e-TAGs: e-Textile Attached Gadgets

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Abstract

The integration of wires and electronics into textiles (e-textiles) has many potential applications for wearable and pervasive computing. Textiles are an integral part of everyday life, from clothing we wear to the carpet we walk upon. Being able to combine electronics with textiles would enable pervasive computing to blend into the background so that the user can go about a normal routine. One of the challenges in e-textile implementation is connecting the electronic components to the fabric cheaply and reliably. This paper describes the design and implementation issues of e-Textile Attached Gadgets (e-TAGs). E-TAGs can use a variety of methods to connect to wires in an e-textile. This design allows for e-textile electronics modules that are easily attachable, removable, replaceable, and interchangeable. This paper presents the system architecture, connection techniques, communication alternatives, and experiences from the construction of a prototype wearable e-textile with multiple e-TAGs.

1 Introduction

The pervasive computing community envisions computing capabilities transparently available anytime, anyplace, and anywhere. Such computing will interact seamlessly with the user and the user's environment, providing the user with the ability to act on and within the user's surroundings. Building this intelligent environment requires integrating computing, communication, and sensing capabilities into everyday items in a cost efficient and reliable fashion.

Textiles are an intrinsic part of our environment, from the carpet on the floor to the chairs that we sit on, from the drapes over the window to the tapestry on the wall, from industrial uniforms to the latest fashionable clothing. Not only are textiles already part of our environment, they make an excellent platform for embedding and integrating computing, communication, and sensing capabilities in a durable, reliable fashion that integrates nearly invisibly into the user's environment. Such an approach can benefit from low-cost, high-volume textile manufacturing techniques, the large surface area of textiles, and the intrinsic strength and flexibility of textiles.

Textiles integrated with electronics, often called e-textiles, are traditional textiles augmented with electronic devices, communications, and power storage/generation capabilities. Although many components, including wires, fiber batteries, and some antennas can be woven or stitched directly into the fabric, other components such as discrete sensors and most chips need to be attached to the fabric. Post-weave attachments abound in the textiles industry, including buttons, snaps, rivets, ribbons, zippers, and rhinestones. In this paper, we consider the design issues associated with an e-textile architecture that incorporates small printed circuit boards (PCBs) that integrate computing devices, sensors, and actuators and communicate over an e-textile backplane. The term *e-Textile Attached Gadgets*, or e-TAGs, is given to these small electronic devices. This paper explores the following basic issues associated with designing such an architecture.

- What factors limit physical e-TAG size?
- What protocol should be used for communication between e-TAGs?
- What type of e-TAG to e-textile electrocmechanical connections should be used? Which is the most reliable? Which is the most durable? Which is the least expensive?
- What are the difficulties when implementing a physical prototype of a fabric e-textile and e-TAGs?

Various approaches to integrating electronics with an e-textile are discussed in Section 2. This research focuses on the use of removable PCBs. Several factors, described in detail in Section 3, motivate this approach. The first is the advanced state of the PCB and electronics parts industry. The second is the potential use of a wide variety of sensors. The last is interchangeability of components within a common architecture.

Section 4 discusses alternatives for communication between e-TAGs. Section 5 explores several connection techniques. A prototype e-textile sweater is discussed in Section 8. Conclusions are presented in Section 9.

2 Background

At one end of the e-textile design space are garments that are designed to hold large electronic devices and provide convenient wire routing. One such product is the SCOTTeVEST [1], a wearable vest designed with a large number of pockets for various mobile devices. Hidden conduits are provided for wiring. Infineon Technologies AG [2] is developing products such as digital audio players designed to integrate with clothing. These are seperate devices, flat wire busses, and flat controls which are designed to easily integrate into clothing.

The other end of the e-textile design space directly connects individual electronics devices onto wires that are manufactured into the textile. An e-broidery summary by Post describes a number of these technologies [3]. Surface mount microcontroller packages and flexible multichip modules have been directly integrated onto e-textiles with e-broidery techniques.

Another option is to use an e-textile with integrated wires and removable electronics modules. Park has presented the Georgia Tech "Wearable Motherboard" which attaches electronic switchboxes to an e-textile along with other advanced sensors [4]. Reinmann presents the concept of "E-Button" sensors, controllers, actuators, and other devices attached to an e-textile [5]. Clothing sensor networks such as those presented by Van Laerhoven [6] would benefit from e-textile and attachment techniques.

This paper explores the design space which uses integrated wires in the textile, predetermined wire connection points, and common electronics in easily manufacturable removable modules. Gorlick's Electric Suspenders [7] explore a similar idea using conductive webbing, customized ball and socket connectors, and a custom protocol over a Controller Area Network (CAN) [8] based network. However, the suspenders are much more limited in terms of shape and device placement than garments in general. The devices on the electric suspenders could only be moved along the length of the suspenders. In general, garments are made from pieces cut from bolts of fabric. The pieces are not rectangular nor are they sewn together with the threads running in the same direction. In contrast to the electric suspenders, our approach is intended to work with garments of all shapes and sizes, and allows devices to be placed anywhere on the garment.

3 System Architecture

Our system architecture consists of detachable PCBs and a network of data and power lines woven into a fabric. Our motivation is to stay as close as possible to existing garment-making techniques, keeping manufacturing costs low while providing for reliability and design re-use.

3.1 Motivation for Using PCBs

The electronics industry has a large investment in PCB technology. Commonly available electronics parts are designed for use on PCBs and the PCB manufacturing process is very mature, with reasonable cost, good quality control, and tight integration of components. Components with small feature sizes and dense, high pin count packages work easily with PCBs but are difficult to use with non-PCB-based manufacturing techniques.

A custom system-on-a-chip (SOC) device could be used to put all required functionality for an e-TAG in a low pin count device. Using SOC devices has two drawbacks, high cost and the difficulty of integrating external devices such as sensors.

The second reason for using removable PCBs is the use of various types of sensors. e-TAGs that contain devices that do not need to interact with the environment directly could be protectively packaged. Biological, chemical, and other environmental sensors, such as those from Triton Systems [9], will need to be exposed. Some of these types of sensors can be exposed to water, while others may need to be removed to avoid being destroyed if the e-textile is washed.

A final reason to use removable PCBs is e-TAG interchangeability. e-TAGs should be able to be reused on different e-textiles for different applications. The interchange of e-TAGs can be to target a new applications, to use on an e-textile with a different form factor, or to move e-TAGs to a new e-textile if the original e-textile is damaged.

3.2 Fabric and e-TAG Architecture

The high-level e-textile architecture targeted in this research consists of power and data buses, electrical

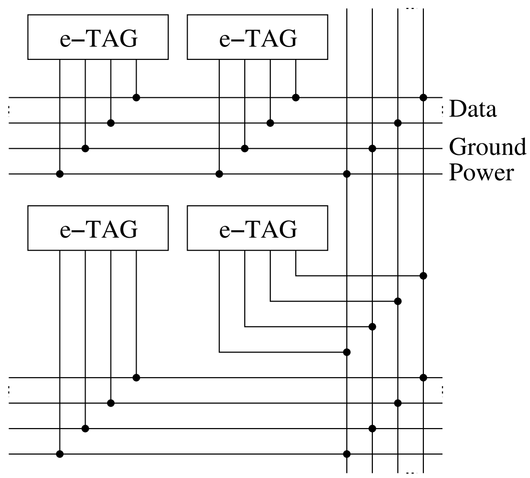

Figure 1: e-Textile network topology

connections between multiple buses, and e-TAGs at various points on any bus (see Figure 1). This shared global bus allows the for a common e-TAG connection and provides a simple network topology. A design with many point-to-point links may be more desirable to implement topologies such as a token grid [10]. However, many point-to-point links will require more complicated e-TAG connections. As a system gets more complex many other network topologies are possible such as hybrids of shared and point-to-point networks. The approach here uses the simple global shared bus with the intention of linking multiple buses in a single textile using more complex, high-level network routing techniques (c.f. [5]).

A long term goal of e-TAG design is to create devices that are flexible enough to be moved between e-textiles, hot-plugged as needed, reprogrammed for new applications, and able to handle e-textile faults. A prototype can explore these goals in a limited capacity. The work presented here is targeted at physical design aspects with proof-of-concept functionality.

The prototype e-textile and e-TAGs designed here are able to perform a few basic tasks. For the initial prototype system these tasks are to accept basic user input by means of switches, display output on LEDs, read microphone data, include the ability to do signal processing on the microphone data, and be able to communicate to an external host using a RS-232 serial port.

Based on these tasks a high-level design decision is that all e-textiles devices will be "smart" to some degree. This is realized by the integration of at least a microcontroller into all e-TAGs. A wide variety of manufacturers produce microcontrollers with on-board features such as digital I/O, analog-to-digital converters, and communication ports for RS-232, SPI, and I^2C. e-TAG size considerations require that many features be integrated into a single device.

The devices need to have an appropriate level of computational throughput for the low data rates required for envisioned applications. A more data intensive application could use an e-TAG with a specialized resource such as a DSP.

The prototype presented here uses two microcontrollers from Microchip that are chosen for their low power, size, and feature sets. The PIC16LF819 is used for smaller e-TAGs with minimal functionality and the PIC18LF242 is used for an e-TAG that has more computational resources.

The tasks resulted in the design of a handful of e-TAGs. The first three use the smaller microcontroller. "Blinky" has an array of four LEDs for user feedback. "Clicky" has two switches and two LEDs. "Mic" has a microphone and analog amplifier and filter circuitry. "Master" uses the larger microcontroller and is designed to provide overall system and bus control and do limited signal processing.

There are two important considerations before the e-TAGs can be fully designed and built. First is the method of e-TAG communication, discussed in Section 4. Second is the connection method between the e-TAG and the e-textile, discussed in Section 5.

4 Communication Method

A design choice that will effect the construction of both the e-textile substrate and the e-TAGs is the communication method. This communications protocol is used to interconnect the devices. The protocol used determines one vital physical parameter: the number of communication wires needed per e-TAG. This parameter determines the minimum density of the connection points. This can be translated into a minimum size for an e-TAG.

The two main areas of consideration are the communications standard to be used and the connection topology of e-TAGs. To reduce the potential effects of noise on e-textile signals, only digital communication methods are considered. This becomes a considerable concern for high-bandwidth devices. A microphone using a single wire to transfer analog data is susceptible to noise. However, converting many microphones outputs to digital data may require more bandwidth than a single shared network can provide. Tradeoffs between acceptable noise and cost and complexity of additional data wires must be considered.

Table 1: Communication Methods

Type	Pros	Cons
1-wire	Simple wiring	Low data transmission rate
I^2C	Microcontroller support 4-wire interface (+, -, clock, data)	Designed for board level integration Distance concerns EM interference
SPI	Microcontroller support Separate clock and data lines	Additional device select lines
Async Serial (RS-232 / CAN-bus)	Designed for off-board communications More robust in noisy environments	Requires transceivers
High Speed Serial (USB / Firewire)	High data transmission rate High-level standards	Complex hardware Cabling requirements
Parallel	Increased bandwidth	Specialized connection High wire count and complexity EM interference

Several possible communication standards that were considered are summarized in Table 1. The first was the simple parallel connection of wires between devices, which would allow for dedicated lines to facilitate the transfer of data and control signals. This reduces the need for time division access on the bus. In some situations this could form the basis for a fast and stable link. However, in an e-textile environment where many devices need to be networked together the manufacturing complexity goes up with the increased wire counts necessary for parallel connections.

Several different serial connections were considered including the 1-wire interface, the inter-integrated circuit (I^2C) bus, the serial-peripheral interface (SPI), asynchronous serial buses such as RS-232 and the controller-area network (CAN) bus, and high speed buses such as USB and Firewire. Our requirements for the link were that it be easy to implement, capable of supporting high enough data rates to network many simple e-textile e-TAGs, be implemented with a low wire count, and be reasonably fault tolerant.

SPI and I^2C are both supported in hardware on many microcontrollers and were the best choice for a prototype e-textile. I^2C was chosen because it reduced the total wire count to four shared wires: shared power, ground, clock, and data. The 1-wire interface, popular on devices such as the iButton [11], has a very low data transfer rate. SPI requires power, ground, clock, two data lines, and possibly device select lines for SPI. I^2C has has both 100 Kbps and 400 Kbps data rates available which are both sufficient for low data rate applications. The hardware support for I^2C helps with low level communication although future e-textile applications are likely to need more advanced protocols.

A production e-textile would likely need some protection against electrostatic and electromagnetic environmental forces. This would require additional devices such as transceivers or optical isolators. This may make buses which require transceivers, such as CAN, more attractive. The small e-textile prototype presented here uses an I^2C bus which is directly connected between devices.

5 Connection Method

The overall design requires the selection of a method of attaching the e-TAGs to the e-textile. The choice of a low wire count protocol makes the connection design easier. Higher wire counts require either a very large connection area or high wire density on the e-textile. Both are undesirable due to form factor and high manufacturing costs.

A 1-wire system is suitable for low communication bandwidth applications. This has been implemented with a multi-layer conductive substrate and attachments that use pins to connect to the conductive layers [12][13]. Due to the low bandwidth restriction this method is not considered for this research.

The following factors were evaluated when considering different connection methods:

- physical strength,
- electrical reliability,
- ease of attachment,
- repeatable re-attachment,

- aesthetics,
- size,
- comfort,
- cost, and
- availability.

The different methods considered for this research, primarily due to high availability of components, are solder, buttons or snaps, and ribbon cable connectors. The above factors are considered when selecting a method to implement. The following sections discuss the advantages and disadvantages of each method.

5.1 Solder

Soldering the e-TAGs directly to the e-textile is an option but has many limitations. An extended goal of the design is to plan for e-TAGs to be used in a mass production setting. The process of soldering each component connection to a wire in the fabric may be too slow or difficult to automate. Welding is a similar process to soldering which may be more practical for automated manufacturing.

While soldering produces a reliable electrical connection to the fabric, the physical strength of the solder connection may be questionable. The actual solder joint itself tends to stay intact but the hardened solder also provides a bending point where the wire itself can break. Soldering is not an option for some types of conductive threads (e.g., stainless steel).

Problems also arise when attempting to align pins on the e-TAGs with the wires on the fabric. Connecting the pins of the board to the fabric is a slower process when soldering because each individual pin needs to be aligned with its corresponding wire. The connection process is not one single step; each wire has to be attached separately. With the dynamic shape of an e-textile to consider, the desired wires may not always be spaced evenly.

If the wires are insulated, the task of removing the insulation at the attachment point also adds to the complexity of the process. Additionally, to avoid exposure of contacts, the solder joints need to be re-insulated. Again, this adds time to the procedure as well as cost.

The benefits of soldering include limited size, weight, and effects on comfort and aesthetics. The connection size itself is reduced to the size of the additional solder. The reduced size minimizes the impact on appearance and comfort. Re-insulating the wires though, may have adverse effects on the appearance of a garment. Although soldering would provide the least bulky and most comfortable connection, the difficulties associated with it would outweigh its benefits.

Figure 2: e-TAG and sweater snap connections

5.2 Snaps

The snap method uses sew-on snaps to make the electrical connections between e-TAGs and the fabric. One side of the snap is connected to the fabric wire, and the other side is connected to the e-TAG as shown in Fig 2. The snaps considered are commonly used in textiles. What is not common, however, is the connection of the snap to a wire woven into the fabric.

One possible method to connect the snap to the wire is with solder. The wire is either already exposed or the insulation has to be stripped from around the attachment point. This method would provide an adequate communication connection but the connection may become physically unstable. Sewing the snap to the fabric with thread helps stabilize the connection while also holding the snap in place on the fabric. Soldering, again, may not be an option due to the properties of some of the potential wires.

Welding the snaps to the wire is a technique similar to soldering. As with soldering wire compatibility with the welding process is also an issue. One of the advantages of welding over soldering would be, given the proper machine, the snaps could be connected to the wire in a more efficient manner than with using solder. Soldering requires the elements to be heated which slows the process.

Another method of attaching the snap to the fabric wires is to use a wire thread. The wire thread could be used to sew the snap onto an exposed piece of the wire. With the possibility of the wire thread coming loose, the stability of this connection is uncertain. Theoretically, a machine could be used to puncture the insulation to allow the wire thread to come in contact with the conductor of the wire. This could be a bit more expensive. Questions are then raised as to whether sufficient contact area between the thread and the wire can be achieved.

Aside from their common use, an advantage of snaps is their ease of attachment and removal. If it is desirable to remove and attach e-TAGs frequently, using snaps would be much easier than soldering or welding. Repeated connect/disconnect cycling could weaken the strength of the connection, compromising the stability of the connection.

The large surface area of the snaps provides a solid platform for an electrical connection. Figure 2 shows the possible size of the snap connection pads. The downside of the larger connection is that it increases the area requirement on one side of the e-TAG. Because a snap is needed for each wire connection, depending on the number of wires needed, the use of snaps could force the connection interface to be the dominating factor in the size of the e-TAG. Because size is an important constraint, the number of snaps needed must be considered before selecting this approach.

One problem common with any of these exposed-wire or contact methods is the potential for wires to contact each other. Even with insulated wires, the use of snaps provides an opportunity for two or more snaps to touch. Insulating portions of the snaps can greatly reduce this possibility at some loss of signal contact area. If the snap connection is always being used by an e-TAG the possibility of crossing wires at the snaps is almost eliminated.

Snaps seem like a reasonable solution given certain designs. Designs using more wires should avoid the snap method due to the higher snap area requirements. Snaps would also benefit systems where e-TAGs need to be added or removed from the e-textile frequently. The snaps themselves also allow the e-TAG to have a low profile on the textile.

5.3 Ribbon Cable Connector

The ribbon cable connectors considered for this research utilize a connection method called insulation displacement. The connections are made within the housing of the connector through the use of a sharp V-shaped contact that cuts through the insulation to connect to the conductor. Figure 3 shows the insulation displacement method on a traditional ribbon cable. Figure 4 shows the layers of a full ribbon cable connector and e-TAG assembly.

Figure 3: Ribbon cable connector with insulation displacement

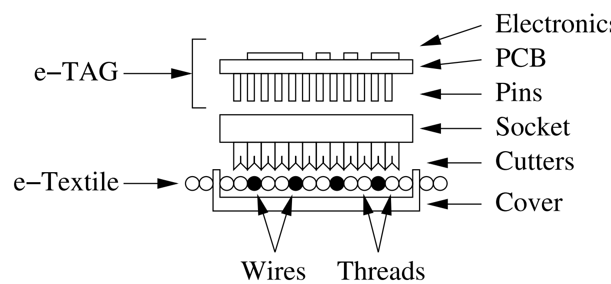

Figure 4: Ribbon cable connector e-TAG assembly

The use of insulation displacement removes the need for mid-wire insulation stripping. The plastic housing of the connector also provides insulation of the contacts. The sockets of this connector allow for easy mating with the pins of the e-TAGs, providing a reliable connection with the convenience of easy removal. When the e-TAG is removed the contacts to the fabric are not exposed.

Multiple pins in the connector can be used for a single wire on the fabric. This helps reduce alignment troubles because an error can be corrected by redundant wiring on the e-TAG. Using more connector pins does increase the size of the connector, but if the connector size remains within other constraints on e-TAG size, then additional pins should not affect the design size. Connectors of this type with various pin counts are readily available.

The ribbon cable connector itself can be removed with little difficulty. This, however, can lead to exposed portions of the wire or the insulation displacement could damage the conductor enough such that the wire is in danger of breaking. A significant prob-

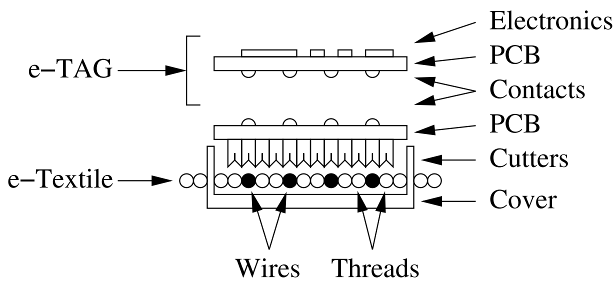

Figure 5: Proposed low profile e-TAG assembly

lem with these connectors is the potential of cutting the wire. If the connector remains intact, wire breaks should not be a problem.

Generally, attaching this type of connector to a group of wires does not take much physical effort. However, in the case where the insulation displacers need to cut through both the wires and the rest of the fabric, the force needed to fasten the connector together requires the use of a clamping tool.

Another disadvantage of the ribbon cable connector is its vertical profile. Ideally, a connector should be customized to reduce its vertical dimension. The plastic housing of the connector could easily be reduced. One approach is to have the insulation displacers directly soldered to a PCB. This would eliminate the use of the plastic housing and pins but would also remove some of the contact exposure protection. Having a structure under the insulation displacers would help align the wires and ensure the connection.

A possible solution is to put insulation displacers on a PCB. This would allow a low profile for the connector. Wire connection redundancy could also be integrated on this PCB. This would simplify and reduce the required contacts to removable e-TAGs. The connector cover extensions that hold on the pin socket can be extended to secure the e-TAG to the connector PCB. A proposed assembly is shown in Figure 5.

5.4 Raised Wire Options

The textile industry is advanced enough to enable almost any required pattern to be woven. It is possible to have short distances where wires in a fabric e-textile are raised above the other threads. This allows for the possibility of simpler connection methods that involve the wires more than the rest of the textile. This can eliminate the need to force connector devices through the rest of the textile. It also allows for one side of the textile to remain uncluttered and relatively natural. This may be important for connections on wearable e-textiles as one surface may be in contact with skin. The

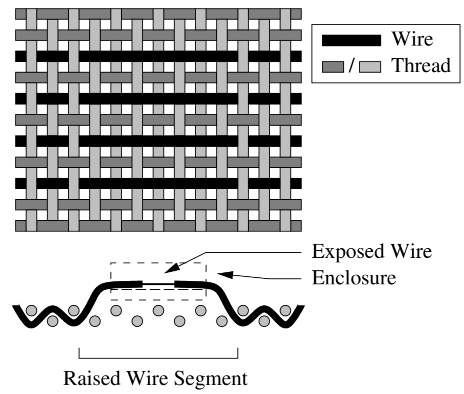

Figure 6: Raised wire weave

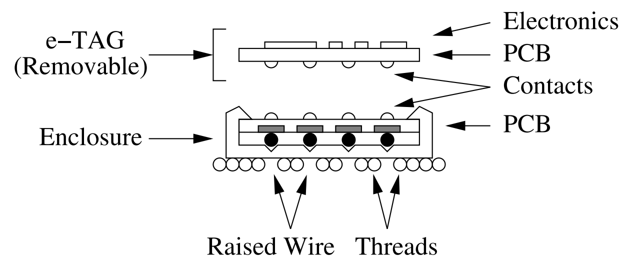

Figure 7: Raised wire connector

tactile feel of the e-textile should be kept comfortable.

The raised wire weave is shown in Figure 6. A bus of a few wires is raised for a short segment. This provides a location to slip part of an enclosure under the wires. One drawback of this approach is that the connector is now only secured by the wires. Novel connector design could allow for specific sew-on locations. The attached e-TAG may also need mechanical stability by means of other attachment technology, for example, sewing through holes in the e-TAG as with a button. The figure also shows a "stripped wire" approach for connections described below.

An example raised wire connector is shown in Figure 7. This connection creates electical contact based on pressure fit design. The connector enclosure has guide slots for wires. Each wire has a small section of insulation stripped off. The wire is then compressed between the enclosure and a PCB with contact areas. The PCB can be secured by a variety of techniques including hooks or a more complete enclosure that would provide more environmental protection. The wire contact PCB could be a more permanent e-TAG or a simple intermediate device that connects to a e-TAG with pin headers, pressure contacts, or flat-flex cable. A problem with this technique is the complexity of reliably stripping sections of wire insulation. The exposed wire sections also have to be kept seperated.

A variation on the raised wire connector is similar to standard insulation displacement connectors. A low pin count and low profile connector can be designed that connects directly to a PCB. This would have the advantage of environmental protection as well as potentially easier and more reliable assembly.

Table 2 summarizes the advantages and disadvantages of each method. For the prototype discussed in Section 8, the ribbon cable method is used most frequently due to its reliability and ease of implementation. The snap method is also implemented for one connection.

5.5 Bus Connections and Cross-Seam Connections

Another design consideration is the necessity of connecting crossing buses and making connections across seams in a textile. Buses in the textile will not necessarily all run in parallel, nor will separate buses necessarily be able to remain separate. Buses in separate regions of a garment, the sleeve of a shirt perhaps, may need to be connected to another region across a seam in the fabric. Connecting these buses allows the components to communicate with each other and allows one common bus to be used throughout the textile.

Two methods of bus connection were considered for this research. The first method, implemented at the junction of the horizontal bus and one vertical bus, used soldering to connect the wires of the two buses. One attempt at connection involved stripping a section of insulation out of the middle of the wires and soldering the exposed portions of wire together. This proved to be quite difficult as the process of removing a center portion of insulation was not fast or simple. The other method was to actually cut the wires and solder the four pieces together. This removed the insulation stripping dilemma but also left the connection weaker.

Although the joints could be hidden reasonably, the exposed connections had to be taped to avoid crossing wires. Figure 8 shows the soldered bus from the inside of the sweater. Even though the soldering was done on the inside of the sweater, the added tape made the connections a bit unsightly when viewed from the inside. The tape also enlarged the connection size and forced some stretching and pulling of the fabric threads, distorting the appearance of the garment somewhat.

Another problem with the solder joints is lack of reliability. Connections had to be repaired after pulling and stretching the fabric. One of the purposes of having a textile-based system is to take advantage of its collapsibility. If the connections within the textile are too fragile to allow bending or pulling, the deformability of the e-textile cannot be utilized.

Figure 8: Taped solder bus connection

Figure 9: Ribbon cable bus connection

A final argument against the use of solder to connect the buses was its lack of mass production potential. Neither the mid-wire stripping nor the wire cutting method would be easily or cheaply implemented in an automated process. This process would introduce numerous alignment problems. As wires in the bus get closer together, assuring that all the correct connections are made would be difficult.

Another approach to joining two buses uses two ribbon cable connectors, one on the horizontal bus and one on the vertical bus as shown in Figure 9. The appropriate connections between the two ribbon cable connectors are then made using single wires. This allowed for some flexibility in the joint while providing a reasonably stable electrical connection. Ideally, a mat-

Table 2: Advantages and Disadvantages for Connection Methods

Type	Pros	Cons
Solder	solid electrical connection, strong physical connection, small, light, comfortable, not noticeable	slow connection process, wire compatibility issues, wire breaks, alignment issues, mid-wire stripping, exposed wire protection, expensive
Snaps	connection/reconnection ease, common use	slow connection process, soldering or welding issues, connection size, weak physical connection, exposed leads
Ribbon Cable Connector	insulation displacement, common part, insulated connection, alignment tolerance, reliable connection	size, installation difficulty, wire breaks
Raised Wire Connector	single textile side, no threads, low profile	weak fabric connection

ing ribbon cable could be used to join the two connectors. This would enhance the stability of the connection as well as improve its appearance. No problems were encountered when making this bus connection.

This same approach could be used to connect buses across seams. A bus could lead up to one edge of the seam and could be terminated by a ribbon cable connector. A similar ribbon cable connector would be attached to the end of the bus on the other side of the seam. A flexible ribbon cable would then allow a suitable connection across the seam. The ribbon cable would allow the seam to flex while still providing a reliable connection.

6 Power

One important design issue is power distribution and power regulation. Power distribution is done on wires in the e-textile. In a global shared power network a battery or other power source can be connected at the same connector locations that e-TAGs use. The power source could be implemented as a smart e-TAG that would measure and report power status. The e-textile prototype designed here uses a global shared power network. Distributed and redundant supply designs may be desirable for larger e-textiles.

There are three possibilities for power regulation. First is global power regulation. This involves a centralized power source and regulator. The regulated power is sent out on the e-textile to individual e-TAGs. This method reduces complexity of the power consumers because only one regulator is needed. However, the drawbacks of this method are that a node can be affected by remote power fluctuations and power line noise, it has low fault tolerance, and e-TAGs with different voltage requirements are not possible.

A second method is local power regulation. This adds hardware requirements to individual nodes but has a number of advantages. The first is that nodes can operate at any voltage required, a significant advantage when a diverse group of sensors must be integrated on the same garment. Signal lines must still follow an electrical standard. The input power lines to each node can also be less controlled. In a large e-textile this lack of control may be unavoidable due to environmental factors. Local filtering of power may be required even with global regulation. The availability of miniature package-size power regulators minimizes the impact of this approach on e-TAG size.

This research uses local power regulation. Each e-TAG includes a Microchip TC55 power regulator and filtering capacitors. On the current e-TAGs the power regulation circuitry occupies a small but noticeable amount of space. With debugging components removed and smaller components used the power components may consume significant overhead. A possible solution is to have a shared local power regulation e-TAG for a small number of local e-TAGs. This may introduce some of the drawbacks of global power regulation but may be acceptable for many applications.

7 e-TAG Prototypes

Prototype e-TAGs were made using a dual PCB technique. The logic section includes the integrated circuits, input and output devices, programming connections and a common pin based connection to communicate with the e-textile. All of these components

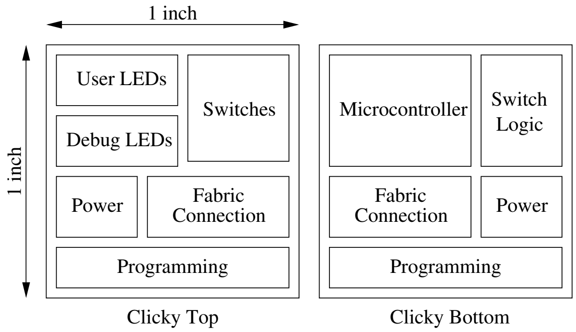

Figure 10: Clicky e-TAG layout

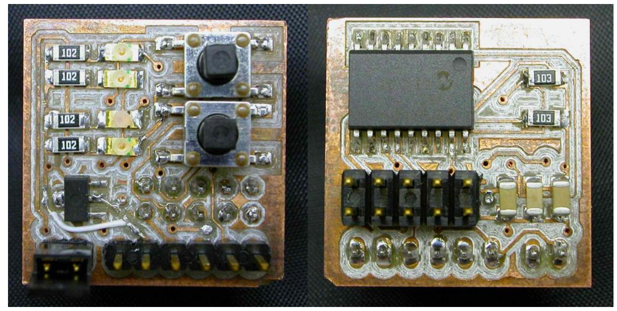

Figure 11: Clicky e-TAG

are integrated onto small printed circuit boards.

A second type of e-TAGs are used to physically attach to the e-textile. They translate between the logic board connector and the e-textile wire layout. These e-TAGs determine the minimum size of the designs.

In the future both sections can be combined into one. The multiple attachment technique allows for more freedom to experiment with the e-textile connections without logic section changes.

Four types of microcontroller enabled e-TAGs were built. The Master e-TAG controls the I^2C bus communication and can communicate with a host using an additional RS-232 transceiver e-TAG. Mic samples audio data and puts it on the network. Blinky is an LED-based output device. Clicky is a switch-based input device.

The smaller logic boards, Blinky, Clicky, and Mic, are roughly 1×1 inches with electronic surface mount parts on both sides of the PCB. The Master logic board is 1×1.3 inches. The PCBs are two-layer and use a minimum 0.010 inch line width. The board size could be reduced by using smaller connectors, removal of unused pins, fewer debug parts such as LEDs, and general usage of smaller parts. Size could be further reduced by using a more advanced commercial PCB process with smaller vias, smaller line widths, and more layers. An area reduction of nearly 50% appears to be possible. However, the area required for the e-TAG to the e-textile connection will limit overall size reduction. Sensor, actuator, and other part sizes will also limit the size reduction.

The PCB layout for the Clicky e-TAG is shown in Figure 10. A fully populated prototype Clicky PCB is shown in Figure 11. The Blinky and Mic e-TAGs shown in Figure 12 and Figure 13 are similar in design and size. The Master e-TAG shown in Figure 14 is slightly wider due to increased microcontroller size and the need for an external oscillator.

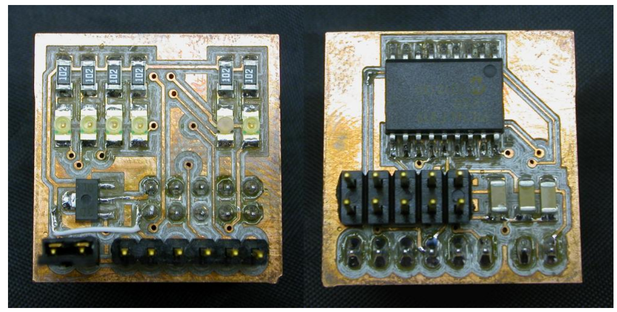

Figure 12: Blinky e-TAG

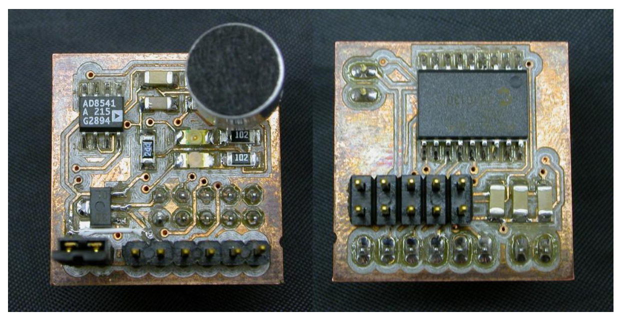

Figure 13: Mic e-TAG

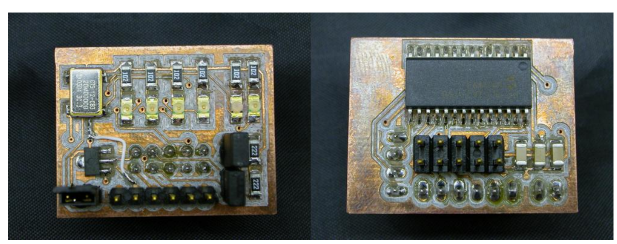

Figure 14: Master e-TAG

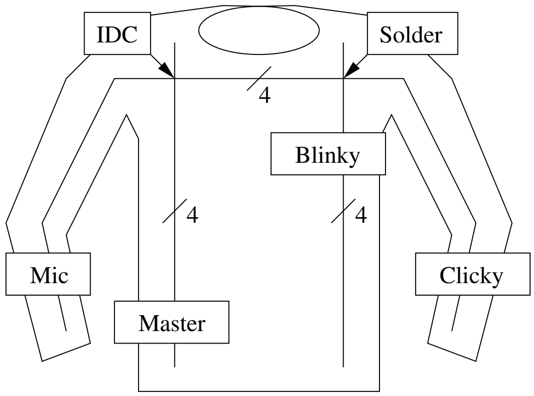

Figure 15: e-Textile sweater layout

Figure 16: e-Textile sweater

8 The Sweater

In order to test the connections, e-TAGs, and communication a generic e-textile substrate was created. The garment used for this project was a small sweater with three buses woven into it. This simplified model is sufficient to demonstrate connections and issues with actual implementation of theoretical techniques. To line up with the connections on the attachments, four 28 AWG wires spaced 0.15 inches apart were used for each bus. The wires were woven into the sweater fabric in an attempt to mimic a typical e-textile.

Figure 15 shows the layout of the prototype e-textile. The prototype is designed for Foss (named after gorilla researcher Dian Fossey [14]). Figure 16 shows Foss wearing the final implementation of the e-textile sweater. Two vertical 4-wire buses are run on either side of the front of the garment. One horizontal 4-wire bus is extended across the chest and down both sleeves. The bus connections are made using the ribbon cable insulation-displacement connectors shown in Figure 9 and the solder joints shown in Figure 8. The e-TAGs were arranged on different parts of the system to test the connectivity of the bus links.

The connection where Blinky is located uses the snap method. All other e-TAG connections use the ribbon cable connector. All but one of the ribbon cable connectors were attached with no difficulties. A crimp tool was used to provide the necessary force to cut through the insulation and sweater thread. The redundant pins used by the connector made up for imperfections in the bus line spacing and wire alignment. Though somewhat difficult to squeeze together, the ribbon cable connector connection proved to be a satisfactory method.

The snap connectors used for Blinky are more difficult to attach. Wire insulation had to be stripped near the connection point. The snap was soldered to the wire and then sewed to the fabric. Each of the four snaps was attached separately. Sewing and soldering took considerably longer than installation of the ribbon cable connectors.

The other problem with connecting the snaps to the bus was aligning the snaps to match the pattern found on the snap e-TAG. Figure 2 shows the snaps sewn onto the sweater along with the snap e-TAG used to connect to the snaps. Though the fabric is still flexible, the snaps had to be spaced similarly to the snaps on the connection board. Spacing too far apart may require stretching of the garment, possibly breaking connections. Spacing too close may make it impossible to connect to the board since the board cannot be collapsed to meet the fabric connection.

9 Conclusions

Of the various connection methods attempted in this research the ribbon cable connectors between e-textile bus wires and e-TAGs proved to be a robust solution to the problem of integrating "soft" fabric goods to traditional electronics mounted on printed circuit boards. These connectors allow the use of redundant wire contacts to increase manufacturing reliability. They offer a cheap and readily available solution that allows simple installation to the underlying wires in an e-textile simply by pressing the insulation displacement knives through fabric and wires.

This work has focused on wearable fabric e-textiles but other potential e-textiles substrates exist. Alternate textiles can range from carpets and wall coverings [12][13] to decorative "party textiles" [15]. With common connectors the e-TAG hardware can used with different e-textiles.

The I^2C serial communications link used is an excellent bus type for small shared networks requiring less than 400 kbps total bit rate for all devices. It is easily implemented and requires only 4 wires throughout the system. Other buses must be considered if device count is greatly increased, e-textile size increases, higher bandwidth is needed, or the e-textile is used in a non-ideal noisy environment.

The current prototype uses I^2C in a master-slave configuration. A multi-master network architecture is often more desirable for message-oriented communication and fault-tolerance. Multi-master would allow sections of the e-textile to become disjoint without causing complete failure. Individual e-TAGs need to use algorithms to compensate for such events and reconfigure e-textile routing as needed. This has been proposed by Reinmann for the E-Button fabric [5].

Simple e-TAGs are easy to design and build. Highly integrated functionality on commercial microcontrollers allows e-TAGs to be designed such that e-TAG to e-textile connection size controls e-TAG size.

A more elegant solution to the physical connection problem is to take advantage of the weave pattern to "float" wires over short distances, eliminating the need to insert connectors through the rest of the fabric. We are prototyping this type of connection and expect it to have a number of advantages, including ease of making the connection, self-alignment of wires, and comfort.

The system created is scalable and with a variety of e-TAGs can be well suited to many different e-textile applications. It is relatively inexpensive to implement, and consists of devices that are standard to the industry, providing for easy prototype development.

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