An Architecture for Electronic Textiles [*]

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ABSTRACT

This paper makes a case for a communication architecture for electronic textiles (e-textiles). The properties and requirements of e-textile garments are described and analyzed. Based on these properties, the authors make a case for employing wired, digital communication as the primary on-garment communication network. The implications of this design choice for the hardware architecture for e-textiles are discussed.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Distributed networks

Keywords

electronic textiles, e-textiles

1. INTRODUCTION

In this paper, we make the case that electronic textiles (e-textiles) occupy a unique corner of the distributed, embedded computing design space and, therefore, require an architecture that is tailored to this space. While previously reported research in e-textiles has primarily examined individual applications, the technology itself supports, and to a large extent, requires a computing architecture that simultaneously supports multiple applications. For example, users should not be expected to choose between garments that support MP3 capability [5], heart monitoring [10], and gait analysis [2]; all three capabilities and more should be available to the user.

In addition to the promise of such applications, advantages claimed for e-textiles [8] include inherent fault tolerance through the availability of many fibers (e.g., mul-

tiple power distribution busses), improved application performance due to the capability to deploy many sensors [9], low-cost due to the use of high-volume textile manufacturing techniques, robust power-aware operation due to the availability of many fibers (e.g., communication busses)[4], and high user acceptance due to the familiarity of textiles. Reaping these advantages, however, requires, among other things, the support of a computer architecture, including hardware and software, tailored to this environment.

In this paper, we analyze the case for such an architecture and then propose a two-tier architecture to meet this need. The hardware architecture is designed to provide fault-tolerant, power-aware, wired communication between many on-fabric nodes. The architecture avoids the use of paths of any significant length in which sensor data is communicated in analog form; such communication paths have inherent weaknesses, for example, in the areas of fault-tolerance and susceptibility to noise. To facilitate this network, while ensuring that the architecture maintains the properties of low-cost and small physical size, the first tier of the hardware architecture is composed of very small, low cost computing devices that are paired with sensors. The second tier is composed of a small number of more powerful computing devices that are capable of running application algorithms.

Section 2 gives a brief overview of the properties of e-textiles as they are relevant to this paper. The case for digital, wired in-garment communication is made in Section 3. Section 4 outlines the proposed hardware architecture. Concluding remarks are given in Section 5.

2. PROPERTIES OF E-TEXTILES

Papers such as [7], [8], and [9] have described the properties of e-textiles across a range of applications. These properties are briefly summarized in this section, with a focus on wearable e-textiles, to provide the basis for the analyses in the following sections.

Garments are inherently easy-to-use; after a certain age, the majority of our population is capable of dressing themselves. E-textile garments can capitalize on this familiarity to simplify the deployment of a computing/sensing system. For example, a pair of pants designed for gait analysis will, by default, have sensors correctly positioned if the wearer has selected a garment size that fits him/her.[1] By contrast, a system in which discrete markers or wireless sensors are attached to the body requires a significant period of time to

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[1]While correct positioning is generally the default situation, there are exceptions; for example, a wearer may roll up his/her sleeves.

correctly position [2].

Garments, of course, do not encounter barriers in the form of user acceptance, as long as they meet fashion and comfort expectations of the wearers. Systems in new form factors, in general, encounter resistance from many users. For example, fall-mitigation devices, even among those prone to falling, are not widely accepted [2]. To "coat-tail" on the acceptance of garments, an e-textile system must not alter the existing garment form-factor. This implies that the additional components must either look like traditional garment components, be hidden, and/or be very small. Garment components such as buttons, sequins, zippers, and rivets offer opportunities for the integration and attachment of new components such as integrated circuits and discrete sensors [6]. Integral aspects of many garments, such as cuffs, collars, and seams, offer locations in which to hide similar components. Direct connection and/or integration into the garment is acceptable as long as the components are small and/or flexible enough so as not to be noticeable to the eye or an irritant to the wearer. It is unlikely that a "one size fits all" approach will be successful because traditional garment designers draw upon a vast range of components to meet the utility, fashion, and comfort requirements.[2]

Aside from those described above, there are additional expectations held by most garment wearers that must be met if we are to capitalize on the acceptance of this form factor. The first of these is cost; for the majority of applications and the majority of wearers, if the addition of "e-textile" functionality significantly increases the cost of the garment, then there will be an additional barrier to acceptance.[3] In addition to cost, wearers of traditional garments expect garments to continue to be useful even in the presence of small flaws due to daily "wear and tear." For example, most wearers do not notice when a single fiber in a garment becomes very worn or even broken, and certainly do not discard the garment due to such a flaw. An e-textile should not cease to function when similar flaws are present; in fact, the large surface area and number of fibers offers an opportunity for extensive fault tolerance.

E-textile garments will ultimately need to flexibly accomodate a wide range of applications, with particular combinations tailored to the needs and wants of individual wearers. Even at this nascent stage in the development of e-textiles, the applications range from medical (c.f., [10]) to entertainment (c.f., [5]). The number of applications is likely to exceed the number of garments that a user is willing to wear at any given time. It is ultimately undesirable to have single function garments, such that a user is forced to choose, for example, between a garment to monitor heart/respiration activity and a garment to monitor physical activity. Garments that can accomodate multiple applications, however, must ensure that resources (such as energy, network bandwidth, and computation) are allocated according to the relative importance of the applications.

3. THE CASE FOR DIGITAL, WIRE-BASED COMMUNICATION

The majority of e-textiles developed to date have relied primarily on a communication architecture in which a collection of sensors distributed across a garment are connected to single collection point via analog conductive fibers. Such an approach is suitable for prototyping e-textile technology and applications, but it presents unacceptable barriers to the uses envisioned for e-textiles as analyzed below.

- The communication of analog sensor data typically requires dedicated communication paths, precluding the type of expansible system required for executing a changing mix of *multiple applications*. In contrast, a digital, switched network can multiplex data from many sources.
- Ensuring *signal integrity* along relatively long paths is often difficult for analog sensor data and is typically application dependent. In contrast, signal integrity of a digital, switched network can be addressed in the design process one time and re-used because it is independent of the sensor data.
- Each new sensor requires its own discrete path, *complicating the design process* by forcing re-design of the physical textile for different sensor configurations. In contrast, a digital, switched network can accommodate new nodes without any redesign.
- The central processing device(s) must be able to accomodate potentially large numbers of sensor nodes. The number of i/o connections to the fabric will increase with the number of sensors, presenting *packaging and attachment* issues that will increase costs. In constrast, a digital, switched network allows for a fixed number of i/o lines for each network interface.
- The *fault tolerance* of the system is reduced because each sensor requires at least one continuous path from the sensor to the processing unit. In contrast, a digital, switched network can route around points of failure in the garment.

A wire-based network offers significant advantages, as analyzed below, over a wireless network for e-textiles. This analysis is directed towards the primary on-garment communication network for the e-textiles; it does not apply to, for example, off-garment communication.[4] In the following paragraphs, aspects of a wearable system are considered, including energy storage and distribution, system deployment, electro-magnetic emission, and low-power operation.

The type of network chosen has a significant effect on how wearable systems are deployed and operated, particularly for the types of applications mentioned in previous sections, in which (at least) tens of sensors are distributed around a user's body. A wireless network initially appears to offer many of the same deployment advantages that are present in wireless home networks as compared to wired home networks. For example, a user can simply fasten (e.g., by velcro), wireless sensor nodes to his/her body and have them quickly participating in a network. This approach, however, requires the user to spend the time to attach the sensor nodes; further, it requires the user to attach the correct sensors to the correct locations on the body. In comparison,

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[2]An alternative, and equally valid, approach is to attempt to capitalize on aspects of the new components to create new fashion [11].

[3]While an analysis of cost will vary significantly by application and technology employed, [3] suggests that it is possible to keep costs in line with traditional textile costs.

[4]There is, of course, typically a need for the garments to communicate with an existing infrastructure. For example, a medical monitoring application may need to periodically report results to a doctor's office, or an MP3 player may need to download new music.

an e-texile system, in which the garment itself contains the conductive fibers necessary for communication, requires a user to simply put on a garment(s). The e-textile approach is not without cost because it does not typically allow for sensors or computing nodes to be moved from garment to garment; re-use of nodes across garments is possible, but it gives up some of advantages described above.[5]

The operation of a wearable computing system is typically faced with a constraint on the amount of energy that can be stored or harvested during operation. Batteries are typically used for energy storage, and although battery form factors are becoming more compatible with wearable systems, the energy density of batteries has remained largely constant. Wearable systems must typically track battery status and allow for batteries to either be replaced or recharged. This presents a drawback for wireless approaches because each sensor node and/or computing node (or local groups of nodes) requires its own battery. Requiring a user to manage tens of batteries is an unrealistic approach. In contrast, an e-textile garment is effectively a backplane for power as well as communication, allowing for the number and location of batteries to be independent of the location of the sensing and computing nodes. This system avoids the duplication of the unnecessary duplication of battery packaging and monitoring mechanisms present in a wireless system.

There are several concerns with respect to the electromagnetic profile of a wearable computing system. User concerns regarding the security of their personal data in computers and computer networks continue to be well-founded. Wearable computing systems have the potential to generate more data that is even more personal. A wireless network for a wearable network must address such security concerns without imposing a significant burden on the wearer; this includes not only during operation, but also during deployment. However such security is provided, it imposes costs in terms of hardware, software, network efficiency, and energy consumption. In contrast, an e-textile system can typically rely upon on the physical security of the conductive fibers in the garment and transmit "clear text" within the garment. Both systems, of course, have in common security issues that must be addressed such as authenticating the wearer and ensuring the security of information stored on the system. In addition to security, many people are concerned with the health effects of RF devices. Whether or not these concerns are well-founded, systems that extensively use RF communication in proximity to the body face a social barrier to adoption. To a similar, but lesser extent, any wearable computing system faces user concerns about any electromagnetic emissions in proximity to the body.

Perhaps the deciding issue, however, is that of energy consumption, for which an e-textile solution offers both obvious and less obvious advantages. Wireless transmission and reception of data clearly requires significantly more energy than wired transmission and reception of data over the same distance. A typical body-worn sensor, however, has a low communication rate, even when reporting data without any processing and/or filtering. For example, an accelerometer in a gait monitoring application may need to report on the order of one hundred one byte samples per second [2], a fraction of the bandwidth available in wireless networks. To examine and put into context the energy required to send and receive such data, we consider two commercial devices, a microcontroller and a Zigbee transceiver. The current consumption numbers for these devices in various operating states are given in Table 1. Assuming perfect efficiency at a transmission rate of 250 Kbps, the Zigbee device would require 0.232 mW to transmit the accelerometer data in the example above. The receiving unit would consume a comparable amount of energy, assuming it was only active during when the transmitter was active.

On the surface, this is a reasonable power consumption rate as compared to the rates of the microcontroller in Table 1. This calculation is not realistic, however, because of the need to manage the entire system of sensor and computing nodes, not just an individual pair. It is reasonable to assume that a single node is the active receiver of sensor information; this node would have a high power consumption rate in comparison to most other nodes as it would always be in the receive mode. The Zigbee device in Table 1 requires 59.4 mW in receive mode. A larger difficulty is the need to actively manage all of the nodes in the system in order to reduce the power consumption of the entire system. For example, during most of the day, the majority of the sensor nodes can be inactive in the gait monitoring application because the user is not walking; a small number of nodes may be active and, when the user begans to move, these nodes can activate the remaining nodes. To reduce power consumption, it is desirable for those nodes to be in a sleep mode, including the computational and communication components of the node. In a sleep mode, the power consumption of both the transceiver and the microcontroller in Table 1 are in the microwatt range rather than the milliwatt range. To be useful, of course, these nodes must be able to be quickly activated. Such an activation, in a wireless network, can only take place if a node is in a receive mode when a sending node is transmitting the signal to awaken. By coordinating time slots, it is possible for a node to periodically re-awaken to "check in" and reduce power consumption; such an approach does result in delays in activation. In contrast, microcontrollers in a sleep mode can be reawakened nearly instantaneously via signalling on a wired network.

Table 1: The current consumption in different modes for a PIC microcontroller and a Zigbee transceiver (both produced by Microchip). The results given are quoted as typical from the manufacturer's datasheets for operation at 3.3V.

Device	Operational Mode	Power Consumption (mA)
PIC1845J10	Sleep	0.025
PIC1845J10	Run at 4 Mhz	4.4
PIC1845J10	Run at 40 Mhz	11.5
MRF24J40	Sleep	0.002
MRF24J40	Receive	18
MRF24J40	Transmit	22

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[5]With the exception of some types of sensors, e-textiles are compatible with typical garment laundering processes (c.f., [1]).

4. THE ARCHITECTURE

The previous sections laid out requirements that include digital communication from sensors, the capability to simultaneously execute multiple applications, small physical size, and a need to keep the costs comparable to traditional garments. Given these constraints, we have opted for a two-tier architecture in which there are a large number of small tier-one nodes (primarily sensor nodes) and a small number of more powerful tier-two nodes capable of executing application code. The tier-one nodes are intended to sample sensor data, perform minimal processing of sensor data, and simple networking; they are intended to be as small and power-efficient. Sampling rates are typically tied to phenomena associated with the human body; for example, walking, respiration, and gestures. Because the sampling rate requirements are primarily associated with such phenomena, the requirements for tier-one nodes can be expected to remain the same. As VLSI technology improves, these tier one nodes should become smaller and more power efficient instead of becoming more capable. Tier-two nodes, however, are primarily intended to run applications; their requirements will change as applications become more demanding.

To take advantage of the large number of fibers in an e-textile, the architecture has many redundant paths in the wired network. Both the nature of the fabric construction (e.g., weaving) as well as the nature of garment construction, dictate that there are physically disjoint paths in the network that are connected by tier-two routing nodes. Because of their limited nature, the network demands placed upon the tier-one nodes are reduced by ensuring that each tier-one node is on the same physical network path as at least one tier-two node. It is the responsibility of these tier-two nodes to manage tier-one nodes.

4.1 Specific Implementation

The physical system that we have designed and implemented (c.f., [3]) has the following properties.

- Tier-one sensor nodes are implemented as small printed circuit boards that directly attach to the fabric, including to conductive fibers, and contain sensors and a small Atmel microcontroller.
- Tier-two nodes use an ARM7-based microprocessor and have more than one network interface.
- The network has multiple independent segments that use the IIC standard and are connected by tier-two nodes that act as routers. Addressing on a single segment uses IIC addresses, but addressing within the context of software services (as described in the previous section) is used for addressing beyond a single segment of the network.

5. CONCLUDING REMARKS

This paper has presented an argument for an approach to communication in e-textile systems. In particular, a case is made for digital, wired communication in e-textiles; this case is supported by observations regarding the construction and operation of e-textiles. This approach to communication is embodied in a two-tier architecture outlined in the paper.

In the near-term, there is a need to investigate the performance of the system across a broader range of e-textile applications and to gather experimental results to guide design decisions made within the architecture. Should this approach be proven effective across a range of applications, there would be a benefit to tier-one nodes and a network that

are specifically designed for e-textiles. Even though the tier-one printed circuit boards can be made quite small and can be concealed in e-textiles, current sensors, microcontrollers, and other components are general-purpose in nature; a design targeted to high-volume e-textile applications would be smaller and more power efficient. In addition, the IIC network standard has not been designed for a large number of nodes or for interconnected IIC busses.

6. REFERENCES

[1] L. Buechley. A construction kit for electronic textiles. In *International Symposium on Wearable Computers*, 2006.

[2] J. Edmison, M. Jones, T. Lockhart, and T. Martin. An e-textile system for motion analysis. In *International Workshop on New Generation of Wearable Systems for eHealth*, pages 215–223, December 2003.

[3] D. Graumann, M. Quirk, B. Sawyer, J. Chong, G. Raffa, M. Jones, and T. Martin. Large surface area electronic textiles for ubiquitous computing: A system approach. In *Mobiquitous 2007*. IEEE, August 2007.

[4] M. Jones, T. Martin, Z. Nakad, R. Shenoy, T. Sheikh, D. Lehn, and 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.

[5] S. Jung, C. Lauterbach, and W. Weber. Integrated microelectronics for smart textiles. In *Workshop on Modeling, Analysis, and Middleware Support for Electronic Textiles*, pages 3–8. MAMSET 2002, October 2002.

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

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

[8] 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, and Z. Nakad. Electronic textiles: A platform for pervasive computing. *Proceedings of the IEEE*, 91:1995–2018, 2003.

[9] Z. Nakad, M. Jones, T. Martin, and R. Shenoy. Using electronic textiles to implement an acoustic beamforming array: A case study. *Pervasive and Mobile Computing*, 3:581–606, 2007.

[10] R. Paradiso, G. Loriga, N. Taccini, M. Pacelli, and R. Orselli. Wearable system for vital signs monitoring. In *International Workshop on New Generation of Wearable Systems for eHealth*, pages 161–168, December 2003.

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