A Service Backplane for E-Textile Applications

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Abstract. *E-textile technology is rapidly progressing, allowing for the development of truly wearable computers as well as very large-scale computing textiles. Efficient development of applications on e-textiles will require significant software services support. This paper analyzes two representative e-textile applications for their software service requirements. Based on this analysis, three services particularly affected by the e-textile design space—fault tolerance, physical configuration, and processing element selection--are described in detail. Each service is considered at the application level, implementation level, and the hardware support level.*

1 Introduction

E-textile technology holds out the promise of truly wearable computers as well as inexpensive large-scale computational devices. To achieve these goals, e-textiles combine high-volume, low-cost textile manufacturing capability with discrete electronics and novel fiber technologies. Industrial weaving machines capable of inserting thousands of meters per minute of weft yarn can efficiently produce large volumes of complex woven textiles while individually controlling the position of every fiber in the design [1]. New fibers are being created for inclusion in e-textiles, including battery fibers, conductive fibers, and mechanically active fibers [2]. Methods are being developed for attaching discrete components to e-textiles, including processors, microphones, and speakers [cite STRETCH & NC State].

Two broad categories of e-textile applications are envisioned, wearable and large-scale non-wearable. Many specific applications in the field of wearable computing have been envisioned and realized, though most suffer bulky form factors [cite some applications]. In the new field of large-scale non-wearable e-textiles, applications include large-scale acoustic beamforming arrays [STRETCH], self-steering parafoils [Draper], and intelligent, inflatable decoys [DARPA]. Both categories of e-textile applications share three common design goals: low-cost, durable, and long-running.

1. **Low-cost** dictates the use of inexpensive, COTS electronic components and yarns as well as the design of weaves/architectures that are manufacturable in current or slightly modified textile production systems.
2. **Durable** dictates that the system must tolerate faults, both permanent and transient, that are inherent in the manufacture and use of the device. In addition, there is an expectation that individual components may not be repairable and that system functionality should gracefully decline as components fail.
3. **Long-Running** dictates that the system must manage power consumption in an application-aware fashion to minimize the need for bulky batteries and/or external power recharge. Power scavenging and distributed power management are essential.

In addition to these constraints, wearable applications should have a comfortable, flexible, and unobtrusive form factor if they are to be adopted by a large number of users, while non-wearable applications should be able to operate with hundreds to thousands of components on fabrics that are tens of meters in length. By their nature, wearable e-textiles have a more complex form factor and are in motion more often than their non-wearable counterparts.

E-textiles are in a transition from a few isolated computing and sensing elements on the fabric to a network of many computing and sensing elements distributed over the entire textile. Compared to previous work in distributed systems, e-textiles will be physically spread over a relatively smaller space, but will have a greater dependence on physical locality of computation, lower bandwidth for communication, and tighter constraints on energy usage. Thus e-textiles represent an extreme corner of the computing design space. Based on this design space, this paper seeks to rationalize a set of services that form a "backplane" for a wide array of e-textile applications, include wearable and non-wearable applications. In Section 2, two representative applications, one wearable and one non-wearable, are analyzed to identify common services. Section 3 describes the backplane services in detail, as well as methods for implementing these services on an e-textile. Conclusions are drawn and work-in-progress is described in Section 4.

2 Application Case Studies

This section describes two e-textile applications and identifies their common software service needs. In the category of wearable computing, a garment that provides the user with precise location information within a building is analyzed. A large-scale, non-wearable acoustic beamforming array is analyzed later in the section. Both textiles are woven as opposed to alternative textile manufacturing techniques such as knitting, embroidering, or non-woven technologies. Woven textiles allow for stable fabrics with a high degree of precision, but impose directional limitations on the fabric, as shown in Figure 1, that have implications for communication within the textile. Virtually all woven e-textiles are expected to use the new fiber batteries and solar cells under development [cite]. This will lead to highly distributed, redundant power supplies for e-textiles in which some parts of the textile have more remaining power than others.

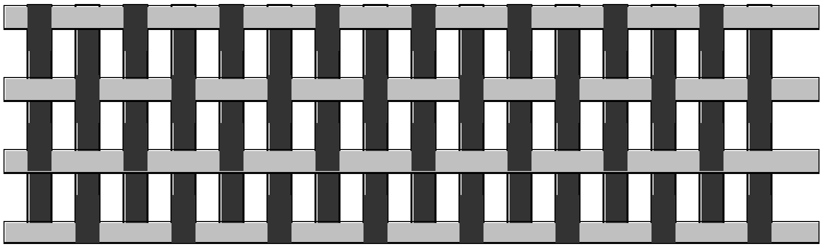

Figure 1: The dark lines indicate the warp and the light lines indicate the wuft in a traditional weaving pattern. The warp lines are unbroken, but their position above or below the wuft may be changed. Each wuft line can be different from the previous one.

These two applications were chosen as reasonably representative of the nascent e-textile technology in that each combines a range of sensors, reasonable computing requirements, and a small number of actuators. Both applications benefit from the wide distribution and large quantity of sensors that can be distributed across the textile.

2.1 Mapper Garment

The mapper garment tracks the motion of the user through a structure by monitoring the user's body position, the user's movement, and the distance of the user from surrounding obstacles. Such a garment would allow users to be given directions in a building, maintenance workers to be automatically shown blueprints for their current room, or users to automatically map existing structures [4]. The user's body position is measured by a set of piezoelectric strips woven into the clothing; by measuring the deformation along tens of strips, the physical configuration of the user's body can be detected [cite wearable paper]. The user's activity, such as walking up stairs, climbing a ladder, walking on a flat surface, can be be detected [4][5]. The user's movement rate can be measured by a small set of discrete accelerometers as well as a digital compass attached to the garment. The distance from obstacles is measured using ultrasonic signals. An array of approximately ten ultrasonic transmitters, also piezoelectric strips, are distributed around the garment to periodically send signals in each direction; a similar number of receiver piezoelectric strips are used to detect the reflected signals, allowing time-of-flight to be measured.

The primary challenge in this application is interfacing to a large number of sensors and actuators in a reliable fashion. Simply attaching the leads of every sensor/actuator to a single processing unit and power supply would not meet the design goal of a durable e-textile. In the event of a tear in the fabric, single leads running to one collection point could lead to significant rather than graceful degradation in performance; in addition, the potentially long leads required would cause degradation in analog signal quality unless significant amplification is applied leading to larger power consumption. The garment needs multiple points at which analog data is converted to digital data; these conversion units, likely in the microcontroller or DSP class, would need to communicate within a fault tolerant network. The sample rate at each conversion point is very low (10/sec-100/sec) for the body position sensors and moderate (100,000/sec) for the occasional ultrasonic reception. Once the data has been converted to a digital format, low power data transmission and coding techniques can be applied.

By carefully managing which sensors and processing units are active, the power requirements of the system can be reduced. For example, the computation of body position can be accomplished with varying numbers of sensors depending on the number and type of positions amongst which the garment is trying to distinguish [cite]. By selecting sensors from around the garment according to local available power, power use can be balanced across the e-textile.

When determining the location of a wall, the garment must activate a transmitter in the direction desired and then sample a receiver for the return signal. This will accurately compute the distance, but gives no information on the *direction* in which it is located. To compute direction, the location of the transmitter on the body, the position of that part of the body relative to the torso, and the direction in which the user's torso is pointing must be known. The location of the transmitter should be known from the manufacturing process and the digital compass can provide the torso direction. A number of techniques are available for determining the location of one part of the e-textile with respect to other parts of the e-textile; in this garment, the body position is available and acoustic beamforming could be used to determine the location of all of the ultrasonic transceiver with respect to one another.

To accurately compute body position requires the analysis of samples from a large set of sensors that have been collected at several processing elements. Due to its nature [cite], the analysis is best done at a single processing element. To initialize the collection of the data, the processing element would send out a query to selected elements such as "give me your current reading" or "give me your reading every 100ms." In both cases, some timestamp should be applied to both the query and the replies, though high accuracy is not required in this particular application.

2.2 Beamforming Array

The beamforming array textile gathers data from a large array of acoustic sensors and analyzes this data to determine the direction of an acoustic emitter (e.g., a moving vehicle or a human voice). Through the use of acoustic beamforming algorithms [cite], a set of three acoustic sensors can identify the direction of a single emitter if the sensors and the emitter are all in the same plane. Identifying the direction of multiple emitters and/or working in three dimensions requires data from more acoustic sensors. Further, given noise and potential miscalibrations in the acoustic data, the use of redundant acoustic sensors is advisable. As shown in Figure 2, if the fabric is large enough, then not only the direction, but also the location of an emitter can be found. Like the mapper garment, for reasons of robustness, the large number of sensors are not all handled by one conversion/processing node; the fabric is sprinkled with many communicating processing nodes as shown in Figure 2.

It is important to note that each acoustic sensor must know its location precisely with respect to the other sensors; small errors in sensor location result in increasingly larger errors as the distance to the emitter increases. Although this is not a wearable textile, it is flexible and thus subject to movement; at a minimum, the initial position of each acoustic sensor must be computed. In contrast to the mapper garment, the positions of each sensor must be known quite accurately. To accomplish this, the textile is augmented with speakers that are physically co-located with a subset of the acoustic sensors; by systematically activating the speakers, the distances between the microphones can be determined. Once enough distances are known, the relative positions of all of the microphones can be computed.

The frequency, direction, and distance of a potential target all affect the optimal selection of a subset of sensors on which to perform beamforming. Because beamforming is fairly computationally demanding, it would be wasteful of resources, including power, to collect and analyze the data from the entire set of acoustic sensors. An efficient strategy, therefore, is to have a small active set of sensors look for emitters while the rest of the sensors sleep to conserve power. Upon the tentative identification of an emitter's characteristics along with an assessment of remaining power at processing nodes, an optimal set of sensors can be activated.

Once a set of sensors is selected, the time series data from those sensors must be collected at a single processor where the beamforming algorithm is to be run. If multiple beams are formed (as in Figure 2), then the direction and intensity data must be combined at a single node; this is much less demanding of communication resources than the exchange of time series data. It is expected that some nodes along potential routes may be asleep, others out of power, and some broken; routes must be found in spite of these drawbacks. In addition, time series data from different nodes must be synchronized; small errors in time can lead to large errors in the computed results.

3 Backplane Services

Analysis of the application leads to the identification of the need for three types of services that are required by both applications and likely to be required by many other e-textiles:

- Fault-tolerant, low-power distributed digital communication
- Computation of the physical configuration of the textile
- Selection of processing elements for tasks based on location, capability, and available energy

Clearly other services, such as distributed clock synchronization, were identified explicitly or implicitly in the case studies. This discussion, however, focuses on those services that have aspects that are particularly challenging in the context of e-textiles. Each of these services requires both hardware and software support. These services are described in the following subsections, where the nature of the service provided is described, along with implementation issues specific to e-textiles.

3.1 Communication

As the case study application analysis shows, the processing elements in the textile require low-power, fault-tolerant communication. At the application level, the addressing scheme used in e-textiles for most applications should resemble schemes proposed for distributed sensor networks [cites] more than it resembles TCP/IP. In the garment mapper, the natural method of addressing an ultrasonic transmitter is to address a location on the user's body, e.g., "a sensor on the left arm." In the beamforming application, the sensors are selected based on their physical location, e.g., "a time series from a sensor approximately five feet to my left."

The routing of data in an e-textile may be a completely unique networking situation. The underlying physical connections (wires) are connected in a two-dimensional interconnection pattern that, absent faults, does not change. This two-dimensional structure is embedded in three-dimensional space, and because of the flexibility of the fabric, that embedding will change over time. Thus, the route from node A to node B does not change, absent faults in the network. The node "five feet to your left" will change, however, as the fabric changes shape. Note that in the case of wearables, the embedding relative to the body is more or less constant; the sleeve of your shirt generally stays on your arm in the same orientation. The embedding of a non-wearable is subject to more change. Achieving "node A to node B" connectivity, and to some extent addressing parts of the body, is a relatively simple task that can rely on traditional networking approaches. Providing the application programmer with a service in three-dimensional space that efficiently uses the underlying connectivity is more challenging.

The proposed service must be robust not only to permanent and transient faults, but also tolerant of sleeping nodes. The route that a message travels must, obviously, be adjusted to account for faults in the network. Message routing should avoid waking intermediate sleeping nodes/switches, but when necessary, must be capable of awakening nodes. For example, the beamforming array is, under normal operating conditions, expected to run the beamforming algorithm two percent of the time, and even during

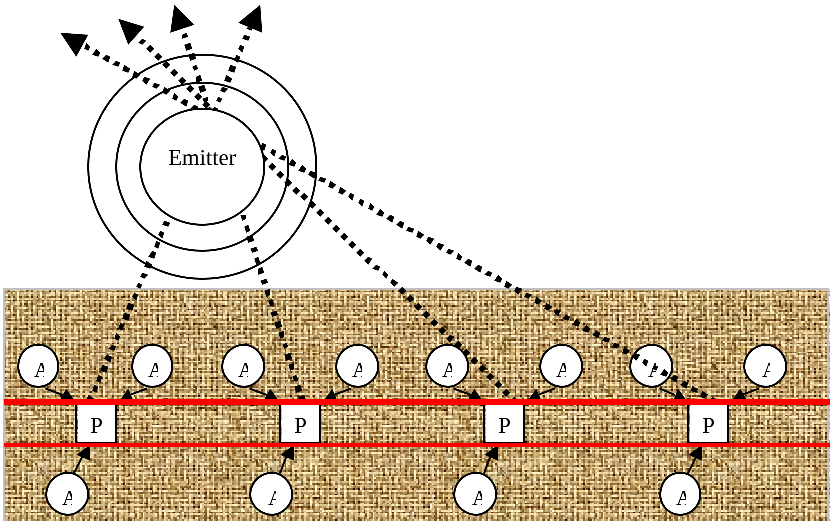

Figure 2: The e-textile contains four processor nodes, where each processor manages a cluster of microphones. Each cluster can find the direction of the emitter; by combining the beams from each cluster, the location of the emitter can be determined. The processors in this textile are connected by a pair of communication lines.

that two percent, only a subset of the processors may be active. If nodes are constant activated to route messages to other nodes, then unnecessary energy expenditures will be made (see Figure 3); if nodes cannot be easily awakened, then messages will be delayed or not delivered (see Figure 3).

While allowing for considerable latitude in the design of the textile, this service does place some demands on the underlying system. The physical interconnect must provide alternative routes between every pair of nodes. The routing mechanism must be able to remotely awaken sleeping nodes/switches. Finally, the routing mechanism must have access to the two-dimensional topology of the system as well as the three-dimensional embedding (at least locally).

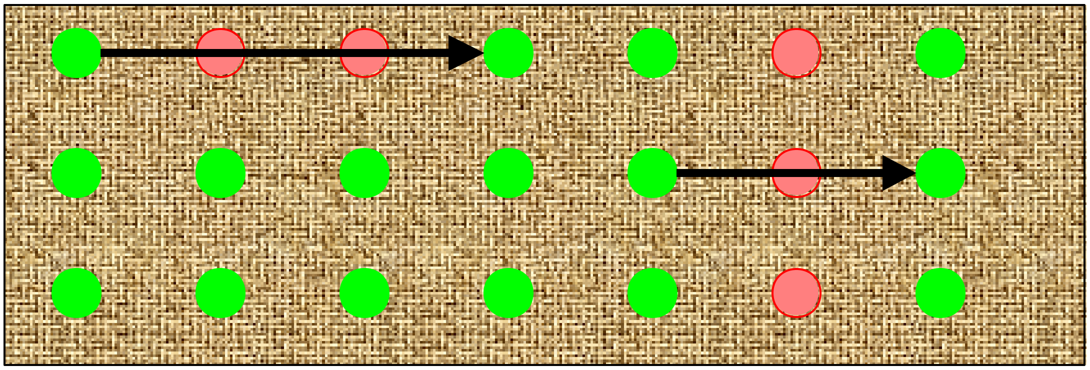

Figure 3: The route on the upper left, from one active node to another, will wake two sleeping nodes (vertical lines) unless an alternate route is found. The message on the right must awaken at least one node to succeed. Sleeping nodes are shown in red stripes; awake nodes are shown in green.(May want to change this color scheme as it does not show in hardcopy.)

3.2 Physical Configuration Information

From Section 3.1, it is clear that the implementation of a high-level API for communication requires that the routing service know the embedding of the e-textile in three-space (or at least on the user's body). To operate effectively, e-textile applications must also have knowledge of this embedding; it is not enough to merely address messages by location. For example, the mapper garment must know the shape of the textile to infer the activity of the user; it must also know which ultrasonic sensors are in a position to sense a particular wall. Note that the first requirement is for the shape of the textile relative to itself, while the second requirement is for the shape of the textile relative to its environment.

The proposed service will respond to several query types from a node.

- "Where am I with respect to the center of the textile?"
- "Where am I in absolute three-space?"
- "Where am I on the two-dimensional fabric?"
- "Where am I on the user's body?"

Note that not all of these queries will be available on every system due to limitations of the e-textile (e.g., no GPS or GPS-surrogate capability) or a lack of need in a particular application.

Two general types of distributed sensor systems are envisioned for implementing this capability. The first type of sensor system employs a set of sensors distributed across the fabric to sense bending motion in the textile. The piezoelectric strips of the mapper garment are an example of one such system. The number of sensors required will be larger for more flexible textiles because of their large number of degrees of freedom in their motion. The second type of sensor system employs acoustic (or other wavelengths) transceivers to determine the distances between pairs of sensors. Once enough distances are known, the relative position of each sensor can be found. The beamforming array employs an example of this type of system. In addition to these sources of relative position, questions of location in absolute space must rely on additional information. Sensors on clothing could be initialized with their position on the garment. An e-textile could be augmented with a GPS unit and/or a digital compass; in the case of the mapper garment, the application itself may provide some of that functionality.

3.3 Processing element selection

As with any efficient distributed system, a de-centralized service for assigning tasks must be implemented. Two features of e-textiles push the requirements on this service into an extreme of the distributed system design space. First, the sensors and actuators available to processors on the textile each have different capabilities; even if every sensor/actuators is of the same type, they are located in different parts of the fabric and, therefore, provide different functions. By design, some level of redundancy does exist to allow the e-textile to survive faults. The second feature is the locally distributed power on e-textile systems. Unlike existing low-power systems that have a centralized power source, batteries and power scavengers are distributed across the fabric, giving each processor access to local power. Because the local power supplies will be depleted and recharged at different rates, the task assignment service must predict and balance remaining power across the textile.

The API for task assignment will provide for two basic interactions, advertising task capabilities and advertising task needs. Applications will advertise the capability to perform application level functions such as “sense bending at the knee,” “acquire a time series in the three meters northeast of center,” or “move the west edge of the textile.” Advertising task needs simply generates a task in search of a node with the corresponding capability. In addition to application-level capabilities/needs, the implementation will automatically exchange information on basic capabilities such as available CPU power [Do you mean performance instead of power?], memory, bandwidth, and available power.

4 Summary and Future Work

This paper analyzed two applications under development at Virginia Tech. Based on this analysis, as well as a consideration of e-textiles as a whole, a set of services was identified that is common to many e-textile applications. Three services that have aspects unique to e-textiles were identified and discussed in detail.

Implementation of these services on e-textiles will require the development of new or modified algorithms for routing, location determination, and task assignment. The implementation of these services will allow for practical performance results to be gathered. Assessing the quality of this and other implementations will require the establishment of benchmarks appropriate for e-textiles.

5 References

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