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Using electronic textiles to implement an acoustic beamforming array: A case study

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Abstract

Highly-automated textile manufacturing equipment has the potential for integrating electronic components into fabric in a low-cost process. These electronic textiles (or e-textiles) have a wide range of potential applications in wearable computing and large-area applications, including medical monitoring, assistance to the disabled, and distributed sensor networks. This paper discusses the design and implementation of a large-scale e-textile that functions as an acoustic beamforming array. The paper conveys the implementation experience and gives results gathered from the prototype. Further, the primary implementation issues and guidelines for future development are identified.

Keywords: Electronic textiles; Smart fabrics; Wearable computing

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1. Introduction

Several research projects have demonstrated the capability of weaving a variety of conductive materials into textiles as well as attaching a range of electronic components,

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particularly sensors, to textiles (cf., [1–4]). The resulting electronic textiles (e-textiles) provide an attractive platform for wearable computing applications and enable the cost-effective construction of large scale, durable sensor networks. Advantages of e-textiles over existing implementation technologies include a familiar form factor, comfort, flexibility, low-cost manufacturing, large surface area, durability, and a wide range of natural and technical fibers from which to choose. Consequently, e-textiles are an enabling technology for pervasive computing, both in terms of garments for wearable computing and textiles such as a carpets, wall-hangings, and upholstery.

For the purposes of this paper, an e-textile is defined as a set of sensors, actuators, and processing elements embedded in or attached to a fabric backplane which routes data and power throughout the textile. Research in e-textiles is still in its infancy, with a wide range of approaches being explored within this working definition. The purpose of this paper is to present a case study on the design and implementation of an e-textile prototype, and then to generalize from that implementation to identify research issues, propose solutions, and outline future research for e-textiles.

The application chosen for this case study is a large e-textile acoustic beamforming array, which can robustly detect and locate passing vehicles via their sound emissions. From a research perspective, this application calls for the integration of a moderate number of sensors and processing elements on to the textile, with all of these elements communicating and receiving power through the textile. This large textile, approximately ninety square feet in area, falls into the category of infrastructure e-textiles; this category of e-textiles includes primarily large textiles such as carpets, wall-hangings, sails, and upholstery. As will be demonstrated later in this paper, the experiences with this prototype have implications for a range of e-textile applications, from wearable computing to large-scale sensor networks.

The design and implementation of an e-textile application pose several computing challenges, including fault-tolerant networking, power-aware operation, effective programming models for distributed systems, and construction of a simulation environment. While there exists significant literature and tools in all of these areas, e-textiles occupy an extreme corner of the design space, having additional constraints that require new solutions to be found for questions that have been studied in related computing domains such as distributed systems and embedded computing. The constraints also create problems that have not been studied before. For example, the physical networks in electronic textiles are inherently a two-dimensional topology whose embedding in three-space changes over time. In many e-textile applications, nodes need to communicate with other nodes based upon their locations in three-space, but the network path between them is determined by the fixed two-dimensional topology; this has significant implications for both the networking and programming environments. Because the quality of the implementation depends on such design choices and features of e-textiles, one contribution of this paper is to establish some guidelines for a successful e-textile design based upon lessons learned from the construction of the acoustic beamformer.

The paper is organized as follows. Section 2 provides background information, including the motivations for the use of e-textiles and descriptions of existing e-textile applications. Section 3 discusses methods for the physical assembly of electronic textiles. Section 4 describes the prototype developed for the acoustic beamforming array application. The experience acquired during this work is distilled into a set of design issues and guidelines in Section 5. Finally, Section 6 draws conclusions and outlines future work.

2. E-textile background

Because textiles are ubiquitous in daily life, they offer a rich array of opportunities for the deployment of e-textiles. In addition to the clothing we wear, textiles uses include upholstery for furniture, carpet and rugs for floors, window shades, wall hangings and coverings, tents, and car interiors. This section begins by describing how the combination of textiles and electronics offers several advantages that make them attractive for wearable and ubiquitous computing, such as ease-of-use, cost-effectiveness, and inconspicuousness. The remainder of this section briefly presents several commercial and research projects that have demonstrated these advantages.

2.1. Motivation for e-textiles

The principal motivation for e-textiles is their potential to be a platform for wearable and ubiquitous computing, a platform that can be seamlessly integrated into a user's daily routine. In Weiser's seminal article on ubiquitous computing, he described technologies that disappear from the consciousness [5]. Because fabrics are such an integral part of our daily life, e-textiles offer the opportunity to invisibly add intelligence to the environment and to the user's clothing.

E-textiles offer **ease-of-use** in many applications, because the user will interact with the garment exactly as with a normal garment. If an application is seamlessly embedded in a form-factor with which the user is familiar, such as a shirt, the need to instruct a user on how to deploy the e-textile to achieve goals such as appropriate sensor placement is eliminated. The sensors on the garment will be pre-placed, and the user must merely don the shirt. In existing wearable systems, components tend to be discrete, requiring the user to place each one individually, for example, attaching them to a belt or securing them at given points on the body [6]. An advantage of e-textiles over discrete components is that by having the wires woven into the fabric themselves, the wires are not as susceptible to becoming tangled together or snagged by the surroundings.

One of the inherent benefits of textiles, developed over thousands of years of human use, is **comfort and customization**. In applications involving contact with people, (e.g., clothing, furniture), textiles offer unparalleled degrees of comfort and tailoring to user preference. In addition, the non-electronic fibers that form the bulk of the textile can be chosen from a broad array of natural and man-made materials to change properties such as heat retention, texture, and permeability to water. In addition to comfort and customization, textiles have the **strength and flexibility** to undergo the rigors of constant, daily use; this strength and flexibility is not present in typical wearable computers.

For many applications such as law enforcement, military, and health monitoring, it is desirable from a user perspective that the hardware be as **inconspicuous** as possible. For consumer applications of wearable computing, devices must be fashionable if they are to be acceptable. Not only are the textiles themselves something that are already part of the environment, but they also allow for components to be integrated within and between layers of fabric and into pockets and seams, as well as into common functional attachments such as buttons, rivets, and zippers [7]. Apart from visual obtrusiveness, the radio frequency (RF) signals emitted by systems based on wireless on-body networks raise additional user concerns such as the privacy of sensitive health-related data, the effects of RF signals close to the human body, and the unwanted determination of a user's location based on such signals. By implementing all intra-textile communication on a wire-based textile network, the need for RF communication can be reduced or eliminated.

Textiles offer a unique ability to integrate multiple types of sensors and processors during the weaving and textile assembly processes. This ability, along with the availability of a large number of conductive fibers in the textile, allows for the possibility of **multiple, integrated applications** within the same e-textile system.

A variety of methods for **power** generation within the textile have been considered, including solar, body heat, and body motion. Further, the capability to communicate over wires rather than wirelessly offers multiple advantages from the perspective of power consumption [8]. In addition to generating and reducing power utilization, e-textiles offer a convenient method of power distribution to an array of devices on the textile, avoiding the need for a large number of batteries.

Production textile machinery is capable of high production rates at **low cost**, while maintaining the capability to weave and embroider precise patterns. The integration of electronics into these extant processes can lead to the production of large-scale e-textiles at relatively low costs.

The wearable computing environment is significantly more challenging than the desktop or portable computing environments from the perspective of durability. Aside from challenges similar to those faced in the portable environment (e.g., dropping, moisture, and static charge), wearable computing devices will be subject to the everyday wear-and-tear to which clothing is subjected. The large surface area of textiles offers the potential for incorporating redundant conductive fibers and components to achieve **fault tolerance** while still retaining a convenient form factor.

2.2. *Related research*

While the e-textiles field is still in its infancy, a number of applications have already been developed in industry and academia, demonstrating some of the desirable properties of e-textiles, and pointing out research issues that must be addressed if they are to be successful.

A number of e-textile applications demonstrate the potential to provide important functionality in a form factor that is easy-to-use, comfortable, flexible, and inconspicuous. The capability to design and manufacture strong, flexible pressure-sensing textiles has been demonstrated by ElekSen. Among other form factors, ElekSen manufactures a fabric keyboard for PDAs that doubles as a carrying case [9]. Eleksen has demonstrated a commercial capability to incorporate similar devices into a variety of textile form factors, allowing for user/textile friendly input devices to augment more complex e-textile systems. A glove with attached piezoelectric sensor cables provides the functionality of a keyboard while eliminating the need to carry a keyboard that can interfere with the user's environment [10]. To provide for robust personnel monitoring in an easy-to-use form factor, the sensate liner was designed and implemented at Georgia Tech [11]. This system has fiber optic cables and conductive cables woven into a shirt to allow the detection and location of bullet holes as well as monitoring the vital signs of the wearer [11]. This technology has been further developed as the Georgia Tech Wearable Motherboard. Similarly, a commercial system, the LifeShirt, uses sensors implanted in a vest to provide FDA-approved continuous ambulatory monitoring of patients. The vest is easy-to-use, comfortable, and can be worn during the wearer's normal daily activities [12].

Another important area for e-textiles is context awareness, as knowing what the user is doing will ensure that a computing system can provide appropriate interaction with minimal user intervention [13]. A wearable system for the classification of user motions has been developed using stress sensors attached to a jacket [14]. This system can provide context awareness in a comfortable and inconspicuous form factor. It is important for context-aware applications to work for most of the population without extensive tailoring to each individual; the design for a diverse population of users of woven e-textile pants for context awareness was described in [15].

Other research has examined the practical issues associated with the integration of electronics into textiles, such as the signal behavior of e-textile conductors and methods for attaching electronics to the fabric. A characterization of signal propagation within e-textiles at frequencies exceeding one GigaHertz is reported in [16]. A method of attaching electronic components such as integrated circuits directly to a woven e-textile is given in [17]. Methods for attaching printed circuit boards as buttons or other textile components are given in [7]. An examination of several practical issues, including the design and analysis of a fabric-based USB cable, is given in [18]. In addition to attaching discrete electronic components to e-textiles, several research groups are developing sensors and other components in a fiber form factor suitable for weaving. These components include conductive fibers [19], piezo-electric material [20] that can be used as sensors and actuators (used as the sensing element in [10]), and fiber-form battery elements. This body of work shows that the integration of textiles and electronics is feasible and has the potential to be manufactured at low cost.

E-textile applications require a distributed computing environment for effective operations, particularly when multiple applications are operating within the same garment. The e-textile environment and associated applications represent an extreme corner of the distributed computing design space because of the limits on power consumption, networking bandwidth, and computational performance [21]. A rich array of sensors, actuators, and processing elements occupy a relatively small space as compared to a typical computing or sensor network. Power is at a premium in the majority of e-textile applications, because they operate untethered for extended periods of time, whether they are body-worn textiles or otherwise. The underlying communication network is typically two-dimensional, but it is embedded in three-space and, in many cases, that embedding will change over time.

Relative to the other aspects of electronic textiles, only a small amount of work has been done on the software associated with such systems. A set of services associated with communication, self-location, and power-aware task assignment is given in [21]. The migration of jobs within a distributed computing e-textile model is discussed in [22]. In previous work, we have created a simulation environment for electronic textiles to enable more rapid exploration of the e-textile design space and reduce the amount of prototyping required to create a functional system [23].

3. Constructing electronic textiles

Manufacturing an electronic textile requires the inclusion of electrically conductive elements and sensors in the textile as well as the attachment of discrete electronic components to the textile. The methods chosen to accomplish these two tasks have implications on the design choices discussed in later sections, including the network topology and the width of a connection between an electronic component and the e-textile. This section describes these assembly issues in detail sufficient to explain the implications for these design choices. We have chosen methods that, as closely as is feasible, use existing textile machinery and processes, so that the cost-effective aspects of textile manufacturing are retained.

There are two primary textile manufacturing techniques for incorporating conductive fibers into fabric: embroidery and weaving. An advantage of embroidery machines is that they can create nearly arbitrary patterns on a fabric; they can also be used on a finished textile or garment. One can envision using an embroidery machine to create the fabric equivalent of a printed circuit board. Such a machine was used in [2] to create keypads on a garment using silk organza fibers with a thin metal strand as the conductive fiber. Disadvantages include operation being limited to a relatively small area, expensive operation relative to other textile processes, and limitations on the type and size of fiber that can be effectively used in embroidery machines.

An alternative approach is to use a loom to weave a textile that includes conductive fibers and sensors in a fiber form factor. Modern looms are highly automated, cost-effective devices capable of computer-controlled, high-speed operation. In the weaving process, there are two sets of yarn that run orthogonally to one another. A set of *warp* yarns, often numbering in the thousands, is attached to the loom during the setup phase. These yarns are parallel to the long, continuous direction of the fabric in a bolt of woven cloth; the ordering of these yarns in that direction will be unchanged during the weaving process. The *weft* yarns are inserted during the weaving process perpendicular to the warp yarns. Prior to the insertion of each weft yarn through the warp yarns, the loom selects which warp yarns are above the weft yarns and which are below. When done in a repetitive fashion, these choices lead to a pattern. Depending on the loom, the weft yarn for each insertion may be made from a small set of available yarns, with four to eight being a typical set size. While weaving places mild forces on the yarns, particularly at start-up, a much wider range of yarns can be used successfully in a loom than in an embroidery machine. Weaving, however, limits the orientation of the yarns to the X–Y plane, limits the number of types of weft yarns, and fixes the ordering of warp yarns. An annotated photograph of the loom used to create the e-textiles in this paper is shown in Fig. 1. The above description gives the background necessary for understanding the potential and limitations of this process; more details can be found in [24].

As with any fabric, the pattern used for weaving e-textiles is a major factor in determining the look and feel of the fabric. Different weaves using the same yarns will

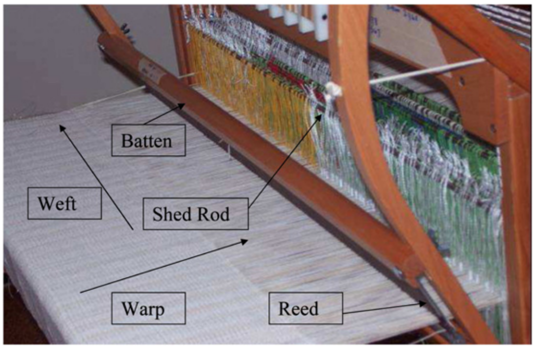

Fig. 1. The basic loom used in creating the prototypes for this research. Newly added filling yarns are held in place with a reed, while the reed is mounted to the batten. The weft yarns are mounted on a shuttle which is inserted through the warp yarns. The shed rod is used to hold the selected warp yarns above the other warp yarns according to the chosen weave pattern.

have different strengths, textures, and appearances. With e-textiles, the weave pattern can be designed such that the electronic fibers are either hidden or visible, as desired for the application. For example, the conductive fibers are likely to be hidden throughout the fabric, but fibers that emit light (e.g., electroluminescent (EL) wire) can be positioned to display patterns within the weave pattern. The choice of the weave pattern and non-electronic yarns can also be used to control the texture of the fabric as well as the appearance. Weaves such as a Bedford cord [25] can be used to surround the electronic fibers entirely, with the electronic fiber being a filler within a raised cord, so that only non-electronic yarns are visible. With the button-size printed circuit boards described below, the weave can be designed to have small pockets for holding the boards securely in place while concealing them from view. These pockets are created by having a group of yarns in one direction (warp or weft) above the yarns in the other direction for a relatively long distance.

In addition to selecting an appropriate weave pattern, some fibers require special handling during the automated weaving process. In previous work, we have shown the utility of piezoelectric materials in electronic textiles [10]. One form factor of these materials is a thin film that can be configured as a sensor or an actuator [20]. If this film is woven in the warp direction, it must be configured in the loom at a different tension than other fibers. Accommodating fibers with such needs is typically done by feeding and tensioning these fibers separately from the other fibers; this slightly increases the cost, but is quite common in the textile industry. In the weft direction, the problem is more difficult, because the shuttle (shown in Fig. 1) used to transport the fibers across the textile in the weft direction is typically not tolerant of a wide range of fiber properties (e.g., very stiff fibers). Options include the choice of looms with different shuttle mechanisms, and in the extreme cases, manual insertion of a small number of special fibers in the weft direction.

As another example, the use of fibers based on shape memory alloys can further complicate the textile weave design and fabrication process. These fibers change shape when an electric current is passed through them, allowing one to modify the shape of a textile. In addition to the engineering challenge of the physical design parameters, this actuator gets very hot during activation, requiring the selection of fibers that will not be damaged by this heat.

The position of the conductive fibers in the weave also determines where on the fabric the printed circuit boards can be attached, and where connections between the warp and weft conductive fibers can be made. The position of the warp yarns is fixed throughout the weaving process, but the position of the weft yarns can be changed relatively easily. Consequently more care must be taken in determining the number and placement of conductive fibers in the warp before the loom is set up, whereas modifying their number and placement in the weft is minor. In the prototype described in this paper, the spacing of conductive fibers in the warp direction was chosen to match the pitch of a standard $0.1''$ header on the printed circuit boards.

While preliminary research into the creation of transistors and other components on fibers is ongoing [26], current and near-term e-textiles must rely on cost-efficient integrated circuits for computation and some sensing capabilities. Different methods of integration and attachment have been investigated (cf., [7,17,18]) and are summarized here to the extent required to understand the choices made in the following sections. As noted in Section 2, a technique for attaching the pins of a chip directly to fine wires in a fabric was described in [17], including a technique for sealing the electronics in such a way as to make the resulting textile launderable. Such an approach places restrictions on the pitch of pins and wires in the fabric (and, therefore, the number of pins on the chip) as well as posing unaddressed challenges for the use of insulated wire; the resulting chip is permanently attached to the fabric. While permanent attachment is acceptable for low-cost chips that can be sealed against the environment, some chips are too expensive to restrict to a single garment, while others – particularly some types of sensors – cannot be sealed against the environment. Temporary, yet secure, attachment of button-size printed circuit boards is described in [7]. This method restricts the connection between the board and the textile to a few pins, but can be used with insulated conductive fibers in the textile. Finally, the integration of standard connectors, such as USB, into narrow textiles to allow integration of standard computing devices such as PDAs and GPS units, is described in [18].

4. Prototype implementation

This section discusses the design and fabrication of a prototype e-textile beamforming array. Several aspects of the design are described, including the fabric construction, the application software, computational elements, communication between elements, and the performance of the system.

4.1. Fabric backplane fabrication

An e-textile relies on the fabric to, at a minimum, serve as a backplane that provides power and communication while acting as a physical substrate for any attached components. A rich array of design options are possible for this substrate, including the choice of conductive yarns, the placement of conductive yarns with the chosen weave pattern, and the number of layers within the fabric. For this application, we investigated two primary designs types, a multi-layer fabric and a single layer fabric.

Fig. 2. An exposed view of the multi-layer fabric.

The multi-layer fabric was used in conjunction with uninsulated wires. Three layers of fabric were used, a top layer with wires arranged in a single direction, a bottom layer with wires perpendicular to those in the top layer, and a middle insulating layer with no wires. Connections between the layers were made using a weave pattern that selectively drew wires from the bottom layer over and across a single wire in the top layer. This multi-layer approach, shown in Fig. 2, allowed for a very simple means of connecting wires to each other or to attachments because no method of selectively removing insulation was required. The two drawbacks to this approach are the potential for shorts associated with uninsulated conductive yarns and, perhaps more importantly, the relative thickness of the resulting fabric. Note that the shorts can occur between conductive yarns in the fabric due to folding and other changes in shape as well as due to conductors external to the fabric.

The other option explored was a single layer design, allowing for more traditional, less-bulky fabrics. This solution, however, requires that at least one direction of the conductive yarns be insulated to avoid shorts due to crossing conductive yarns. For our prototypes of this option, such as that shown in Fig. 3, we explored insulating a single direction as well as both directions to avoid faults similar to those possible in the multi-layer, uninsulated option. The primary drawback to this option is the increased difficulty associated with removing insulation from conductive yarns. In addition, while there exist several types of thin, flexible conductive yarns (cf. [2]), insulated versions are not commonly available; insulation significantly increases the size and decreases the flexibility. For this reason, we have opted to use either stainless steel insulated fibers such as those from Bekintex [27] (see Fig. 4) or tinsel wire insulated with a detergent resistant coating (see Fig. 5). The resulting fabric is launderable; the e-textile prototype, however, cannot be submerged because the circuit boards are not sealed and the microphones chosen are not waterproof.

4.2. Power-aware acoustic beamforming

The function of the prototype is to find the location of a passing vehicle based upon the vehicle's acoustic emissions. The system does this by combining multiple lines-of-bearing to the vehicle; a single line-of-bearing is shown in Fig. 6. These lines-of-bearing are computed using an acoustic beamforming algorithm under the assumption that the vehicle is in the far field and lies in the same plane as the e-textile.

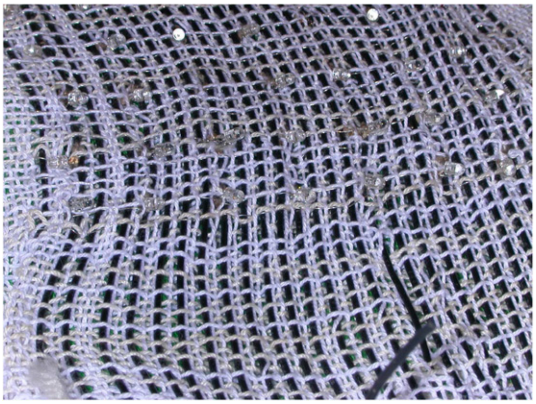

Fig. 3. A single layer fabric with insulated fibers running in one direction and uninsulated fibers in the perpendicular direction.

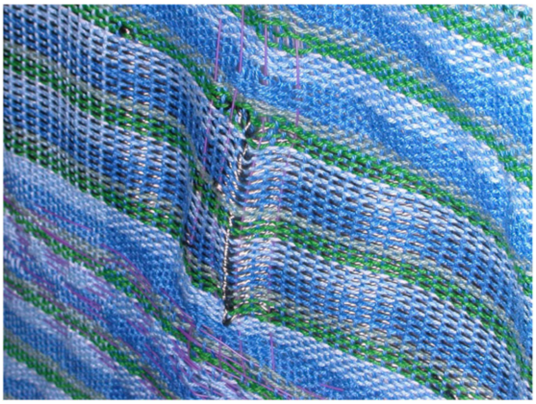

Fig. 4. A woven prototype containing multiple uninsulated stainless steel fibers.

Fig. 5. Tinsel wire insulated with a detergent resistant coating.

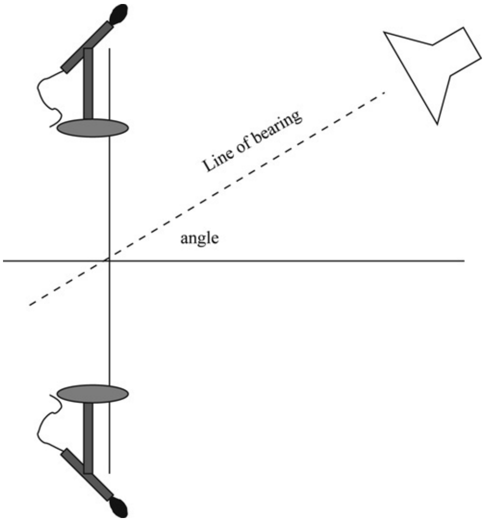

Fig. 6. Acoustic beamforming is used to determine the line of bearing of an in-plane noise source.

An important goal of the application is to operate at low power because the fabric is intended to run for extended periods of time without an external power source. Standard implementations of acoustic beamforming are implemented using floating point arithmetic. The most power efficient digital signal processing chips, however, do not have hardware support for floating-point arithmetic. Given the need for power-aware operation, we chose a fixed point implementation of a time domain acoustic beamforming algorithm that also has the ability to change several variables in an effort to trade off computation for accuracy [28]. These values include the number of microphones from which to collect acoustic data, the sample rate and length of samples collected, and the number of search angles to test for the line-of-bearing.

The use of acoustic beamforming to detect vehicles imposes several restrictions on the spacing and sampling of the microphones. The primary frequencies of interest for the prototype application lie in the band from 100 to 180 Hz. This implies a minimum theoretical sampling rate of 360 samples per second, and more in practice. Further, to avoid aliasing, the microphones participating in the same beamforming computation should be separated by no more than one-half of the shortest wave length. The shortest wavelength in this application is approximately six feet depending on the speed of sound, leading to a minimum separation between microphones of three feet. In the far field, assuming that the acoustic source lies in the same plane as the microphones, a minimum of three microphones is required to find the direction of the source. As will be discussed later, aside from these theoretical limitations, the accuracy of the system can be improved in practice by increasing the number of microphones and the sampling rate.

4.3. Acoustic beamforming array

As described in the preceding paragraphs, the acoustic beamforming algorithm uses data from a set of closely spaced sensors to find the line of bearing from the sensors to

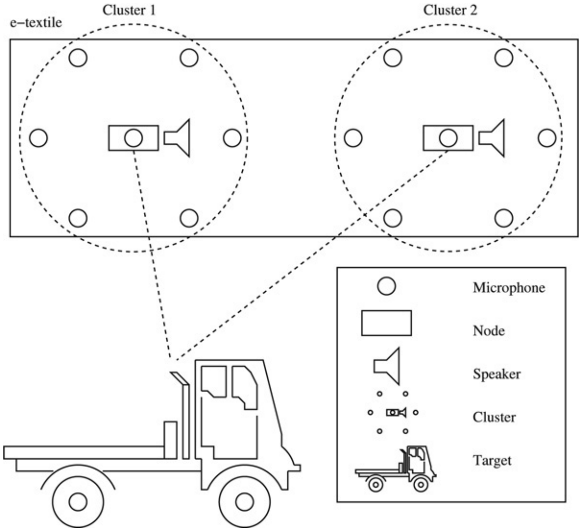

Fig. 7. A conceptual rendering of an acoustic beamformer with two clusters.

the acoustic source. The computational element computing this line of bearing is called a *node* in this discussion; the set of sensors associated with a single node is called a *cluster*. Finding the location of such a vehicle requires combining one or more lines of bearing to fix a location; this concept is illustrated in Fig. 7. The accuracy of the location computed via this triangulation is very dependent on the spacing between clusters; wider spacing results in more accurate position computations.

The system could produce a location result using two closely-spaced clusters with three microphones in each cluster. Such a system, however, would be inaccurate in practice as well as fail to produce results when even a single component fails. The acoustic beamforming array in this paper was designed with four clusters composed of seven microphones in each cluster, as shown in the schematic in Fig. 8. A seven microphone cluster was chosen because of the improved performance in the presence of noise as well as the ability to tolerate the loss of microphones; the system is capable of recognizing the loss of a microphone and reconfiguring the software accordingly. An example of a single cluster prototype is shown in Fig. 9, in which six microphones are spaced regularly at a distance of approximately eighteen inches about the computing node that is co-located with a microphone. The four clusters are placed in a regular spacing on a thirty-foot long fabric. The use of four clusters allows for improved accuracy when combining multiple lines of bearing to find a location as well as the potential to tolerate faults with two redundant clusters.

In addition to providing a flexible, easy-to-deploy substrate, the fabric also houses the means of power distribution and communication. While the potential exists, the power distribution network embedded in the fabric is not fault-tolerant; short circuits or disconnects in this network will lead to failure. The communication network embedded in the fabric that is used to combine the computed lines of bearing information is fault tolerant. The communication of this line-of-bearing information takes place over

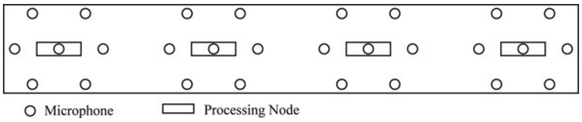

Fig. 8. A depiction of a four-cluster textile in which each cluster has seven microphones.

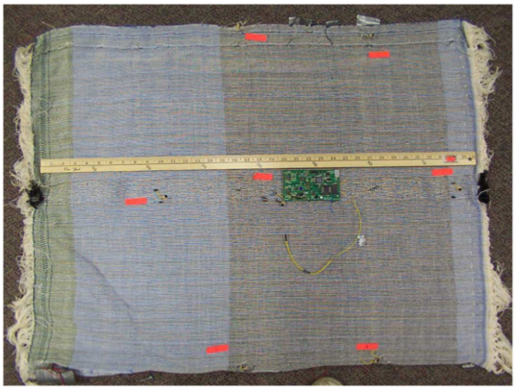

Fig. 9. A one-cluster acoustic array shown with a yard stick for scale.

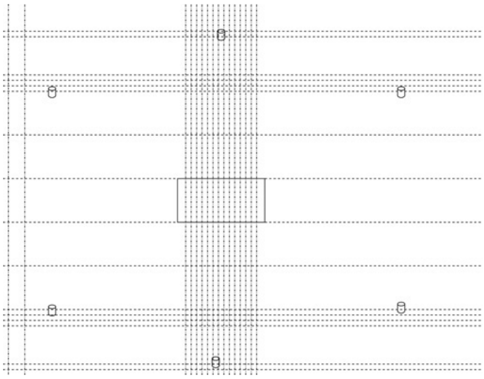

Fig. 10. The textile schematic of the acoustic beamformer shown with one node and six microphones along with the conductive fibers in the fabric.

conductive fibers woven into the fabric. By weaving in extra fibers and interfacing to those fibers through each node, redundant communication lines are provided at little extra cost and with no change in the flexibility of the fabric. Each node is connected to multiple conductive fibers, with only one required to communicate the line of bearing information. A diagram of the wiring for one cluster is shown in Fig. 10; this pattern is simply repeated to create a multi-cluster fabric.

4.4. Component communication

Communication among different types of components is required in this prototype. The communication of data from the microphone to the processing node is done in raw, unamplified analog form; this choice and the implications are discussed in more detail in Section 5. The communication of data from the prototype to the "outside world" is accomplished, for prototyping purposes, via a serial port to a handheld computer.

The nodes communicate amongst themselves to send computed lines of bearing as well as to wake up one another. The nodes can enter a sleep mode when they are not in use. One of the ways in which a node can be made active again is through a signal via one of its communication lines; i.e., another node requires the services of the sleeping node and prods it awake. This capability presents a significant power advantage over an implementation employing wireless communication between nodes. This capability allows a node to enter a sleep state and be woken up on demand, with little or no delay. Accomplishing this with wireless communication would require the equivalent of a low-power, wireless wake-up radio function. Such a function must be immune to external signals, either noise or deliberate manipulation to consume power though unnecessary wakeups. Unfortunately, no wake-up radio is currently available that has comparable power consumption while providing immunity to external signals, leading either to a system that constantly powers a receiver or a system that awakens periodically to listen to its neighbors; one is forced to tradeoff latency for power.[1]

The actual communication between nodes is relatively straightforward in the prototype. The node hardware, described in the Section 4.5, has three rings available for communication, but only two are actually in use. Communication on a ring is accomplished using a serial format similar to RS-232, but implemented using the general-purpose I/O pins of the DSP to control the communication instead of a built-in communication peripheral such as a UART or more sophisticated serial communication devices such as SPI or I2C. This choice was made primarily to preserve maximum flexibility in the communication scheme, because prior to constructing this large textile, we did not know what type of noise to expect on our communication lines. This choice is evaluated in Section 5. Each node builds simple, fixed-length packets that contain either a computed line of bearing, a request for a line of bearing, or a message that the node is in an error state.

4.5. Hardware and software of the processing node

Given that it was not possible to directly connect integrated circuits of any complexity directly to the fabric, a circuit board was designed for this project. The board was designed to amplify the microphone signals, convert the analog signals to digital form, run the beamforming code, provide the wake-up circuitry, and communicate with the other nodes. Two constraints on design were that the board must allow for power-aware operation and that it must have many observation points for debugging and measurement purposes; the

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[1] Note that wireless communication from the fabric to the outside world is unavoidable, but is a relatively infrequent event that does not require the beamformer to supply continuous power to a receiver.

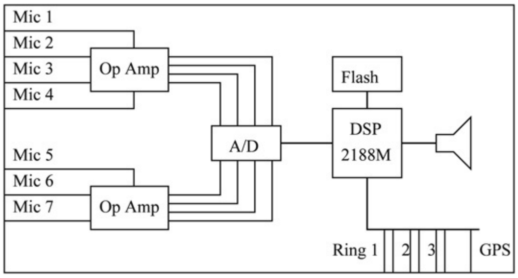

Fig. 11. A block diagram of a node shows the components as well as the microphone and communication connections to the fabric. Additional communication lines are included to allow for redundancy and a serial connection to a GPS unit is provided.

second constraint led to the board being larger than is required for normal operation. The first requirement led to the selection of the ADSP-2188 [29], a low-power, fixed-point digital signal processor. On the ADSP-2188, the beamforming algorithm uses 25% percent of the processing time at a sample rate of 8192 samples per second from a seven-microphone cluster and nearly 100% of the on-chip data memory, making it well-suited for experiments across a range of sample rates and cluster sizes. Depending on the final selection of the number of microphones per cluster and the sample rate, a less powerful processor could possibly be chosen. In addition to the communication wake-up capability, the DSP can also be configured to awaken when an external circuit detects that the magnitude of an incoming acoustic signal exceeds a predetermined threshold. This capability allows the entire fabric to enter a sleep mode until a vehicle approaches. Two additional components are a speaker that can be used to help determine the status of the microphones as well as a flash memory from which the DSP is booted. The block diagram of the node is shown in Fig. 11.

All processing on the board is event-driven, with events being generated by a timer, by the A/D chip, by the serial port, or via the communication and wake-up circuits. These events cause interrupts to be serviced, resulting in data being read or written to external ports and/or internal memory. The beamforming algorithm is invoked whenever a full buffer of data from all active microphones is available; this computation takes place in the background while other events are serviced, including the filling of another buffer of microphone data. Because all the events have well-defined, nearly constant service times, this approach guarantees that all tasks can be completed on time. By simply changing the timer setting, the sampling and communication speeds can be varied, up to the capacity of the DSP and A/D to satisfy the processing and sampling requirements.

4.6. Prototype performance

In this section, the performance of the prototype and associated design decisions are experimentally examined. The performance metrics are energy consumption and the accuracy of the beamforming results. The experiments use a combination of physical measurement and simulation to explore a wider range of the design space than could be practically explored using physical prototypes alone. Exploration of the design space

Fig. 12. The four-cluster beamforming textile during a field test of functionality.

includes a comparison of communication using the textile backplane to RF communication between clusters using Bluetooth modules.

4.6.1. Power characterization

The power consumption of the functioning prototype, shown during a field test in Fig. 12, was extensively characterized. This characterization was performed during its operation using an Agilent 3458A Digital Multimeter capable of over one hundred thousand samples per second interfaced to a GPIB card [30].

The energy consumption of a single cluster was analyzed during the operation of the beamforming algorithm for a range of microphone sampling rates and for different numbers of microphones. Regardless of the number of microphones or sampling rate, the beamforming algorithm was configured to compute the direction of arrival once per second and communicate that value to its neighbor. When not actively computing or sampling, the computational node enters an idle state in which power consumption is reduced. The power consumption rates for all aspects of the beamforming computation, including running the algorithm, collecting data, communicating data, and waiting in the idle mode, are given for the various combinations in Table 1.

In its operational mode, the prototype can accept its power from a range of voltages. Under the expected duty cycle profile and with the power-savings features of the hardware prototype enabled, the prototype has been run for multiple days using a single 9 V battery. A more refined version of the beamforming array could be equipped with flexible film batteries, flexible solar cells, or fiber-form-factor batteries.

In Section 4.6.3, alternative architectures using wireless communication are evaluated and compared to the e-textile approach. To provide the basis for the comparison, the same experimental apparatus was used to characterize the power consumption of a Bluetooth radio module suitable for replacing the fabric-based intercluster communication. The Bluetooth Application Development Kit from Teleca AB [31] was selected for this purpose. This kit employs the Ericsson ROK101008 module compliant with Bluetooth Version 1.1. The power consumption of this kit in five Bluetooth operational modes is given in Table 2.

Table 1
The average power consumption by activity for a range of numbers of microphones and sampling rates

State	Number of microphones	Sampling rate	Power consumption (mW)	Time (ms)
Idle	–	–	9	–
Beamforming algorithm	–	–	200	–
Receiving	–	–	159	–
Sending	–	–	179	–
Sampling	3	2048	62	61
Sampling	3	4096	70	76
Sampling	3	8192	89	108
Sampling	5	2048	66	85
Sampling	5	4096	79	98
Sampling	5	8192	104	130
Sampling	7	2048	70	112
Sampling	7	4096	88	127
Sampling	7	8192	124	160

The rightmost column also gives the running time for the beamforming algorithm for a range of sampling rates and number of microphones.

Table 2
The average power consumption in five operational modes for a Bluetooth radio module

Operational mode	Power consumption (mW)
Standby	100
Inquiry:Scan	204
Inquiry:Send	261
Paging:Scan	100
Paging:Send	261

4.6.2. Energy versus accuracy

This section explores the tradeoff between power consumption and accuracy as the number of microphones and clusters is varied. As the number of microphones and clusters increases, the accuracy will tend to improve, or at least not degrade, and the power consumption will increase.

To explore this tradeoff in detail and under controlled circumstances, we constructed a simulation environment, termed TailorMade, based on the Ptolemy II system [32]. TailorMade takes advantage of Ptolemy's capability to mix simulation models to model the behavior of acoustic signals in a continuous domain while modeling the behavior of the computing environment in the discrete event domain. Specifically, TailorMade was used to model the movement and acoustic signature of a vehicle, the propagation of that signal, and the reception and conversion to digital form of that signal with the addition of Gaussian noise at every microphone in the simulated fabric.

TailorMade models the e-textile computing environment by representing each of the computational nodes as well as the communication and power networks on the fabric. The operation of user applications running on a processor is modeled by running some

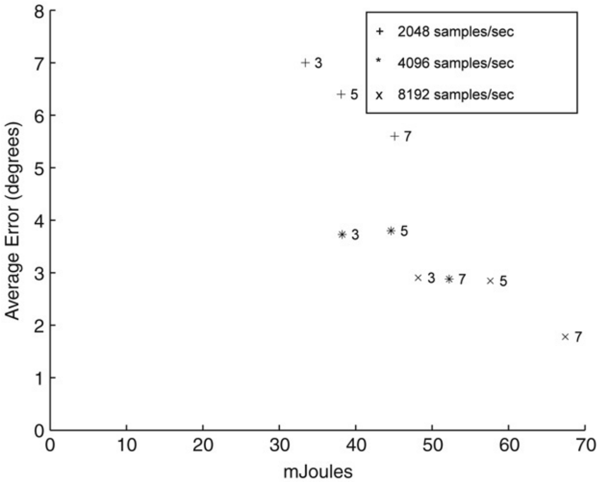

Fig. 13. The effect of the number of microphones and sampling rate on the tradeoff between accuracy and energy consumption. The x-axis gives the energy consumption per direction of arrival computed and and the y-axis gives the average error in degrees for the given number of microphones and sampling rate. Each datapoint is annotated with the number of microphones used.

user application C code inside of a virtual machine actor constructed within the Ptolemy environment. This virtual machine is capable of responding to and creating events with Ptolemy; it does not, however, perform a cycle-accurate simulation of the code's execution. Instead, the actor tracks the amount of time spent in each state of the beamforming algorithm and uses experimental data on power consumption from Table 1 to compute the power consumption estimates. The TailorMade environment is described in more detail in [15]. TailorMade allows a wide range of parameters to be varied, including the movement of the vehicle, the number of microphones, the placement of microphones, and the number of clusters.

The first design decision to be explored is the effect of the sampling rate and number of microphones on accuracy and energy consumption. In this experiment, the energy consumption for computing a single direction of arrival on a single cluster is computed. Regardless of the sampling rate, one-quarter of a second of data is collected and used to compute the direction of arrival. The average of the error in degrees for the computed direction of arrival over a range of vehicle positions for each configuration was tabulated. The results for a range of configurations are given in Fig. 13, showing the tradeoff between error, energy consumption, sampling rate, and number of microphones. These results highlight the effectiveness of selecting a seven microphone cluster in terms of accuracy and energy consumption.

In the second design decision, the effect of the number of clusters and sampling rate on accuracy and energy consumption are explored. This experiment was performed in the same manner as the previous experiment, except that the number of microphones was held constant at seven and the number of clusters was varied. In this case, the position of the vehicle was computed using the direction of arrival computed by each cluster as

Table 3
The average error (degrees) of the computed direction of arrival for a range of spacings between clusters and sampling rates when using a two-cluster system

Cluster spacing (ft)	Sampling rate	Average error (degrees)
16	2048	Inf
16	4096	1.73
16	8192	1.00
24	2048	5.92
24	4096	2.46
24	8192	0.97
32	2048	5.21
32	4096	2.49
32	8192	0.88

described in the preceding sections. When more than two clusters are used, a least-squares method is employed to compute the position. The accuracy of the computed position can be computed using a number of metrics; to make the results comparable to those in Fig. 13, the accuracy of the direction of arrival to the computed position is reported here. The results for a range of configurations are given in Fig. 14. From these results, one can conclude that two clusters is generally the most power efficient choice. This conclusion is subject, however, to two caveats. First, while the operation of two clusters is efficient, it does not allow for any redundancy; if one cluster fails, then the fabric is no longer capable of computing the position of a vehicle. Second, in the cluster configurations explored, the length of the fabric was held constant at twenty-four feet. As the number of clusters increases, the spacing between clusters decreases. As noted previously, however, the accuracy of the computed position is improved by a larger spacing. To illustrate the effect of the spacing on accuracy, a range of cluster spacings are explored in Table 3; note that the closest cluster spacing combined with the lowest sampling rate resulted in an infinite error, because the directions of arrival computed by the two clusters were nearly parallel. In practice, the best choice of the number of clusters will depend on the desired size of the fabric and the required level of fault tolerance.

4.6.3. Comparison to wireless communication

In this section, the same combination of experimental measurement and simulation is used to compare the use of RF communication between clusters. The rationale for this comparison is two-fold: (1) it provides some quantification of the claimed advantages of communication within the textile; and (2) it allows an exploration of an architecture combining the two approaches, dubbed the hybrid architecture. In the hybrid RF-textile architecture, only the intercluster communication is RF-based; the microphone data is still collected through the textile and power must either be distributed through the textile or a battery must be installed within each cluster. The hybrid architecture will be able to sustain intercluster communication even when the fabric between clusters is damaged, but as the results in Table 4 show, this comes with increased energy costs. There are two contributors to the increased energy cost. First, the Bluetooth module, as shown in Table 2, consumes power at a rate roughly comparable to the DSP itself. Second, to maintain

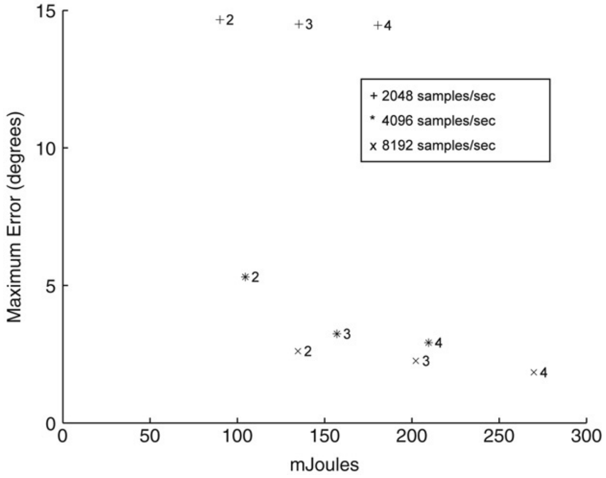

Fig. 14. The effect of the number of clusters and sampling rate on the tradeoff between accuracy and energy consumption. The x-axis gives the energy consumption per direction of arrival computed and the y-axis gives the maximum error in degrees for the given number of clusters and sampling rate. Each datapoint is annotated with the number of clusters used.

Table 4
The energy costs in mJoules per direction of arrival computed for a range of sampling rates and number of clusters for the pure e-textile and hybrid architectures

Architecture	Sampling rate	Two clusters (mJ)	Three clusters (mJ)	Four clusters (mJ)
E-textile	2048	90	136	182
Hybrid	2048	290	437	583
E-textile	4096	105	158	211
Hybrid	4096	305	459	612
E-textile	8192	135	203	271
Hybrid	8192	335	504	672

The number of microphones was held constant at seven.

wireless communication, the Bluetooth module cannot enter a low-power state; even in standby mode, it consumes significant power. The DSP, however, can enter a sleep mode when it is not actively working and can be woken up by external communication through the fabric as described in Section 4.4. Because the Bluetooth module must remain in the relatively power expensive standby mode, it dominates the power budget of the hybrid architecture.

4.6.4. Textile performance interaction

While the flexibility of textiles offers many advantages, including wearability and ease of deployment, it also poses disadvantages for some applications. This is particularly true in the prototype textile in which the beamforming algorithm requires that the spacing between microphones be known; any inaccuracy in the microphone spacing will lead to inaccuracy in the computed line-of-bearing results. If the textile is wrinkled, twisted, or otherwise distorted, then the accuracy of the beamforming results will be adversely affected.[2] In the multi-cluster case, where the location is being computed from the combination of multiple lines-of-bearing, the results depend on an accurate estimate of the distance between the clusters; if the textile is not fully extended, then these distances will not be correct.

This problem is not unique to e-textiles; the majority of sensor systems require knowledge of the location of sensors to construct an accurate depiction of the physical world. One solution to this problem is to precisely place the physical sensors during deployment. For applications in which placing the sensors in specific locations is sufficient, textiles offer some deployment advantages over other approaches. For example, in the beamforming prototype, the problem is reducing to completely unrolling the fabric on a relatively flat surface (as shown in Fig. 12). As another example, consider wearable computing applications, in which the deployment of sensors can be reduced to simply putting on a shirt or pants. To further enhance the precision of sensor placement, the flexibility of the textile can be controlled through the choice of fibers and weave pattern. For example, in traditional textiles, shirt sleeves are often elasticized around the wrists to keep them in place; a similar approach can be used to ensure sensors on an e-textile garment remain in place. Similarly, the choice of stiff fibers can help maintain a desired shape such as that required in the beamforming array.

In some applications, however, it is either undesirable to physically place the sensors, or the sensors may be moving over time. In such situations, the system must be able to determine the location of its sensors and update this information as required. While the solution is often application specific, potential solutions using ultrasound for an e-textile garment are described in [34]. Such an approach could be added to an e-textile beamforming array.

5. E-textile design principles

Given the experience described in this paper with the acoustic beamformer, it is possible to generalize from those experiences to form an initial set of design principles to guide future research endeavors. Perhaps the most important lesson learned during this project has been the need for a flexible architecture upon which a variety of modified and new applications can be constructed. One of the strengths of textiles is that a variety of garments and other products can be assembled from the same bolt of cloth. The architecture and woven textile described in this paper are fairly restrictive in terms of the placement and number of sensors, as well as the use and spacing of clusters and communication. In the first part of this section, we focus on the incorporation of power distribution and communication within the textile. In the second part of this section, we examine issues associated with the architecture.

5.1. Power distribution and communication principles

The goal in this section is to outline a set of design principles that, when followed, will move away from prototypes designed from scratch and move towards re-use of design

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[2] The effect of textile movement on the accuracy of beamforming is investigated in [33].

and materials. We propose the use of insulated conductors embedded through weaving, carrying primarily digital signals. While some prototypes have been successful in using uninsulated conductors, the majority of applications dictate the use of a single-layer textile that may undergo folding and contact between different sections of the textile. For this reason, it is imperative that, as in many electronic applications, the conductive fibers be insulated. Given the choice of insulated conductors, incorporating them via weaving rather than embroidery is a necessity dictated by the inability to use commercially available insulated fibers in an embroidery machine. Embroidery, however, can be useful in placing special features into the fabric such as keypads that use uninsulated wire and the principle of capacitive coupling [2].

The use of digital signals is dictated by the need to share conductors, re-route data through conductors, and use interchangeable parts. The transmission of microphone data in the acoustic beamformer, as well as the sensor data in virtually every e-textile prototype, has been in analog form. An analog approach, however, almost certainly precludes a generic, fault-tolerant architecture. It is quite difficult to detect faults on analog sensor lines and then automatically re-route analog data. Further, the electrical characteristics for each type of analog sensor are different, requiring the receiving processing nodes to be tailored to a specific category of sensor. For example, the signal processing node in the acoustic beamformer is targeted specifically to microphones of a certain type; it is quite efficient in its ability to filter and process data from those microphones, but a board re-design is required if those microphones are exchanged for another type of sensor.

In the prototype, a custom serial communication protocol was used for interprocessor communication because the nature of the noise on the communication lines in the large textile was not known prior to the construction of the prototype. Experiments on the prototype, including observation on an oscilloscope, however, showed well-shaped signals at serial communication speeds exceeding 1 Mbps, far in excess of the speed required in this application.[3] Given this experience, we would rely, in future prototypes, upon the more efficient and widely supported communication standards such as I^2, CAN, and SPI that are often present as peripherals on microprocessors, microcontrollers, and DSPs. On the prototype, these three bus standards could directly replace each of the point-to-point connections, or they could be used to change the communication topology. Unlike the point-to-point scheme used in the prototype, in these bus-based schemes the choice of the specific standard will depend on applications requirements, such as the level of fault-tolerance desired, the complexity of the individual processors selected, the network topology desired (particularly if multiple buses are required), and the physical distances in the prototype.

5.2. Architectural principles

This section gives design principles with the aim of arriving at an architecture that reduces design time and allows the re-use of fabric designs in multiple applications. In addition to re-targeting an architecture, it is important that the architecture be capable of

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[3] More information on digital communication in e-textiles can be found in [16].

Fig. 15. A fabric with a fine-scale weave pattern with conductive fibers that allows for multiple placement points for components.

supporting more than one simultaneous function. The low-level design principles in the previous section facilitate a more general architecture, but also place requirements upon that architecture.

By embedding the conductive fibers via weaving, the number and location of paths for data and power are fixed. In the beamformer textile, a repeated pattern was woven, where the pattern represented a single cluster. Because configuring yarns in a loom for a new weave pattern is expensive due to labor costs, we propose the use of more generic patterns on a smaller scale that will allow the use of a single weave design, and resulting bolts of fabric, for multiple applications. Such patterns involve more conductive elements at more locations, but can allow many potential sensor locations as well as multiple paths for fault-tolerant communication and power distribution. An example of such a weave pattern is given in Fig. 15, in which four conductive fibers are woven in a grid pattern throughout the fabric in a regular four-inch grid.

The need for digital communication implies that every sensor node must be capable of communicating its sensor signal in digital form. Towards this end, we propose an architecture that relies on extremely small and low-power microcontrollers co-located with each sensor. Such microcontrollers are commonly used for converting and communicating sensor data in other applications. Because these microcontrollers will be used throughout the fabric and we wish to maintain essential textile properties, they must be as small as possible. Rather than relying on Moore's Law to provide increased computing power, we expect this class of microcontrollers in the architecture to rely on Moore's Law to provide the same computing power at decreased size and energy consumption.

The final design principle for the architecture and generic computational nodes communicating over standard communication buses is facilitated by the use of uniform digital communication at the lower levels. By avoiding the communication of analog sensor data, it is possible to use generic computational nodes rather than the specialized computational module used in the acoustic beamforming fabric. Generic computational nodes can be targeted to a number of tasks, including the processing requirements of simultaneous tasks. In addition, the use of digital communication and generic computational nodes allows for the use of industry standard communication buses such as

I2C that are widely available on a range of microcontrollers, microprocessors, and digital signal processors. The acoustic beamformer communicated via a nonstandard format that was quite well-suited to its needs, but would likely be insufficient to support a wider range of tasks. A single I2C bus, or other standard format, is unlikely to fully address the need for generic, fault-tolerant e-textile communication [4], but building upon this structure allows for us to take advantage of a standard feature in many processors [35].

6. Conclusion

This paper presented a discussion of the design decisions and experiences associated with building a prototype large-scale electronic textile. This prototype e-textile, an acoustic beamforming array, was analyzed for its energy consumption, its accuracy, and the design decisions associated with the tradeoff between the two metrics. Based on the experiences, a set of design principles was distilled with the aim of developing architectures for e-textiles that can be targeted to multiple applications.

There are many avenues for future research to be pursued. At the physical level, there exists a need for robust connectors for attaching electronic components to insulated conductive elements in the fabric. At a higher level, the communication schemes in this paper were relatively simple. It should be possible to derive a communication architecture that is energy-efficient, fault-tolerant, and can serve a wide range of e-textile applications. Preliminary discussions of such architectures are given in [35], but more work is required.

As with any new architecture, effective programming is a concern. As the architectures for e-textiles become more focused, it will become important to move beyond programming individual processors to programming an application for the textile as a whole. Finally, as noted in [21], there is a significant need for middleware to provide common services such as communication and self-organization to applications.

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References

[1] S. Park, C. Gopalsamy, R. Rajamanickam, S. Jayaraman, The wearable motherboard: An information infrastructure or sensate liner for medical applications, in: Studies in Health Technology and Informatics, vol. 62, IOS Press, 1999, pp. 252–258.

[2] E. Post, M. Orth, P. Russo, N. Gershenfeld, E-broidery design and fabrication of textile-based computing, IBM Systems Journal 39 (3–4) (2000).

[3] D. Marculescu, R. Marculescu, N. Zamora, P. Stanley-Marbell, P. Khosla, S. Park, S. Jayaraman, S. Jung, C. Lauterbach, W. Weber, T. Kirstein, D. Cottet, J. Grzyb, G. Troester, M. Jones, T. Martin, Z. Nakad, Electronic textiles: A platform for pervasive computing, Proceedings of the IEEE 91 (2003) 1995–2018.

[4] Z. Nakad, M. Jones, T. Martin, Communications in electronic textile systems, in: Proceedings of the 2003 International Conference on Communications in Computing, CIC 2003, 2003, pp. 37–43.

[5] M. Weiser, The computer for the twenty-first century, Scientific American 265 (3) (1991) 94–104. September.

[6] K. Van Laerhoven, O. Cakmakci, What shall we teach our pants? in: Proceedings of the Fourth International Symposium on Wearable Computing, ISWC 2000, October 2000, pp. 77–83.

[7] D. Lehn, C. Neely, K. Schoonover, T. Martin, M. Jones, e-TAGs: e-Textile Attached Gadgets, in: Proceedings of Communication Networks and Distributed Systems: Modeling and Simulation, January 2004.

[8] M. Jones, T. Martin, Z. Nakad, R. Shenoy, T. Sheikh, D. Lehn, J. Edmison, Analyzing the use of e-textiles to improve application performance, in: Proceedings of the IEEE Vehicular Technology Conference 2003, Symposium on Wireless Ad hoc, Sensor, and Wearable Networks, VTC 2003, October 2003.

[9] Eleksen, Ltd., 2004. Available online: http://www.eleksen.com.

[10] J. Edmison, M. Jones, Z. Nakad, T. Martin, Using piezoelectric materials for wearable electronic textiles, in: Proceedings of the Sixth International Symposium on Wearable Computing, ISWC 2002, 2002, pp. 41–48.

[11] E. Lind, R. Eisler, G. Burghart, S. Jayaraman, R. Rajamanickam, T. McKee, A sensate liner for personnel monitoring applications, in: Digest of Papers of the First International Symposium on Wearable Computing, ISWC 1997, 1997, pp. 98–105.

[12] P. Grossman, The lifeshirt: A multifunctional ambulatory system that monitors health, disease, and medical intervention in the real world, in: International Workshop on New Generation of Wearable Systems for eHealth, December 2003, pp. 73–80.

[13] M. Satyanarayanan, Pervasive computing: Visions and challenges, IEEE Personal Communications 8 (4) (2001) 10–17.

[14] J. Farringdon, A. Moore, N. Tilbury, J.J. Church, P. Biemond, Wearable sensor badge and sensor jacket for context awareness, in: Proceedings of the Third International Symposium on Wearable Computing, ISWC 1999, October 1999, pp. 107–113.

[15] T. Martin, M. Jones, J. Edmison, R. Shenoy, Towards a design framework for wearable electronic textiles, in: Proceedings of the Seventh International Symposium on Wearable Computing, ISWC 2003, October 2003, pp. 190–199.

[16] D. Cottet, J. Gryzb, T. Kirstein, G. Troster, Electrical characterization of textile transmission lines, IEEE Transactions on Advanced Packaging 25 (2) (2003) 182–190.

[17] S. Jung, C. Lauterbach, W. Weber, Integrated microelectronics for smart textiles, in: Workshop on Modeling, Analysis, and Middleware Support for Electronic Textiles, MAMSET 2002, October 2002, pp. 3–8.

[18] P. Wilson, C. Carey, B. Farrell, J. Gassner, P. Haugsjaa, M. Pan, J. Teverovsky, C. Winterhalter, J. Fairneny, Electro-optic fabrics for the warrior of the 21st century, Soldier Systems Center-Natick, Tech. Rep. TR-99/030L, July 1999.

[19] G. Spinks, B. Kim, G. Wallace, R. John, Electroformation of conductive polymers in a hydrogel support matrix, Polymer 41 (2000) 1783–1790.

[20] Measurement Specialties, Inc., Piezo technical manual, piezoelectric film properties, 2002. Available online: http://www.msiusa.com/PART1-INT.pdf.

[21] M. Jones, T. Martin, Z. Nakad, A service backplane for e-textile applications, in: Workshop on Modeling, Analysis, and Middleware Support for Electronic Textiles, MAMSET 2002, October 2002, pp. 15–22.

[22] P. Stanley-Marbell, D. Marculescu, R. Marculescu, P. Khosla, Modeling, analysis and self-management of electronic textiles, IEEE Transactions on Computers 52 (2003) 996–1010.

[23] T. Martin, M. Jones, J. Edmison, T. Sheikh, Z. Nakad, Modeling and Simulating Electronic Textile Applications, in: ACM SIGPLAN/SIGBED 2004 Conference on Languages, Compilers, and Tools for Embedded Systems, June 2004.

[24] P. Tortora, B. Collier, Understanding Textiles, Prentice Hall, 1997.

[25] M. Goutmann, Fabric Structure: Basic Weave Design, Philadelphia College of Textiles and Science, 1994.

[26] A. Bonfiglio, D.D. Rossi, T. Kirstein, I. Locher, F. Mameli, R. Paradiso, G. Vozzi, A feasibility study of yarns and fibers with annexed electronic functions: The Arianne project, in: International Workshop on New Generation of Wearable Systems for eHealth, December 2003, pp. 258–264.

[27] Bekintex, 2003. Available online: http://www.bekintex.com.

[28] J.R.A. Riley, S. Thakkar, J. Czarnaski, B. Schott, Power-aware acoustic beamforming, in: Proceedings of the Fifth International Military Sensing Symposium, December 2002.

[29] Analog Devices, DSP Microcomputer, ADSP-2188M, 2003. Available online: http://www.analog.com/productSelection/pdf/ADSP-2188M_0.pdf.

[30] Agilent Technologies, Inc., Agilent 3458a multimeter data sheet, 2002. Available online: http://cp.literature.agilent.com/litweb/pdf/5965-4791E.pdf.

[31] Teleca Comtec AB, Bluetooth development kit information sheet, 2002. Available online: http://www.comtec.teleca.se/info_development.asp.

[32] Ptolemy Project, Heterogeneous modeling and design, 2003. Available online: http://ptolemy.eecs.berkeley.edu.

[33] R. Shenoy, Design of e-textiles for acoustic applications, Master’s Thesis, Bradley Department of Electrical and Computing Engineering, Virginia Tech, 2003.

[34] C. Einsmann, M. Quirk, B. Muzal, B. Venkatramani, T. Martin, M. Jones, Modeling a wearable full-body motion capture system, in: International Symposium on Wearable Computers, October 2005, pp. 144–151.

[35] Z. Nakad, M. Jones, T. Martin, Fault tolerant networks for electronic textiles, in: Proceedings of the 2004 International Conference on Communications in Computing, CIC 2004, June 2004, pp. 100–106.