Communications in Electronic Textile Systems

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Abstract - *Electronic textiles (e-textiles) are emerging as a novel method for constructing electronic systems in wearable and large area applications. This new type of processing system merges textile and electronic technologies. This paper studies the communication requirements between the computing and sensing elements of an e-textile. This communication is studied through the construction of a prototype as well as through modeling and simulation. A new algorithm based on token grid schemes is presented that takes advantage of the e-textile physical configuration.*

Keywords: e-textiles, interconnection networks, fault tolerance, embedded systems

1- Introduction

The textile industry has reached a highly resourceful stage with the different types and qualities of fabrics that can be manufactured. The fabrication process is fully automated and can be controlled to the lowest level, down to each cross of warp and weft. This automation and control offer a cost-effective means of manufacturing fabrics to be used in conjunction with electronics to form the basis for a new type of processing system known as computational fabrics or electronic textiles (e-textiles). Fabrics exist in every aspect of our daily life. This abundant presence provides an excellent backplane for the ubiquitous deployment of electronics.

E-Textiles are envisioned to be useful for applications in human monitoring, wearable computing, and large area sensor networks. Various examples and techniques for creation of e-textile systems are introduced in [1][2]. Fiber-form components offer intrinsic integration into textiles for added concealment and comfort; such fiber components include batteries [3] and acoustic sensors [4]. Piezo-electric material [4] was used in [5] to sense the movement of the fingers while being integrated in a glove. The Georgia Tech Wearable Motherboard (GTWM) [6] is to be used in a combat situation to assess the seriousness of a soldier's wound and communicate this data. The interconnections in this fabric will determine the location of a bullet penetration. The GTWM can be used as a PAN (personal area network) where the devices carried by the user can interact and share data [6].

Communication between components within the fabric presents several challenges and opportunities that place such communication at an extreme point of the design space. While inherently strong and flexible, e-textiles are going to be subject to a large number of manufacturing flaws as well as tears and abrasions during normal use. Unlike printed circuit boards or VLSI chips, it is not acceptable to throw away a shirt or discard 99 out of 100 bolts of fabric due to flaws. Such an approach would result in an unacceptable increase in costs. It is therefore necessary that the communication scheme be able to configure around permanent and transient faults.

The sensor algorithms that run on e-textiles, for example the acoustic beamforming algorithm discussed in [7], require information from sensors at specific physical locations, yet the flexibility of fabric means that the relative and absolute locations of elements on the fabric will change. Given this, the communication scheme must support location-specific rather than node-specific communication and addressing [8]. Note that the implementation should take advantage of the fact that the physical connections on the fabric are inherently a two-dimensional grid that, absent faults, does not change even as the locations of elements change. Finally, stand-alone e-textiles must be power-efficient, requiring computational elements to sleep whenever possible. Communication must account for the cost of activating and routing around such nodes.

To investigate these issues, an e-textile prototype, an acoustic beamformer, has been constructed in the Configurable Computing Lab in the Electrical and Computer Engineering Department at Virginia Tech. This system is able to determine the position of a large vehicle using an acoustic beamforming algorithm adapted from [7]. Four stand-alone beamforming clusters co-exist on this fabric; the separate results are computed and communicated to the other clusters in the system for a unified, more accurate result.

Communication between components within the e-textile will be discussed in Section 2. The physical prototype and the simulation environment will be examined in sections 3 and 4 respectively. Section 5 will report results from prototype measurements and simulation. Section 6 will conclude the work and show future focus.

2- Communication

This section will focus on the communication issues in an e-textile system. The communication between the different components on an e-textile will depend on the level of complexity of these components. Different components can exist in such a system, including sensors, actuators, and processing nodes.

The fabric implementation offers a set of novel issues different from regular systems. The relative distance between sensors and processing nodes is variable and this variation can render a sensor useless to a specific node at a given time or extremely useful at another (line of sight detection for example).

2-1 Node - Sensor Communication

Node to sensor communication depends on two factors: the level of sophistication of the sensor and the distance between the processor and the sensor. As an example of the former, a microphone sends it values at all times. A smarter sensor would provide its data when queried and go into a sleeping mode between requests. On the other hand, a component can be in range to sense or communicate, or far enough to be dormant. A sensor that is 10 cm away at a specific point in time is not guaranteed to be there if the textile changes shape. This raises the need for distance finding algorithms, also needed for node-to-node communication. The distance-finding algorithms are implemented as a service in the e-textile architecture to allow a node to query components for their relative locations [5]. Acoustic sensors for example, will use a time of flight algorithm to determine their relative location based on an acoustic signal reception. A processing node can be augmented with a microphone at a fixed location to determine its location.

2-2 Token Grid Network

Separate processing nodes in the system need to communicate. The manufacturing faults and tears in the fabric expected in e-textile applications require a fault tolerant interconnection network. The low-power consumption necessary for e-textiles requires processing nodes to enter into a dormant state to conserve power; the communication protocol should operate with "sleeping" nodes, by treating them as failed nodes, and be able to re-establish communication when they leave the dormant state. There should also be a way to wake up such nodes when need arises.

The Token Grid network presented in [9][10] will be modified for use as the interconnection network. Other types of networks were examined for feasibility, but do not necessarily map well to e-textiles. For example, in an e-textile system the number of nodes to be connected is not known *a priori* and that number is expected to change throughout the lifetime of the system. The node degree increases linearly with an increase in the dimension of a hypercube [11]; this poor scalability factor renders architectures similar to the hypercube unsuitable for e-textiles. Tree-type architectures rely heavily on specific nodes for connections between different branches, which does not map well to the faulty environments of e-textile applications. The scalability and fault-tolerance of the token grid are the primary attractive features. A token traversing the network can be used to keep information about the topology as well as the current state of the nodes, another benefit of the token grid.

Each node in the token grid is connected to two token rings. Figure 1 shows a schematic of such a grid with four row rings and four column rings. This architecture offers a significant advantage in throughput as compared to common rings or bus networks. The throughput of this network architecture increases with the number of nodes. This increase in throughput is a significant benefit in systems for which the number of nodes on the grid is not known. This physical aspect of this architecture maps well to the inherent X-Y nature of a weave.

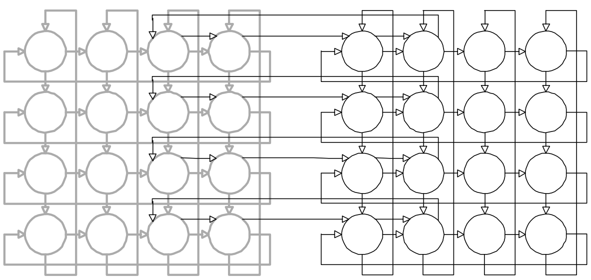
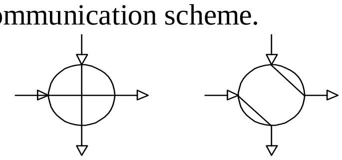


Figure 1 A Token Grid with four rows and four columns is drawn in gray (adapted from Figure 1 [9]). The new grid architecture has an added “transverse” dimension (gray and black grids).

The network interface of each node on this network has two configurations as seen in Figure 2. In the DR (Double Ring) configuration (Figure 2-a), the rings converging at this node are separate. In the SR (Single Ring) configuration, the rings are merged and operate as a single ring. Special tokens are released in such a situation as is explained later in more detail. A scheme that offers a slowly degrading performance upon failure while keeping full connectivity in the network is presented in [10]. An e-textile operating in faulty conditions necessitates the use of fault tolerant schemes. Similar low-level switching techniques were used in VLSI array processors [12], but our approach is for a more general communication scheme.



(a) Double Ring (b) Single Ring

Figure 2 Communication through a node can be configured as a Double Ring or a Single Ring (adapted from Figure 2 [9]).

2-3 Variation to the Token Grid

Communication between the clusters will be controlled in a scheme similar to the token grid. A new dimension, shown in Figure 1, was added to the grid because the number of nodes in one ring cannot be increased indefinitely. This is dictated by limitations on the fabric size, especially in the width direction. Other restrictions are based on the maximum delay allowed for a packet traversing a ring. This increase adds to the ability of the system to support large numbers of nodes. More grids can be added in the horizontal direction when needed to the grids in Figure 1. Some nodes will get duplicated direct connections, and more indirect routes are available to increase fault tolerance. The scalability, fault tolerance, dynamic configuration, and operation in rugged environments of e-textile systems pushed the addition of this extra dimension. The number of network interfaces (inputs and outputs) of each node in the new grid, the textile token grid, must be increased from two (token grid) to three.

Another extension is the addition of a sleeping ability to each node. This adds to the power efficiency of the system but also to the complexity of sending, receiving, and routing data. The original token grid took care of the channel faults by a scheme that caused the full throughput to decrease gradually while maintaining full connectivity. The textile token grid should be able to keep full network connectivity with node failures and channel failures as well. The token in the new network has a more complex job than its predecessor. The token will be used to get control over the ring to enable transmission as in the original version. It will be used to transfer information about the number of nodes on the ring it is traversing as well as the ID of the master of the token. The token will also hold information about which nodes are awake or asleep. This information will be used to determine the path to be taken by the transmitted data and the token as it traverses the ring. The token will also indicate which sleeping nodes are to be woken up. A node that needs the specific sleeping receiver to wake up adds this information to the token. Merger requests will be added to the new token by nodes that need to send outside their direct connections. This information is then processed in the node that will merge. When the circumstances allow (all the respective tokens are captured) the node will go to the merged state and the node that requested the merge will send the packet.

The Token Grid represents low-level hardware addressing, where the connection is between Node (1,2,3) and Node (1,0,3); the numbers represent the different rings a node belongs to. The application level addressing will use the communication services discussed in [8]; communication with the node 10 cm to the right, and 10 cm down will be translated to the specific ring IDs with the use of the location queries.

3- Hardware Implementation

A computational fabric serving as an acoustic array capable of determining location and direction of motion of a vehicle while tolerating faults will be used as an example system to support the concepts presented earlier. This section will study the system's specific aspects.

The implemented system receives acoustic data from several microphones, process this data, determine the direction, and communicate this data. Long running times in potentially hostile territory require the implementation of a fault-tolerant scheme. The system will be augmented with extra sensors, seven microphones, only three of which are absolutely required to determine the direction of the sound in two dimensions [8]. A nomenclature will be introduced to ease this discussion. A *node* is the component receiving the signals from the microphones; it processes this data and computes the result. A *cluster* is a node and the microphones directly connected to it. A cluster develops the direction information as a stand-alone system. The use of redundant clusters as seen in Figure 3 adds to the fault-tolerant aspect and helps in achieving a more accurate result. The multiple clusters can compare the results and check the strength of the signal received at each cluster. An algorithm that computes the composite result is under testing. Pure acoustic data can be shared between nodes.

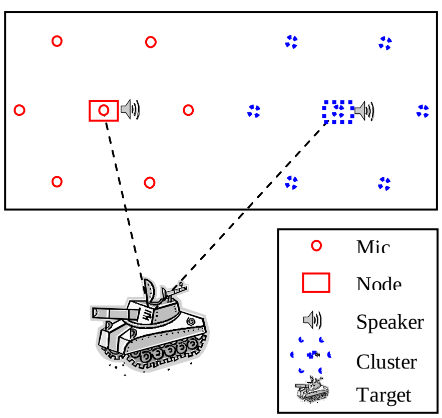


Figure 3 A conceptual rendering of a computational fabric with two acoustic array clusters.

The use of fabric in this system adds to the complexity of the acoustic beamforming technique. The position of the microphones will change when the fabric is moved. The relative locations of the microphones should always be determined to have an accurate computed result. The nodes in the system will be augmented with speakers in a fixed location relative to the central microphone. These speakers will be used to determine the location of the microphones and other clusters with a time of flight test. GPS receivers can be used to fix the location of a subset of the components; the positions of the other components will be determined from the relative distances to the fixed points. For correct results in location determination and acoustic beamforming, the microphones have to be a maximum of a wavelength (speed of propagation of sound) apart. Accuracy also suffers if the microphones are placed too close together.

The fabric carries all the interconnections needed between the clusters and between each cluster and its components (microphones, speaker, GPS unit, etc). Figure 4 shows the implementation of one cluster on fabric as a stand-alone system.

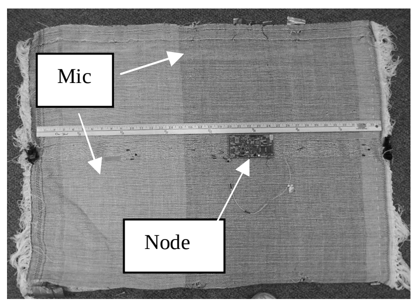


Figure 4 An implemented one cluster acoustic array, shown with a yardstick for scale.

Power conservation is important and thus the components of each node should be capable of entering a low power sleep mode. These nodes should wake up when there is a significant acoustic signal or when other nodes in the system need their input. The problem of power management in an e-textile is quite different from other battery-powered electronic devices. The power sources and the power consumers are distributed around the system. Achieving optimal power consumption will consider this distribution and assign tasks accordingly.

The interconnection network was tested in a 30-foot implementation that carries four separate clusters. Two different modes of this network can be used, the first is a simple four node ring, without the use of the protocol Figure 5 (a); the second is a small variation to have two types of networks and is shown in Figure 5 (b). The acoustic beamformer helped in testing our theories, simulation environment (next section), and interconnection network. New implementations of physical projects will help in testing the more complex versions of the network.

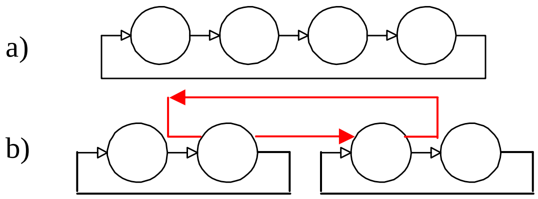


Figure 5 The four clusters can be configured as one simple row ring (a) or two row rings and one transverse ring (b).

4- Simulation

Building a separate prototype to conform to every decision point or aspect of the project is extremely time consuming, thus the need to simulate the system, test several options, and implement the best result.

Creating a simulation environment is a complex and a large undertaking, thus the decision was made to use an already existing simulation environment. The communication scheme between processing nodes on a computational fabric along with the entire operation of the system, from the sensor behavior to the processing done on the nodes, can be simulated using Ptolemy-II [13]; thus covering all the significant aspects of the system.

Ptolemy provides a heterogeneous simulation environment targeted to the simulation of embedded systems. Ptolemy can represent systems that mix different technologies and devices [13]. An e-textile system is constituted from different interacting components ranging from complex processing nodes to simple acoustic sensors. The high-level simulation and the inclusion of multiple interacting systems in the Ptolemy simulation environment map directly to such a computational system. Significant aspects of the physical world can be added to the simulation; for example, the sound of a passing large vehicle.

The ability of Ptolemy to simulate all aspects of the system aids us in testing the communication protocol in use, while simulating the whole operation of the system. The theory of the interconnection network can be tested in both optimal and faulty situations. ID assignment to sensors and nodes at initial power-up can also be tested. The specifics of this prototype (microphone distances for example) can be refined to get a better result, after testing in the simulation environment. Figure 6 shows a Ptolemy model representing the acoustic beamformer and a passing truck.

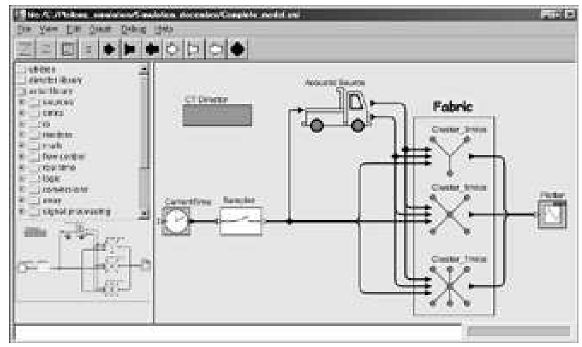


Figure 6 A Ptolemy model simulating the acoustic beamformer and a passing truck.

5-Results and Discussion

The goal of a deployable system is to report a pre-determined result to its master. Computation on the system will be required along with communication to sensors and separate elements to reach an accurate result. This section will first discuss the wired versus wireless implementation of such communication and then proceed to study design guidelines in connection with computation and communication in relation to power consumption; both of these sections will rely on the prototype introduced in Section 4 in the concepts discussed.

5-1 Wired Versus Wireless

The problems of withstanding fabric tears and difficulty of attachment on the textile raise the question of using wireless instead of wired connections. Considering the application discussed in Section 4, two other configurations using wireless connections can be foreseen, a fully wireless and a hybrid scheme.

The hybrid configuration will implement wired communication for the sensor-to-node connection and wireless communication for the node-to-node connection. Table 1 shows the power values for different modes of operation in an Ericsson ROK101008 [14] module (compliant with Bluetooth version 1.1). Table 2 provides the measured values of power consumption during the different communication phases in our prototype (using 8 meter long wires); the values provided are for the minimum and maximum speed and power values reported. These values show the great increase in power consumption necessitated by wireless communication. Wireless links offer a better solution to fabric tears than redundancy, but the large increase in power renders the fully wireless scheme unrealistic for stand-alone systems, especially for implementations requiring constant data flow between sensors and processing nodes. A major disadvantage of node-to-node wireless links is the inability of the processor node to go into a full sleep node; the wireless module has to stay in the standby mode using 100mW to avoid missing communication from other nodes. A fully asleep node in the prototype, fully wired scheme, required 9mW, a state from which it can be awoken by an acoustic or a communication signal. This greatly impacts power management in wireless implementations.

Table 1 Power values for the different operation modes in a wireless Bluetooth module.

Operation Mode	Inquiry		Paging		Standby
	Scan	Send	Scan	Send	
Power (mW)	204	261	100	261	100

Table 2 Measured communication power consumption values for the implemented prototype.

Communication Rate	Wait (mW)	Send (mW)	Recv (mW)
256 Kbps	0.135	0.179	0.159
8 Kbps	0.056	0.058	0.056

In the wired solution, a more elaborate interconnection network has to be implemented to route around faulty nodes, sleeping nodes, and broken connections; the wireless implementation is simpler in that respect.

5-2 General Guidelines

Figure 7 shows a general concept of e-textile systems based on the acoustic array prototype. The communication to computation ratio depends greatly on the type of communication used and the complexity of the sensing elements. A sensing element can be a regular microphone with analog data to be processed at the node or could include an A/D and transmit digital results when queried. In the following discussion all the channels are considered wired.

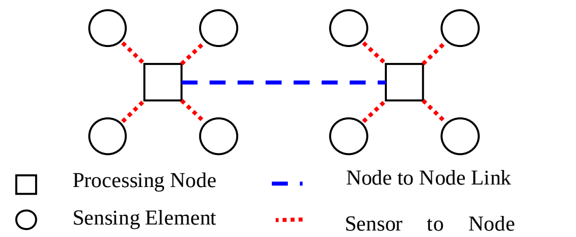


Figure 7 General conception of a sensing e-textile system covering the sensors, processors, and communication channels.

The main variables controlling this system's processing are the number of clusters, the number of sensors attached to each node, the number of node-to-node connections at a specific node, the sensed data format (analog or digital), sampling rate, size of data chunks (digital case) of sensor values, size of data chunks (node-to-node), and the frequency of communication (protocol overhead and pure data). Power consumption can be controlled using idle states at the nodes and more sophisticated sensors.

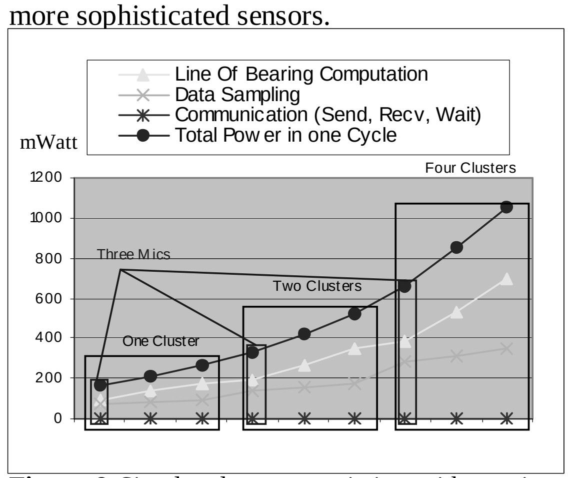


Figure 8 Simulated power variation with varying the different design variables.

Figure 8 shows the simulated power consumption variation depending on changing a subset of design variables. In the portrayed example the fixed variables were: sample length 512, sampling rate 4000 samples/sec, communication speed 256Kbps, analog sensor data, send and receive one data chunk per cycle, and a data chunk 68 bytes. A cycle is the time required to sample all of the data needed to provide a line of bearing result. Data sampling and processing are carried at the same time (sampling requires more time). The varying values are: number of clusters (1,2,4), number of microphones (3,5,7). The expected increase in power consumption (seen in mW) can be viewed as both variables are increased. The power values recorded (measured and simulated) offer insight to the general design of the system. Power consumed from communication is negligible in this case. The use of wireless communication in this configuration would have incurred a 100mW (standby mode) increase as a minimum, a significant portion of the total power consumption (200 – 1052 mW).

The choice between simple sensors or sophisticated ones has a significant impact on the system design. Sophisticated sensors (acoustic data) would include the microphone along with the required analog circuitry and a controlling processor. The total sensor would report its data in digital format when queried. The communication lines connecting these sensors to the nodes are not "tied up" anymore; this scheme increases fault tolerance, sensors can be connected to multiple masters rather than a single master. These sensors can also operate in a broadcast mode enabling multiple nodes to acquire data as needed. Communicating digital data minimizes the error from noise as the analog signal propagates the length of the wire. The design guidelines mentioned are dependant on communication and computation, power consumption was used as a metric for comparison; time is another metric to be used, but was not significant in our application.

6-Conclusion & Future Work

The e-textiles group at Virginia Tech plans to create a software/hardware architecture that will enable future researchers to develop e-textile systems and explore the design space created by these systems. The physical prototypes being constructed along with future prototypes will help in testing and refining this architecture. The simulation environment will be fully developed to cover general e-textile systems, represent their operation, and help in refining their design. Communication between components is an integral part of this architecture. The protocols used have to address the low-power, fault-tolerant, and location-dependence requirements of e-textile communication. The ultimate goal is developing e-textiles as a software/hardware architecture that is easily applied to extant or novel applications and offers a low-cost, durable, and long-running implementation base.

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