisting of two traces in a copper plated fabric. *Right* iron-on insulators have been applied to the traces

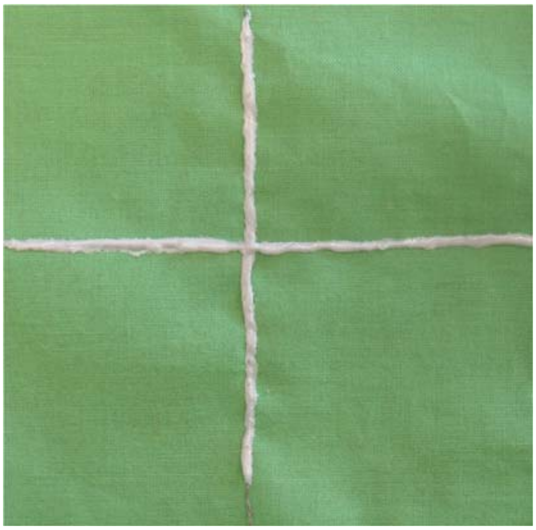

Fig. 14 Two criss-crossing traces prevented from contacting one another by applications of puffy fabric paint

more, like the other insulating techniques we have examined, they can be creatively employed to decorate as well as insulate.

3.5 Preliminary washing tests

We believe strongly that wearable e-textiles, handmade or manufactured, should truly be *wearable*. They should be able to withstand the stresses of use—they should be able to be worn and washed. This section will first describe our criteria for considering an e-textile technique or material robust enough for use. Then, within this context, we will discuss preliminary testing of the durability of the materials and techniques we have described.

It is not unusual for traditional garments to specify special washing requirements. One would not, for example, throw a favorite cashmere sweater into a washing machine or dryer. We believe that e-textile materials, like traditional textile materials, should not be deemed unusable when they fail to stand up to rigorous wash tests. If certain components require special handling—like hand washing in cold water, for example—this should not necessarily preclude their use in e-textiles. Though materials that break or degrade under the stress of intense testing may not be suitable for some devices, many can be fruitfully utilized in other areas. For example, a material that is unsuitable for use in a soldier's uniform might be applied successfully in an evening gown. Thus, we consider a material or application usable as long as it can be worn and washed in some reasonable fashion.

The electrical characteristics of most e-textile materials change with use. This can present significant challenges to applications that require high precision. However, the applications we are interested in—namely, low-frequency digital applications—require only coarse-grained consistency of materials. For example, for simple digital applications, like our wearable LED displays, it may be acceptable for the resistance of a material to change by as much as 5–10 Ωs across its lifetime. The vast majority of our applications utilize currents in the mAs, and device input resistance in the low MΩ range. As a result, small changes in line resistance do not result in any significant signal or power loss. In addition, line resistance would need to change by an order of magnitude for the intensity of LEDs to change noticeably.

We do not factor in analog effects like impedance matching or loss in our testing due to the relatively low bit-rate of data transfer in our applications (8 kbps or less). At these frequencies and currents, there are no significant capacitive coupling issues. We have designed our communication protocols to adapt to the large time differences in the system clocks of the chips we use. (We have so far relied on our chips' internal and imprecise RC oscillator clocks for timing.) Admittedly, impedance factors would matter at the high frequencies required for large-bandwidth applications, but low-bandwidth applications are the focus of our current research. In other words, we are willing to be more fault-tolerant than other researchers have been (cf. [25]). We are willing to consider alternative/gentle washing techniques and materials that do not wear flawlessly.

Having set the stage for our testing, we will now explain our experiments. Unless otherwise specified, each wash cycle took place in a commercial washing machine using the warm wash and cold rinse settings. The wash temperature was approximately 20°C. We used Arm & Hammer FabriCare powder detergent in each cycle. The samples were put through drying cycles in a commercial clothes dryer at the high temperature setting. We used a simple digital multi-meter (RadioShack model #22–811) for all of our measurements. This meter reads only to the 0.1 Ω and has an accuracy of ±0.8% [26].

The rest of this section will detail the results of our preliminary washing tests for each of our methods. It should be stressed that these experiments represent our first efforts to establish the viability of our techniques; more thorough testing should be conducted to determine how durable our e-textile devices are under other circumstances.

3.5.1 Fabric PCBs

There are two issues to investigate in regard to the durability of iron-on circuits: how well does conductive fabric hold up and how well do solder joints wear? We tested two types of conductive fabric: a Cu coated fabric and an Sn/Cu coated fabric, both manufactured by Less EMF [22]. We ironed traces 100 mm long and ranging in width from 1–20 mm to a piece of cotton fabric. We put the samples through five washing cycles and one drying cycle. It should be noted that the Cu 1 mm trace separated from the cotton substrate it was ironed to. None of the other traces suffered this fate; however, the durability of the iron-on adhesive may depend on the type of backing fabric being used.

Slade et al. [25] do not distinguish between Cu and Sn/Cu coated materials in their washability reporting, citing that both exhibited poor performance, losing 98% of their conductivity after ten washing cycles and one drying cycle. However, we found that while Cu coated fabrics degrade extremely quickly, the Sn/Cu coated fabrics hold up much better. Table 1 shows the results of the washing studies for these materials. As can be seen in the table, after our washing and drying, the Cu coated fabrics had lost all useful conductivity. The Sn/Cu coated fabrics on the other hand were much more robust. However, the 1 mm Sn/Cu trace suffered cracks along its length that destroyed its conductivity. Further investigation should be undertaken to investigate the relationship between the surface area and shape of a trace and its wear characteristics. Additional research should also be undertaken to determine how well Sn/Cu coated fabrics hold up in other circumstances, given the poor performance cited in Slade et al.'s study.

Table 1 The washing results for exposed iron-on circuits

Material	Initial resistance across trace (Ω)	After washing (Ω)
1 mm Cu	11.7	>400 M
3 mm Cu	2.8	>400 M
5 mm Cu	1.5	20 M
10 mm Cu	0.8	1.8 M
20 mm Cu	0.6	790 K
1 mm Sn/Cu	1.3	Broken trace
3 mm Sn/Cu	0.6	2.3
5 mm Sn/Cu	0.4	1.0
10 mm Sn/Cu	0.2	0.4
20 mm Sn/Cu	0	0.4

We also tested iron-on circuits covered with iron-on insulators. We tested four traces each of Cu and Sn/Cu coated iron-on circuits, identical to the ones described above. They were ironed to a piece of cotton and then covered with a protective layer of ironed-on cotton. Again, each of the traces were washed five times and dried once. To measure the resistance across each trace, we first stitched through each trace with silver coated thread. Then we covered the iron-on traces with the iron-on insulators, leaving the stitching accessible on the back of the fabric. Our measurements were taken from the stitching. Because silver coated thread has some resistance, the initial measurements for this study are higher than the initial measurements given in Table 1.

Table 2 shows the results of our assessments. These are striking, especially for the Cu coated fabrics. Iron-on insulators seem to drastically reduce the wear experienced by metalized conductive fabrics.

To test the solder joints on our iron-on circuits, we washed three iron-on circuits each with eight solder joints. One was encapsulated with urethane resin, one with puffy

Table 2 The washing results for iron-on circuits protected with iron-on insulators

Material	Initial resistance across trace (Ω)	After washing (Ω)
3 mm Cu	2.6	3.3
5 mm Cu	1.3	1.6
10 mm Cu	0.9	1.2
20 mm Cu	0.7	0.9
3 mm Sn/Cu	1.2	1.5
5 mm Sn/Cu	0.7	0.7
10 mm Sn/Cu	0.7	0.7
20 mm Sn/Cu	0.4	0.4

fabric paint and one with epoxy resin. Each circuit was washed five times and dried once. All of the joints encapsulated in urethane resin survived the washing, four of the joints encapsulated in fabric paint survived and seven of the joints encapsulated in epoxy resin survived. The fabric paint peeled up from the conductive fabric, and the solder joints underneath it did as well. One of the epoxy coated joints failed, not because the solder connection failed, but because the conductive fabric cracked at the point where the epoxy encapsulation met the fabric. We believe the epoxy caused the fabric to become brittle. We hypothesize that the joints encapsulated in urethane resin escaped this fate because the high viscosity resin soaked into the fabric more thoroughly. However, more investigation is needed to verify these hypotheses. Our examination illustrates the importance of encapsulation, but more testing is needed before we can confidently endorse any particular encapsulation method.

3.5.2 Electronic sequins

We believe the evidence we have collected indicates that the sequins are appropriate for use in the contexts we envision. We tested five LED sequins stitched into cotton fabric with stainless steel thread. The sequins were washed five times, then dried, washed another five times and dried once more (for a total of ten washings and two dryings). All of them withstood the washing and drying without breaking. We put another four sequins, stitched onto cotton with stainless steel thread and encapsulated in clear fabric paint, through two additional washing and drying cycles (for a total of 12 washings and four dryings) and none of these broke or exhibited degradation. We also tested an LED shirt similar to the one shown in Fig. 8, but containing 84 LED sequins—we washed this shirt once and dried it once, and none of its sequins broke. Finally, we washed the shirt shown in Fig. 8 by hand in cold water and allowed it to drip dry—it suffered no loss of functionality.

3.5.3 Socket buttons

Socket buttons wash well; we washed an eight-pin socket button with four contacts five times and dried it once. None of the contacts were damaged during the process. We also washed a 40-pin socket button with 25 connections in a different test—this button was washed once on the warm cycle and dried once on the high temperature setting. It also held up well; the only problems we encountered were a result of the fraying of conductive threads on our stitching. This fraying could eventually cause neighboring stitches on a socket to contact one another. We believe that this problem can be addressed by applying a suitable protecting substance, like fabric paint, to the stitching on the sides of an IC socket, preventing most fraying but allowing for electrical contact at the socket.

3.5.4 Insulators

As would be expected, couching stitches wear beautifully, exhibiting no more wear than the cloth to which they were attached. We washed five couched traces ten times and dried them twice. As was described above, to test the iron-on insulators, we washed eight iron-on circuits covered with protective iron-on patches. None of the insulators separated from their backing fabric during the testing. However, we do know from previous experience that when improperly attached, iron-on patches can peel off after repeated washings. In ongoing investigations, we will strive to develop strict procedures for handling iron-on insulators to prevent this from happening. Another solution to this problem is to stitch as well as iron the insulators. Puffy fabric paints also withstood the washing process quite well. We washed five stitched traces covered in fabric paint, like the one shown in Fig. 14, ten times and dried them twice. We detected no deterioration in any of them. It is still uncertain, however, whether the paints may crack or peel after extended wear; this is an issue that requires further study.

3.5.5 Washability conclusions

Most of the techniques we have explored seem to be robust enough to withstand a standard washing procedure, though more thorough testing is required before any of our techniques are deployed in industrial settings. Table 3 presents a summary of our preliminary washability findings.

It must be emphasized that the techniques and materials labeled as washable in this table may not be able to withstand rigorous washing or extended wear. The table is only intended to summarize our preliminary results.

4 E-textile craft: developing tools and encouraging practitioners

Having described our techniques, it is possible to step back and discuss a variety of issues suggested by them. In this section, we will first examine how a toolbox of do-it-yourself e-textile techniques might be put together and then detail our preliminary efforts at getting novices involved with this technology. We will conclude the section with a discussion of the motivating ideas behind our work in the area of e-textiles–ideas that stem from our broader interests

Table 3 Preliminary conclusions of our washability studies

Item	Washing procedure	Preliminary results
LED sequins	Ten washing cycles two drying cycles	Washable
Iron-on circuits(Sn/Cu conductive fabric)	Five washing cycles one drying cycles	Needs further testing
Iron-on circuits (Cu conductive fabric)	Five washing cycles1 drying cycles	Not washable
Iron-on circuits (with iron-on insulators)	Five washing cycles one drying cycles	Washable
Iron-on circuits (solder joints)	Five washing cycles1 drying cycles	Needs further testing
Socket buttons	Five washing cycles one drying cycles	Washable
Insulator (couching)	Ten washing cycles two drying cycles	Washable
Insulator (iron-on)	Five washing cycles one drying cycles	Washable
Insulator (fabric paint)	Ten washing cycles two drying cycles	Washable

in educational technology, and that center on the effective democratization and end-user control of ubiquitous computation.

4.1 Toward do-it-yourself e-textiles

What would a do-it-yourself e-textile toolkit look like? We envision it as a library of materials and techniques. At the core of the materials library would be a range of conductive threads and fabrics. The thread database would include spun stainless steel threads, metal plated threads and metal wrapped threads. The fabric library would contain a range of woven, knit and metal plated conductive cloths. Additional library components might include fiber optic materials, and, as they are developed, new materials like fabric based transistors, batteries and solar cells.

The technique component of the library would include, in addition to those described above, procedures developed by other e-textile researchers; many engineers have developed imaginative techniques that would be appropriate for do-it-yourself e-textiles and we will now examine a few of these. In a sense, the founders of this area might be considered to be Post and Orth et al. Their excellent work explored several simple but powerful methods for working with e-textiles [15, 16, 19]. Many of the techniques they pioneered—the use of gripper snaps as conductors, the stitching and embroidery of conductive traces, and the fabrication of simple cloth switches to name a few—would be invaluable to garage, living room and classroom e-textile tinkerers.

Lehn et al. [27], in designing e-TAGs, also developed simple and innovative techniques that would be useful for our purposes. In particular, they creatively experimented with ribbon cable connectors as a means of attaching components to fabric (Park et al. also report using this technique [10]). Ribbon cable connectors or insulation displacement connectors (IDCs) can be press fitted onto fabric much like gripper snaps, but each connector provides several small electrical contacts instead of one large one. Lehn et al. also built small traditional PCBs that could be plugged into and out of textiles in various ways, and we imagine that this technique could be fruitfully utilized by advanced e-textile crafters. Finally, Tröster et al. explored a number of packaging techniques and present an interesting survey of these in [28].

Another powerful class of e-textile techniques that we have not examined is cloth creation through weaving, knitting or other means. Park et al. [10], Orth [19], Locher et al. [29], and many other researchers have woven conductive materials with traditional yarns to make their own e-textile fabrics. Complex circuit designs can be woven directly into cloth using these methods. Similarly, fabrics can be crocheted and knit with conductive fibers. Weaving, knitting and crocheting are popular hobbies, so it is reasonable to assume that many of the techniques researchers have explored in these areas could be used by the e-textile crafting community that we envision.

As we have discussed, the basic materials for an e-textile toolkit—the threads, fabrics and electronic components we have mentioned in this paper—are already commercially available and not difficult to obtain. (As part of our work in this area, we are maintaining a website with information on where to buy these supplies [24].) Likewise, many of the techniques described in this paper are quite easy to employ; and, as has been touched on, similarly suitable techniques have been written about in scholarly publications. What is needed now is to introduce information that is well known to the research community to a wider audience. The remainder of this section will describe our first attempts at doing so.

To support this work, we have developed an *electronic sewing kit*. This kit currently consists of a length of conductive thread, a needle, a soft fabric switch, one or two stitchable LEDs and a power supply. A picture of one of our kits is shown in Fig. 15.

To begin introducing e-textile materials and techniques to new audiences, we have held e-textile workshops with a variety of groups [30,31]. Figure 16 shows images from a

Fig. 15 A first attempt at a simple do-it-yourself e-textile kit consisting of a needle threaded with conductive thread, a snap-on battery, a fabric switch and stitchable LEDs

sewing circuits workshop we conducted with a group of high school girls. Each girl was given a kit like the one shown in Fig. 15. The session began with a brief description of the kit and its contents, and a short introduction to circuits. A workshop leader (the first author) demonstrated what the kids should do by designing and beginning to sew a circuit into a fabric patch. The participants then embarked on their projects; the kids designed artistic patterns and electrical circuits, drawing out pictures with the markers and sewing out circuits with their needle, thread, switch and LEDs. Throughout the session, the workshop leaders were available to assist the participants with their work. At the end of a session, participants were allowed to take home whatever artifacts they had built.

We have conducted six sewing circuits workshops in various settings and with different groups of people. We have worked primarily with children (ages 8–16), but also held one workshop with adults. The workshops ranged in length from 30 minutes to two hours and the number of participants in each workshop ranged from three to nine. Workshops generally took place with groups of people of the same age. Each workshop followed the basic framework described above.

In a related but different workshop, a group of novice adults sewed stitchable LEDs into pieces of computationally enhanced quilt squares [31]. Along with stitchable LEDs and conductive thread, each participant was given a blank quilt square. Every quilt square contained a microcontroller that allowed it to communicate with its neighboring squares. Snaps on each square's sides were used to physically connect the squares and to route digital signals between them. Patches were capable of displaying the signals and then passing these signals along to neighboring squares. Each participant stitched his LED to embroidered pads leading from the microcontroller, and once the stitching was completed, the participants could snap their patches together to create dynamic quilts. Figure 17 shows a *quilt snap* quilt and a stand-alone square.

The results of these preliminary workshops have been encouraging. In all of the workshops, almost all of the participants were able to complete working circuits despite the fact that for many of them this was their first introduction to circuits and/or sewing. The participants, particularly the children and young adults, seemed interested and engaged in the activities. For example, one teenage sewing circuit attendee remarked that she was going to attach her patch to her backpack and another teenager said she would incorporate it into a school project. Although these are of course anecdotes from early pilot tests, they do lend plausibility to the more ambitious scenarios we will discuss in the next section.

In all of the workshops, the participants employed stitchable LEDs, but we have not yet used any of the other techniques we introduced in this paper in a workshop setting. We are looking forward to holding longer workshop sessions where we can introduce participants to more of the technology described here.

Fig. 16 A sewing circuits workshop. *Left* a group of girls at work. *Right* a participant's finished e-textile patch

Fig. 17 Quilt snap constructions. *Left* A dynamic quilt. *Right* A stand-alone square snapped onto a backpack (*right*)

4.2 E-textiles and educational technology

The techniques we have introduced in this document represent initial technical steps in a broader, longer-term project—namely, the development of educational systems and artifacts based on e-textiles. For example, given the right materials and setting, a shirt like the one depicted in Fig. 8 could be designed and constructed by a high school student. Such an activity would integrate aesthetic, engineering and intellectual challenges, drawing from the domains of physics, electrical engineering and clothing design. Moreover, once built, the shirt allows its wearer to create programmed displays (e.g., of cellular automata systems); it thus brings into the realm of e-textiles and wearable computing a representation of interesting, and decorative, ideas in the mathematics of dynamical systems.

The previous paragraph suggests several themes that we believe should be central in educational technology: the ways in which technologies are adopted (or rejected) by student culture; the ways in which powerful engineering, mathematical or scientific content can be tastefully introduced into a wide variety of children's artifacts; the ways in which such content can be employed, in certain contexts, as a means of personal expression and identification. The brief scenario above, for instance, may be a bit fanciful, but it at least suggests the way in which clothing–a central element of virtually every generation of youth culture–could potentially be the medium of both personal aesthetic display, creativity and intellectual challenge. For many students, the idea of devising a graphical effect to display on a desktop screen might have only a limited appeal; but the idea of devising that effect to decorate *oneself*, to express an idea, to show off—that might be irresistible.

Conceivably, student-constructed, student-programmed or student-controlled e-textiles could be used as the basis of a variety of educational applications. For example:

1. Students already employ an immense variety of "wearables", and the techniques described by the paper might allow students to integrate electronics into this incredibly rich medium for personal expression. For example: A younger child might be able to add simple but playful effects to his Halloween costume by stitching a few LED sequins and a battery sequin into it. A middle school student might modify a favorite pair of jeans to display and wirelessly communicate secret messages to her friends. Children on sports teams might customize their uniforms (a baseball player's uniform, for instance, might include a running display of his batting average). Kids interested in science might build clothing capable of displaying their heart rate, the ambient temperature, or other observable physical properties for which electronic sensors are available.
2. Considered simply as wearable displays employing a matrix of LED sequins, student-programmed clothes could be used to display not only "standard" cellular automaton systems as in the earlier-shown prototype, but also a variety of other systems and effects. Even at fairly low resolutions and refresh rates, programmable clothes might show physical effects such as patterns of magnetization, growth of fractal "diffusion-limited aggregation" systems, chemical waves, and many others (cf. [32] for a profusion of examples).
3. Socket buttons might be thought of as ports through which a student could "swap in and out" distinct programs to run a display on a garment. Thus, a student might carry about in her pocket a small collection of microcontrollers, any one of which could be plugged into a socket button to control the current behavior of her garment. Such notions lead naturally into still more elaborate scenarios in which programs take on the role of "collectables" in student culture–and once students can create and own large numbers of socket-button-ready programs, they can easily go still further. Students might create their own garment-

controlling programs that could then be swapped, purchased, given as gifts, hoarded, and so forth. In this manner, one might over time see the development of an effective student "economy" of garment-controlling programs (not unlike the informal economies that develop around artifacts such as baseball cards or virtual resources in certain multi-player video games).

4. Not all student-constructed or student-programmed e-textile artifacts need, in fact, be wearables; one could list a variety of plausible scenarios in which other sorts of fabric artifacts become enriched or augmented with homemade e-textile functionality. Students might, for instance, contribute patches of programmed fabric to create larger tapestries or quilts; or they might create e-textile ribbons (a form suggested by the bracelet shown earlier), or weavings composed of these ribbons; or they might create programmable displays on fabric book covers, curtains, or handbags.

The purpose of presenting these examples is merely to suggest how fertile the prospects might be for e-textile crafting among children. Unlike most school-sanctioned computer use undertaken by students, these scenarios highlight the ways in which e-textile crafts could be integrated into the day-to-day social structures of students' worlds. The pervasive aspect of e-textile crafts (in comparison to desktop programming) is crucial in allowing those crafts to find new and meaningful roles in children's lives. At the same time, unlike many other e-textile applications (real and imagined), those described in the paragraphs above focus on the ability of *users* (e.g., students) to create, decorate, program, reprogram, and customize their own e-textile artifacts, rather than simply to purchase such artifacts ready-made. We believe that the techniques described in this paper represent necessary early steps, then, toward the development of an "e-textile crafting culture" among students (and adult hobbyists as well).

We are also intrigued by the possibility that by bringing simple e-textile methods to a broader audience it would be possible to enhance not only the accessibility of e-textiles, but also the accessibility of electronics and computation more generally. E-textiles afford a particularly advantageous introduction to electronics: needles and thread are much less intimidating than soldering irons, and simple e-textile techniques are much less dangerous, involving no hazardous materials or tools. Furthermore, the qualities of fabric and the traditional application of textiles in areas like fashion may entice new and diverse groups to experiment with creative electronics and programming. We are particularly interested in the possibility that e-textiles may present a unique opportunity to engage women and girls in electronics and computer science.

5 Future work

We intend to continue to pursue three concurrent paths of work in e-textiles. First, we intend to keep building prototypes ourselves, and we hope that through these investigations we will discover materials and techniques that will inform our interests in educational e-textiles. Second, we intend to begin investigating ways to make the programming component of e-textile activities more accessible. Finally, we intend to continue holding workshops with the goal of introducing e-textile materials and techniques to a broader audience. The rest of this section will briefly describe our plans for upcoming work in these areas.

Our next round of e-textile prototypes should be more sophisticated than the simple LED displays described in this paper. Our work in this area will be focused on designs and activities that are most likely to excite kids and impact youth culture. For example, we are interested in enhancing the aesthetics and interactivity of clothing and textiles, guided by evidence that children (and adults) are fascinated with self-expression through what they wear. Specific applications we intend to research are e-textiles employing wireless communication devices, sensor arrays, and a wide variety of output devices (e.g. motors and speakers).

A second area that we would like to explore in building our next round of prototypes is the issue of the programmability of e-textiles. Implementing interesting behavior on e-textiles requires elements that can be programmatically controlled, and the devices best suited to controlling e-textiles are microcontrollers. However, microcontroller programming is generally perceived as a challenging activity requiring extensive programming skills and expertise in handling complicated hardware and software systems. Several systems intended to make embedded computation more accessible have been developed (cf. [33–36] for some examples), but the ones we have investigated are not suitable for e-textile applications. The devices tend to be large and bulky, and the architectures restrictive. Notable exceptions are the LogoChip developed by Robert Berg [35], a system that allows users to program microcontrollers using a Logo-like programming language, and the Arduino [36], a similar platform that employs the Processing and C languages. We want to begin investigating ways to introduce kids and hobbyists to microcontroller programming in the e-textile context. This may involve simply writing LogoChip or Arduino libraries, but could entail developing our own programming languages, interfaces and hardware to help novices use existing microcontroller technology.

In proceeding with our attempts to bring e-textile technology to new audiences we also plan to continue our sewing circuits and quilt snaps workshops, and intend to hold longer meetings to allow attendees to complete more sophisticated designs. We would also like to begin working with high school and middle school aged students in longer, more open-ended "electronic fashion" sessions in which children would be able to design, build and program their own electronic clothing. Finally, we need to undertake more thorough evaluations of the workshops we conduct. As our previous discussions have touched on, we see many fruitful areas for interesting assessment in this area. Questions we are interested in exploring include: how an e-textile based introduction to electronics might impact students' retention of and interest in the subject versus a traditional introduction; whether there are significant gender differences in the way students respond to e-textiles; and what types of artifacts students choose to build with e-textile tools.

6 Conclusions

E-textiles represent one particular genre of ubiquitous computing; but it is a genre that offers tremendous opportunities for creative contributions by students, hobbyists, and amateurs. From our own viewpoint—as researchers interested in e-textiles and educational technology—the ability of students and children to design, decorate, program, and customize their own fabric-based artifacts is especially powerful, since clothing and fabrics occupy such a central and meaningful aspect of young people's lives. Unlike so many other efforts in educational technology, e-textile crafts offer students a natural combination of aesthetics, challenging engineering and design, and personal expression. Moreover, as we have argued, such activities represent an introduction to still other, and broader, realms of electronics, programming, and mathematics.

The techniques described in this paper should thus be understood in the context of this larger project of nurturing a popular, democratized, and even child-friendly genre of ubiquitous computing. They represent early steps in this project, but they are (we believe) useful steps. Their utility is, ideally, not only as specific techniques for e-textile crafting, but also as illustrations of a more general belief in the value of widely available and diffused expertise.

To put it another way: as computing moves further and further from the desktop, it is important that it not become the exclusive province of a rarefied caste of specialists. Computer science has deep historical roots in the world of hobbyists, garage tinkerers, and other "amateurs". One can trace back innumerable important ideas in the field—in home computing, in interface design, in computational graphics and music—to the work of exuberantly obsessed young men and women. The e-textile research community (and the ubiquitous computing community more broadly) should likewise take care to empower their youngsters, and to nurture the participation of the "amateurs" from whom so much of the professional community has sprung.

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