Towards a design framework for wearable electronic textiles

Thomas Martin, Mark Jones, Josh Edmison, Ravi Shenoy
Bradley Dept. of Electrical and Computer Engineering
Virginia Tech
Blacksburg, VA 24061

Abstract

This paper presents a design framework for wearable electronic textiles. The focus is on the design and simulation issues that arise from the interaction of the electronic textile, the human body, and the environment. To assist in design choices within this framework, a simulation environment is described that uses Ptolemy II to integrate models of the physical environment, human locomotion, sensor behavior, network communication, power consumption, and software execution. We describe results for two e-textile design case studies, a shape-sensing garment and a wearable phased array of microphones, demonstrating how the design framework encompasses the effects of design variables for wearable electronic textiles.

1. Introduction

Electronic textiles (e-textiles) are fabrics that have electronics and interconnections woven into them. Components and interconnections are a part of the fabric and thus are much less visible and, more importantly, not susceptible to becoming tangled together or snagged by the surroundings. Consequently, e-textiles can be worn in everyday situations where currently available wearable computers would hinder the user. E-textiles also have greater flexibility in adapting to changes in the computational and sensing requirements of an application. The number and location of sensor and processing elements can be dynamically tailored to the current needs of the user and application, rather than being fixed at design time.

The design-state space for e-textiles and their applications is huge; choices include the type and construction of yarns, weaves, components, system software, interconnection networks, as well as other areas. Wearable computers constructed from e-textiles represent an extreme form of distributed computing: physically spread over a relatively smaller space, but having a greater dependence on physical locality of computation, lower bandwidth for communication, less available energy, and requiring knowledge of the dynamic shape of the human body. To address these issues, we are using a combination of simulation and physical prototypes.

Neither prototyping alone nor simulation alone is adequate. Prototyping is too costly to cover the full range of the design space even for a single application, let alone across many applications. As an example, consider a garment that requires sensors to be placed on the wearer's joints. Creating a garment tailored to each individual would be too expensive, so discrete sizes of garments will be needed. But if too few sizes are created then the sensor positions will be wrong on many wearers. Finding the allowable variation in sensor placement via prototyping only would require many different size garments to be created, and perhaps several iterations of prototypes for each size. This would be expensive in both time and money.

Simulation, on the other hand, must be grounded in reality. Exploring the design space via simulation without verifying the results is useless. Consequently, some prototypes must be built to ensure that the simulation is giving reliable results.

E-textiles to date have been created in a trial and error fashion (prototype, evaluate, prototype, evaluate). The novelty of this paper is that it describes a framework for evaluating the e-textiles design space without building physical prototypes for every possible configuration. The framework is a work in progress, but the paper discusses the issues that we have identified, the areas that must be modeled in order to successfully explore the design space, and results from currently available portions of the framework.

Our goal is to (a) create designs that generalize well, i.e. the same design will work for most of the population, and (b) in the event there is not a design that generalizes well, create designs that require minimal tuning to an individual. Simulation provides a large set of advantages including but not limited to, the ability to control motions used for experiments, evaluate the quality of solutions over a wide range of subjects, and extract critical implementation information such as the dynamic range of variables at design-time, rather than after the prototype is built and other design decisions solidified.

The remainder of this paper is organized as follows. Section 2 describes the related work in e-textiles and context awareness via sets of sensors. Section 3 discusses the design issues for wearable e-textiles. Section 4 presents two design case studies using our framework, a wearable acoustic beamforming array and a garment that senses its own shape. Finally, Section 5 describes our conclusions and future work.

2. Related work

The main areas of work related to our design framework are electronic textiles and wearable sensors for context awareness.

2.1. Electronic textiles

The wearable motherboard project and related work at Georgia Tech has led to the creation of a system for monitoring a user's health, including heartbeat and respiration as well as the location of a bullet wound [13][16]. Applications include monitoring infants for Sudden Infant Death Syndrome as well as monitoring the status of soldiers on the battlefield. In these projects, wires were woven into the fabric for communication of data along with optical fibers to detect the location of bullet holes. Discrete sensors were attached and computing analysis was done outside of the garment. Further work at Georgia Tech has investigated the use of FPGAs as self-configuring, fault-tolerant switches.

In industry, a range of products is either on the market or under development. ElekSen has developed a fabric keyboard that serves a dual-purpose in that it can be folded into a carrying case for a PDA device. This company has also developed fabrics for user interaction with vehicle interiors as well as health-care applications [7]. Durability tests show the fabric is as durable as normal textiles and that the sensing capability does not degrade over millions of user cycles. Infineon has produced a wearable MP3 player [12]. The primary contribution in this work is a method for packaging and attaching the digital and analog components in a washable, durable form factor with pins at a suitable pitch for fabric.

We have constructed a number of e-textile prototypes, including large-scale (up to thirty feet long) acoustic-beamforming textiles that can determine the location of vehicles [17]. These woven prototypes (see Figure 1) are embedded with a communicating network of sensors and computing devices and can run continuously for significant periods of time on a standard nine-volt battery. We have also investigated the inclusion of novel materials, including thin piezoelectric films, into e-textiles [6]. Our vision for e-textiles includes having novel fibers woven into the fabric, such as fibers that can sense chemicals, act as batteries, or change color dynamically [24].

2.2. Wearable Sensors for Context Awareness

One of the primary areas of study in wearable and pervasive computing has been context-awareness, sensing where the user is, what the user is doing, and what objects and people are nearby [4][10][25][26]. Much of the research in the area has focused on the type of sensor to be used, for example, using light, acceleration, magnetic field, and temperature to discern the user's location inside a building. Another main focus has been on where to locate the sensors on the user's body to achieve the best results and to be as unobtrusive and comfortable as possible [8]. Systems based upon discrete sensors require considerable effort to be fitted to the user, both in terms of comfort and quality of sensing. Furthermore, these context-awareness systems have generally been tested on a limited number of individuals using a single hardware prototype.

The number of options for sensor type, placement on the body, and processing algorithms is too large to be adequately explored using prototyping. To alleviate this problem, we utilize human motion data [3] in conjunction with simulation to investigate the type, number, variety, placement, configuration, and communication of sensors as well as the effects of these decisions on the top-level application. Additionally, the ability to control the input motion data allows for evaluation of these various sensor choices over a wide variety of individual classifications such as height, weight, age, and gender, making generalization an inherent part of the design phase.

3. Design issues for wearable e-textiles

A major challenge for designing wearable e-textiles is that the design issues span a diverse range of areas, including:

- Physical environment,
- Sensor behavior,
- Human body and motion,
- Motion/draping of clothing,
- Manufacturability (weave & piecework),
- Networking,
- Power consumption, and
- Software execution.

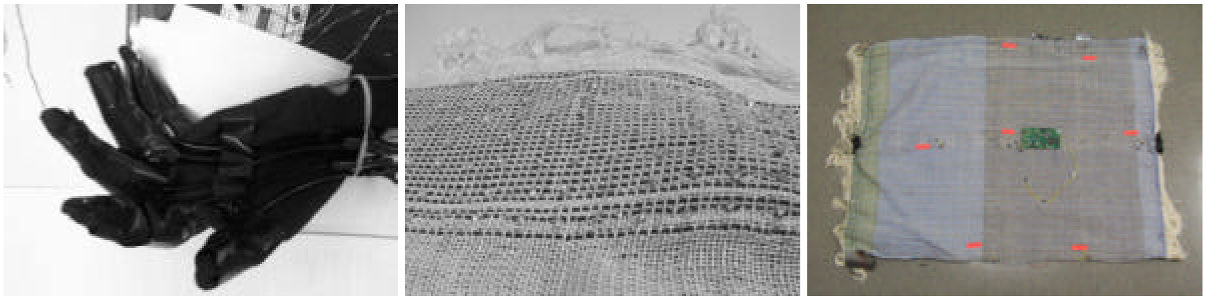

Figure 1. Virginia Tech e-textile prototypes: Shape-sensing glove, an LED array display, and a single-cluster beamforming fabric

We are addressing these issues within the context of Figure 2, with the goal of manipulating the design variables to optimize the design metrics. Design variables include those made at weave time such as the type and placement of fibers in the weave, including fibers that can act as sensors, batteries, and wires. Weave time decisions will impact design variable choices made in the garment construction phase including the cutting and assembly of the garment, the number and type of sensors and processors as well as the topology of the network. The choice of design variables will be evaluated in several domains, including the physical environment being sensed, the movement of the human body and the garment, as well as familiar computer architecture domains. The metrics resulting from the evaluation include the manufacturing cost of the garment, the visual appeal and comfort of the garment, the functionality of the garment in the chosen application, and the power consumption.

Finding the right values for the variables will require evaluating many points of the design space, which can best be done cost effectively in simulation with only the occasional prototype. The evaluation domains, however, are diverse; no single simulation environment provides the required functionality (e.g., OPNET doesn’t have a model for how clothing drapes on a user). To address these simulation needs, we have selected Ptolemy II as a means of integrating a wide range of simulation capabilities. Ptolemy II provides the type of diverse environment required to handle very different simulation domains and an open architecture that can accommodate interfacing to other environments [20]. For example, Ptolemy II has provisions for simulations in the continuous domain, which is useful for simulating the physics of the environment, while simultaneously providing a discrete event domain that is appropriate for computation.

In the following subsections we explore the design issues in more detail, describe the type of simulation that is required, and detail some of our current capabilities in those areas.

To make the discussion clear, we must distinguish between *fabric* and *garment*. The *fabric* is the woven cloth that comes from the loom. The *garment* is the piece of clothing created by cutting the fabric into pieces and sewing those pieces together.

3.1. Physics and Sensor Behavior

An important category of applications for e-textiles is sensing the user's environment and the user's actions. An e-textile fabric provides an interconnection network for sensors and processing elements at a much lower power cost than using wireless networking [15]. The fabric itself may be capable of sensing depending upon the fibers that are woven into it (e.g., piezoelectric film strips, chemical sensing fibers). Thus a design framework for e-textiles must incorporate the behavior of the physical environment, particularly the stimuli provided to the sensors.

Consider, for example, simulating the propagation of sound from a source to an array of microphones. To be useful, this simulation must accurately model the differing time of arrival at each microphone, the noise in the environment, and the dissipation of the signal as it travels. Like most physics, this is modeled best using equations in the continuous domain. Relatively simple equations can be modeled directly in Ptolemy, while more complex systems such as the transport of airborne chemicals may require interfacing to existing simulation software.

In addition to modeling the physical environment, the behavior of the sensors themselves should be modeled. The models for these sensors typically include the A/D conversion unit with sampling rate. Models should characterize not only the sensing capability (e.g., detection, position, velocity, or acceleration), but also characterize the nature of the error and dynamic range. These models typically form the bridge between the continuous and discrete domains and are easily characterized within Ptolemy II.

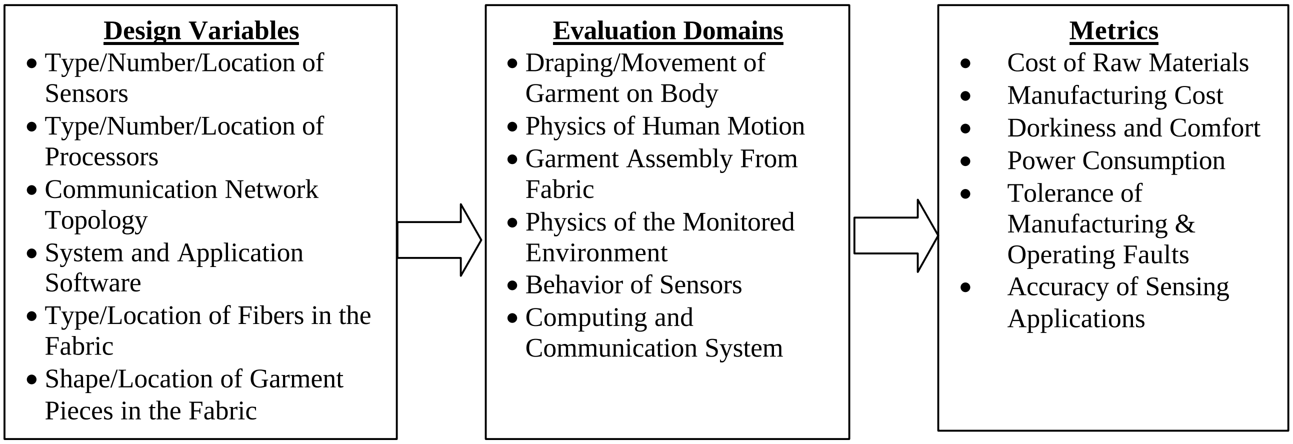

Figure 2. Design variables, evaluation domains, and metrics for e-textiles.

3.2. Wearable Textiles Modeling Issues

In the case of wearable e-textiles, the human body is an important design issue[9]. There are at least two aspects of the human body that must be considered: body size and human motion. Body size is a static (design time) issue, but human motion is a dynamic (run time) one. Size and motion affect sensor placement on a garment; we expect many wearable applications will require sensors placed relative to the wearer's body, e.g., on the knee, as opposed to sensors placed a fixed distance from each other. Size will determine initial placement on a garment, while motion will affect which set of sensors is active while the garment is in use. Both aspects must be considered in the design of an e-textile application if it is to be useful in everyday use by a large segment of the population. There are multiple sources of data for body motion/size. We can use the output of programs that create animations of the human body or we can use data recorded from actual human motion [3]. In both cases, we capture both the range of human sizes and types of motion *if* we sample across a range of people that includes different sizes as well as variants in motion.

In the case of loose-fitting garments, the motion of the fabric relative to the body and draping of the fabric will also affect sensor placement. As the user moves, the garment will change its shape but the change in shape of the garment may not correspond exactly to the movement of the body [5].

Related to garment size is the issue of manufacturability. By manufacturability, we mean the difficulty of constructing both the fabric and garment using existing weaving and piecework techniques of the textile and clothing industries. For example, one of our existing prototypes uses uninsulated stainless steel thread. But in our discussions with a textile company we discovered that this would be incompatible with an industry-standard technique for halting a loom when a thread breaks. Because the creation of the fabric and the creation of the garment are two distinct manufacturing phases, manufacturability of the e-textile in each must be considered. The issues in each phase are not wholly orthogonal, however, such as when the patterns on the fabric pieces must be aligned where they join on the garment. Software exists for determining the patterns that must be cut from fabric to allow for proper fit, draping, and match to fabric patterns (c.f. [27]). At this point, no method exists for allowing for wires, sensors, and processors embedded in fabric to be properly mapped to cut pieces for a garment.

3.3. Architecture Modeling

Like all computing systems, e-textiles have a number of architecture-related issues that must be explored, including networking, power consumption, and software execution. For e-textiles, networking means the communication between sensing and processing elements on the garment. Weaving processes constrain yarns to run only in the X and Y directions with some travel between layers possible. This constraint implies some limitations on the topology of the underlying network. In addition, the conductive properties and the reliability of the conductive yarns and physical connections impose additional constraints. Based on our design goals, there is also a requirement for a fault-tolerant network, because of alignment problems of threads when the garment is initially created and tears in the garment during its lifetime. There exist several simulation environments capable of handling network modeling; while simple networking scenarios are easily modeled in Ptolemy II, the open source properties of NS-2 make it an excellent candidate to handle complex scenarios when properly interfaced to Ptolemy II.

One factor that will be common to wearable computing applications of e-textile technology will be power consumption. E-textile systems differ from other low power systems in that the power sources will be modular and distributed in order to maintain flexibility. Whereas other low power systems must optimize energy use from a single power source, fabric substrates will likely have to optimize energy use from many power sources. Consequently, the optimization problem is more difficult for fabrics. To make the fabric tolerant to tears and other faults, paths from power sources to sensor and computation nodes must be dynamic, allowing power to be routed around damaged sections of the fabric. Finally, because of the physical locality of computation, e.g. a node will search for other nodes within a given physical region for beamforming, power consumption will be non-uniform across the fabric without some form of dynamic load-balancing of power. No suitable environment exists for this aspect of architecture modeling in any form; we are designing and implementing a modeling and simulation tool specifically for this problem.

Software execution entails both the functionality of the software and its performance. We envision that e-textile applications will require a common set of software services for handling physical configuration and processor/sensor element selection [11]; both application-dependent code and the application-independent software services must be handled by the design framework. Because Ptolemy II is extensible, we were able to create a module provides the capability to run the same software on both the e-textile and simulation with only minor modifications, allowing us to test functionality and estimate performance in simulation without having to have the final hardware e-textile platform. Similar extensions could be made to provide interfaces to processor simulators.

Our design framework, integrated using Ptolemy II, is a work in progress. With respect to the list of issues presented earlier in this section, in its current state the framework incorporates all of the issues except manufacturability and draping of fabric. Our initial version of the framework addressed the issues of networking, power consumption, software execution, and the physical environment, based upon our experience with large (non-wearable) e-textile acoustic beamformers [17]. We have recently addressed the issues of sensor behavior, human motion, and body size. The results described in the next section were generated using the framework and illustrate its ability to explore the design space for wearable e-textiles.

4. Case studies of two applications

This section describes case studies of two applications we are currently designing using our framework, an acoustic beamforming garment and a garment that senses its own shape.

These particular applications were chosen for several reasons. First, they have been implemented by other wearable computing researchers using discrete components. Second, we believe an e-textile implementation for these applications will improve upon current implementations because of the ability to adapt direction and fidelity of the sensing and processing. They represent a range of communication and processing requirements, permitting us to use the framework across a large portion of the design space. Finally, the design of the fabric and garment for both applications depends heavily upon human motion and body size, and thus illustrates the impact of these issues on the design process.

4.1. Acoustic Beamforming Case Study

Within the proposed design framework, we consider the design of a first case study, a wearable acoustic beamforming garment. Like the system in [2], the beamforming garment's job is to determine the direction of the person in a room who is currently speaking, including the user, to allow for further processing of that source (e.g., noise reduction for speech-to-text translation, on-the-fly foreign language translation, or the determination of camera focus). This simple garment computes the direction of the strongest acoustic source, operating under the assumption that only one person will be speaking at a time with a perceptible pause between speakers; more complex algorithms/systems are required for multi-source resolution [18]. Further constraining the design, we assume that the user is only interested in speakers to his/her front. Like all mobile systems, it is important that the power consumption of the system be minimized. Our two design metrics, therefore, are the accuracy of the computed location and the power consumption of the system during operation.

Our design process takes advantage of the significant experience in prototyping that we have gained through the construction of several acoustic beamforming textiles; these textiles, however, were not designed for wearing, but rather for deployment on horizontal surfaces for the purpose of detecting and locating vehicles emitting sound in the 100 Hz range. To assist in constructing and evaluating these prototypes we constructed an instance of the Ptolemy-based simulation environment described in Section 3. The physics component reflects basic acoustic propagation while the application software component runs a multi-microphone acoustic beamforming algorithm [23]. We have already characterized the power consumption for this software running on a low-power digital signal processor along with accompanying A/D conversion and microphone amplification. The output of our simulation is the accuracy of the computed location and the power consumption of the system, our two design metrics. Given this extensive prototyping information, we can design a satisfactory prototype without further experimentation.

To focus this discussion, we limit our design variables to only the number and position of microphones to be included on a shirt as well as the sampling rate at each microphone. These design variables have a direct impact on the accuracy as well as the power consumption of the

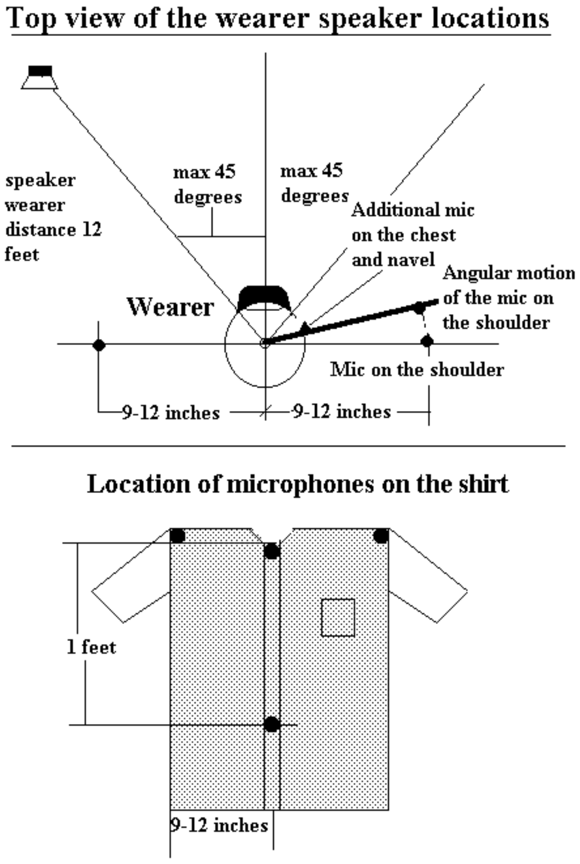

Figure 3. Geometry of wearable acoustic beamformer

system. The beamforming algorithm takes the positions of the microphone as input, the accuracy of the output depends on the accuracy of these positions. In addition, the microphone spacing as well as the sampling rate in conjunction with the source frequency affects the accuracy of the system. We will focus our evaluation on the effect of human motion and variation in body size on the choice of the number/position of microphones as well as its effects on error and power consumption.

Simple physics dictates a basic choice of location on the body that is as stable a platform as possible. Like [2], we assume that microphones will be positioned on each shoulder as well as near the stomach; we also consider the use of an additional microphone at the center of the chest to potentially improve accuracy. The scenario under consideration is shown in Figure 3 in which the system must determine the location of the speaker to within K degrees to correctly identify a speaker as well as differentiate between the user and another speaker. Although Figure 3 shows four discrete microphones, our design will have many more microphones than that available on the garment; at any given instant in time, however, the system will select a subset of those microphones to be active.

Within this scenario, we consider the effect of different user sizes on the accuracy and power consumption of the system when we use three or four microphones and vary the sampling rate from 2048 to 8192 per second; these potential values for the design variables fall within the range of what we have built in prototype systems. Table 1 presents these results for a range of body sizes found in [22]. Note the change in the maximum frequency detected as function of body size and the number of microphones; given the maximum frequency of interest for typical speech is 300 Hz [2], we see that the 3 sizes mentioned (small 36 inches, medium 40 inches, and large 44 inches) can all have microphones on the shoulders and still estimate the angle of arrival for frequencies below 300 Hz. For body sizes outside this range, different microphone placement will have to be considered. For smaller body sizes, accuracy suffers, requiring a faster sampling rate (and more power consumption) to compensate. Note that the number of microphones has a small effect on power consumption and accuracy, allowing a small set of microphones to be selected.

To examine the effect of body motion on the accuracy of the system, we consider the motion of the shoulders as it affects the determination of the distant speakers. Considering the physics of human motion, these are the most likely to affect accuracy given the nature of the beamforming algorithm. Table 2 presents the results for the two extreme sizes in Table 1 for the change in accuracy as both shoulders move forward 10 degrees, one shoulder moves forward by 10 degrees and one shoulder by 20 degrees. If we, for example, select fifteen degrees as the maximum allowable error, then we see that sampling rates must increase to compensate for the various motions. Another approach would be to constantly recompute the new position of the microphones in a manner similar to the system initiation mechanism in [2].

This information can be used to guide the location of wires within the woven fabric. Garments of all sizes will be cut from the same woven fabric, thus this fabric must have support for alternate/replicated microphone positions that are configured when the garment is constructed. When the simulation environment is augmented with components to reflect weaving and garment construction, the design process will include restrictions on the position of the microphones, cost of alternate/replicated microphones, and the cost of fabric wasted during garment construction.

4.2. Shape-sensing Garment Case Study

Our second case study involves a garment that can sense its own shape, similar in function to [8]. The garment can detect the position of the user's limbs and trunk, with potential uses in physical therapy, sports training, context awareness, and user input devices. Unlike the previous case study, we did not begin the process with accurate models for the sensors nor have we constructed a wide range of prototypes (with the exception of [6]).

Table 1. Accuracy of beamforming, maximum frequency, and energy consumption vs. chest size, number of microphones, and sampling rate.

Chest (in.)	Number of mics	samples per sec	f_{max} (Hz)	Maximum error (deg)	Power (mW)
36	2	2048	363	22	99
		4096		11	144
		8192		5	235
	3	2048		22	111
		4096		11	169
		8192		6	286
40	2	2048	327	19	99
		4096		9	144
		8192		7	235
	3	2048		19	111
		4096		9	169
		8192		5	286
44	2	2048	297	15	99
		4096		9	144
		8192		5	235
	3	2048		15	111
		4096		9	169
		8192		4	286

We began with the task of using simple experiments and simulation to examine the behavior of sensor types in response to stimuli in within the range of human motion. These experiments, described in Section 4.2.1, are used to construct Ptolemy II models of the sensors for further simulation. In Section 4.2.2 these models are used to explore the effect of the differences in human motion across a range of subjects, joints, and motion types. These results and methods can be used to guide the design of the sensor circuits in making such choices as dynamic range of the A/D and signal amplification in a fashion that is robust across the population.

4.2.1 Sensor model construction

This section details the sensor models that we created for use within the design framework for the shape-sensing garment. The selection of the types of sensors to be modeled for shape sensing was driven by the underlying physical principles of motion and the desire to capture or summarize them. Using our experience with piezoelectric film sensors [6] and the use of accelerometers in [10][25], piezoelectric films and accelerometers were chosen as the sensors to be modeled. The sensor models used in the simulation were constructed with two key strategies in mind: (1) reduce the operation of sensor to fundamental principles, (2) model commercially available sensors to allow an easy transition to the prototyping phase. These models are implemented in Ptolemy II. They are initialized with their physical location on the user's body and take as input the position of the body (in XYZ triples) as a function of time.

In the case of the piezoelectric film strips, previous work described in [6] led to the selection of the Measurement Specialties DT4-052K piezoelectric film sensor. Using the equivalent analog circuit [14] and the assumption that the frequency of human motion (typically << 10Hz) is much less than typical cut-off frequencies of the sensor characteristic (100Hz+ depending on input impedance), it can be shown that the sensor's output voltage will reflect the rate of change of the physical stimulus. As a result, the piezoelectric films may be used to detect joint angular rate of change or placed on the bottom of the foot to act as a force sensor. For the purpose of this case study the piezoelectric films were used to measure the knee, elbow, ankle, and armpit joints. The model of the piezoelectric film uses three XYZ triples to define its placement, two of which correspond to the attachment points for the ends of the film and the third representing the attachment point for the center of the film. The model considers stress induced only in the lengthwise direction of the film and also includes a method for introducing random error. In order to verify the model, a simple pendulum apparatus was constructed and a piezoelectric film was used to measure the rate of change of theta, the angle defined by the pendulum arm and the arm attached to the pivot point. Figure 4 compares results measured from the experimental apparatus to results from our simulation of our model for a single swing cycle. The slight irregularities in the actual data acquired from the constructed pendulum are likely a result of a slight torsion effect. Future version of the model will likely include such second order effects and a more accurate representation.

Table 2. Accuracy of beamformer vs. shoulder movement: sampling rate required to achieve maximum 15 degree error is highlighted.

Chest, inches	Number of mics	Samples per sec	fmax, Hz	Maximum/Average error (degrees)			
				No shoulder movement	Both shoulders move forward 10 degrees	One shoulder moves forward 10 degrees	One shoulder moves forward 20 degrees
36	2	2048	363	23/11	22/11	27/11	32/13
		4096		**11/5**	**11/5**	**15/6**	20/10
		8192		5/2	5/2	9/5	**15/9**
	3	2048		23/11	23/11	27/12	32/13
		4096		**11/5**	**11/5**	**15/6**	20/10
		8192		5/2	5/2	9/5	**15/9**
44	2	2048	297	**15/7**	**15/7**	19/8	24/8
		4096		8/3	8/3	**15/5**	20/5
		8192		3/1	4/1	7/5	**14/2**
	3	2048		**15/7**	**15/7**	19/8	24/8
		4096		8/3	8/3	**15/5**	20/5
		8192		3/1	4/1	7/5	**14/2**

The accelerometer model is based upon the ADXL150/250 analog accelerometer. As stated in the data sheet [1], the output voltage of the device is characterized by the equation $V_{out}=V_{dd}/2–(Sensitivity*V_{dd}/5*a)$ where sensitivity g is acceleration due to gravity, sensitivity is in mV/g, and a is acceleration in g's. The simulation model calculates this equation given the acceleration gleaned from the motion data input in an XYZ triple. The accelerometer model was also verified using the simple pendulum by placing the accelerometer on the head of the pendulum and measuring the acceleration along the horizontal axis. Figure 5 shows the results of the simulation as compared data collected from the accelerometer circuit placed on the pendulum.

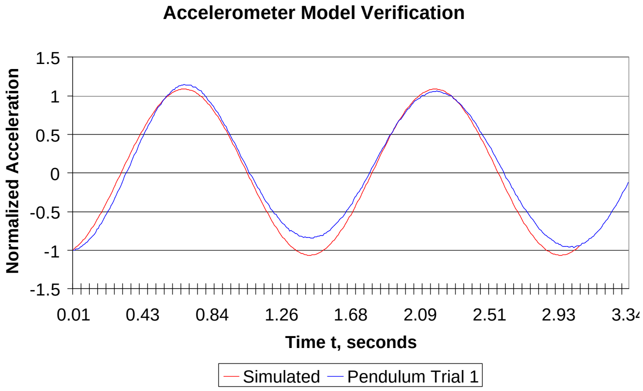

Figure 5. Simulated and measured accelerometer data for pendulum test

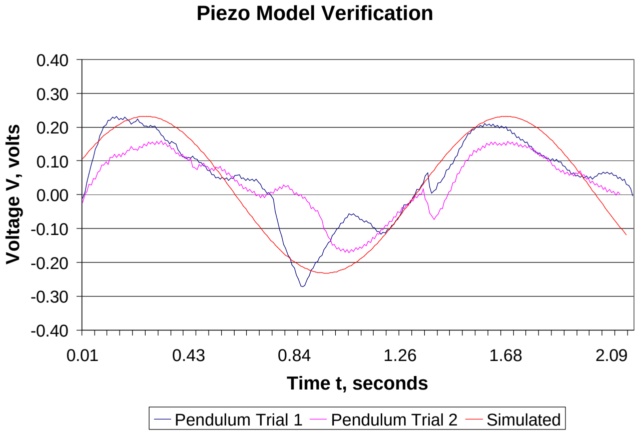

Figure 4. Simulated and measured piezoelectric film data for pendulum test.

4.2.2 Effect of variation in human size and motion

With the sensor models constructed, the next step is to analyze human motion and body size to determine the range of accelerations that will be encountered. As mentioned earlier, the use of simulation allows for the extraction of design parameters prior to prototyping that, without simulation, would not normally be available until after prototyping across a range of subjects. Table 3 depicts the minimum, maximum, and average acceleration values for the left/right hip, knee, and heel joints across a group of twenty subjects, using the data from [3].

The data in Table 3 indicates that a single accelerometer sensitivity configuration will not sufficiently accommodate the various dynamic ranges across the body. Using a similar table incorporating all motions to be considered in the design, the ideal accelerometer sensitivity configurations can be calculated for various joints that will generalize across the set of motions. The table also includes the average angular velocity of the knee joint. This type of metric is useful for both characterizing various motions as well as guiding the design of analog/digital piezoelectric film interface circuitry. While the table represents a small subset of possible measurements, it illustrates the ability to generalize dynamic range characteristics allowing for easier and more successful sensor calibration.

Simulation not only allows for the generalization of

Table 3. Acceleration in the forward direction and angular velocity data for walking, running, and jumping

Action:	Walk			Run			Jump		
	Acceleration, mm/s^2			Acceleration, mm/s^2			Acceleration, mm/s^2		
Joint:	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
Left:									
Hip	-33	27	10	-80	110	30	-160	149	17
Knee	-117	134	38	-286	371	108	-255	341	47
Heel	-364	198	61	-793	395	164	-657	392	56
Right:									
Hip	-27	25	9	-59	117	29	-183	149	18
Knee	-133	127	40	-258	402	112	-285	356	47
Heel	-217	217	136	-861	556	172	-615	292	58
Avg. angular velocity, degrees/s	116			250			133		

motion characteristics but also allows for generalization across the target population. This type of information assists in the development of a set of guidelines for sensor placement and application development across all wearable textiles. It is extremely important to understand how the properties of motion to be measured vary with people of different with varying biological statistics.

To illustrate difference in motion across the population, we used the Ptolemy II model to measure acceleration of the knee joint across a range of subjects from the database of user motion in [3]. Anthropometric statistics indicate that based on knee-heel distance, these subjects fall between the 10th and 50th percentiles of the population. Figure 6 plots the maximum and average measured acceleration at the knee joint for these subjects as well as the knee-heel distance. The results show considerable variation across subjects, with a weak correlation to body size.

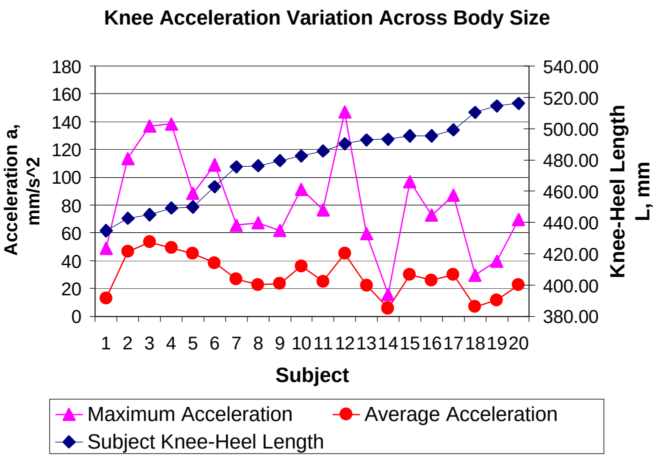

Figure 6. Average and maximum acceleration of the knee, and knee to ankle length across subjects

Such variation can have a significant effect on application performance. To illustrate this, we constructed a simple neural network that processed the output of the previously described Ptolemy sensor models and classified user motion as either walking or running. By training the neural network with motion from different users, we saw significant differences in the accuracy of the classifications produced. Figure 7 plots the accuracy of the classification across subjects (the first set of subject data sets are walking and the later sets are running) for several different training sets. Note, for example, that using a single "slow" user results in very poor accuracy for faster users, while the converse is true when using a single "fast" user. Consistently reliable results were produced when using both users to train the network.

These experiments illustrate that it is possible to explore design parameters using the framework without constructing a physical e-textile prototype. At this time, the current system does not reflect the fabric and garment manufacturing process. The sensor locations will be constrained by either the placement of piezoelectric strips woven into the fabric or potential attachment locations/wires in the fabric for the accelerometers. Further constraining the location choice will be the discrete number of garment sizes manufactured. The sum of these constraints will result in sensor locations that will vary across users, for example, for some users a sensor may be located directly on the knee, while for others it may be located slightly below the knee.

5. Conclusions and future work

The design space for e-textiles is too large to be efficiently explored by only building prototypes. The stricter constraints faced by e-textiles require new solutions to be found for questions that have been studied in related computing domains such as distributed systems and embedded computing. The stricter constraints also create problems that have not been studied before, such as optimizing energy usage when both the power sources and power consumers are distributed throughout the system, or allocating tasks to processing and sensing elements located on the body based upon the motion of a user and objects in the user's environment. The best method to find the answers to these questions and to explore the e-textile design space is through a design framework that combines simulation with prototype construction.

A successful design framework for e-textiles must encompass a broad range of areas, including physics of environmental phenomena, sensor behavior, human motion, body size, manufacturability, and computer architecture. In this paper, we have presented the beginning phases of such a framework and examples of its use in the design of two wearable e-textile applications. Previous work [15] has focused primarily on the inclusion of computer architecture-related features to e-textile modeling and simulation. Our focus in this paper has been primarily on the design framework itself

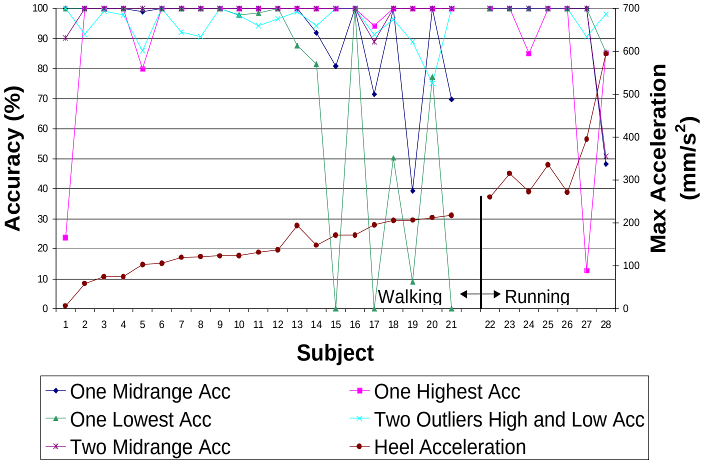

Figure 7. The accuracy of user motion classification across subjects plotted for different training sets.

with particular attention to aspects of the framework related to variation in human size and motion. Future work on the framework will include the additional modeling capability for fabric and garment construction as well as the draping/motion of fabric relative to the human body. The use of Ptolemy II to integrate and build the environment allows us to use existing tools for some aspects of the system.

Through continued application of the design framework and exploration of the design space, we can begin to build a more general set of guidelines and design rules for the successful development of e-textiles applications. With respect to variation in human size, shape, and motion, we plan to quantify the effect of this variation on a range of applications as well as standardizing methods to address this issue during design. In addition to the impact on e-textile design, the effects of human size, shape, and motion are also relevant to the design of many non-textile-based wearable computing applications, and with little effort, our framework could be extended to those applications.

Acknowledgements

This research was partially supported by the National Science Foundation under contract # CCR-0219809 and by the DARPA Information Processing Technology Office, E-Textiles Program, under contract #F30602-00-2-0548.

References

[1] Analog Devices ADXL150/250 Accelerometer Data Sheet. http://www.analog.com/UploadedFiles/Datasheets/573918736ADXL150_250_0.pdf.

[2] Basu, S.; Schwartz, S.; Pentland, A. “Wearable phased arrays for sound localization and enhancement,” Proceedings of the Fourth International Symposium on Wearable Computing, Oct. 2000, pp. 103 - 110

[3] CMU Graphics Lab Motion Capture Database, http://mocap.cs.cmu.edu/search.html

[4] Clarkson, B.; Mase, K.; Pentland, A. “Recognizing user context via wearable sensors,” Proceedings of the Fourth International Symposium on Wearable Computing, Oct. 2000, pp. 69 - 75.

[5] Eberhardt B., Weber A, and Strasser, W. “A Fast Flexible, Particle System Model for Cloth Draping.” *IEEE Computer Graphics and Applications*, vol. 16, No. 5, Sep. 1996, pp. 52-59.

[6] Edmison, J., Jones, M., Nakad Z., and Martin, T. "Using piezoelectric materials for wearable electronic textiles," *Wearable Computers, 2002. (ISWC 2002). Proceedings. Sixth International Symposium on* pp. 41-48, 2002.

[7] Eleksen, Ltd. "ElekSen Product Description WebSite," http://www.eleksen.com

[8] Farringdon, J.; Moore, A.J.; Tilbury, N.; Church, J.; Biemond, P.D. “Wearable sensor badge and sensor jacket for context awareness,” Proceedings of the Third International Symposium on Wearable Computers Oct. 1999, pp. 107 - 113

[9] Gemperle, F.; Kasabach, C.; Stivoric, J.; Bauer, M.; Martin, R. “Design for wearability,” Proceedings of the Second International Symposium on Wearable Computing, Oct. 1998, pp. 116-122.

[10] Golding, N., and Lesh, A. “Indoor navigation using a diverse set of cheap, wearable sensors,” Proceedings of the Third International Symposium on Wearable Computing, October 1999, pp. 29-36.

[11] Jones, M., Martin, T. and Z. Nakad "A Service Backplane for E-Textile Applications," *Workshop on Modeling, Analysis, and Middleware Support for Electronic Textiles (MAMSET)* pp. 15-22, 2002.

[12] Jung, S. Lauterbach, C., and Weber, W. "Integrated Microelectronics for Smart Textiles," Workshop on Modeling, Analysis, and Middleware Support for Electronic Textiles, October 2002.

[13] Lind, E.J., Eisler, R., Burghart, G., Jayaraman, S., Jayaraman, S., Rajamanickam, R., and McKee, T. "A sensate liner for personnel monitoring applications," *Wearable Computers, 1997. Digest of Papers., First International Symposium on* pp. 98-105, 1997.

[14] Measurement Specialities "Piezo Film Sensors, Technical Manual. Measurement Specialties, Inc," 2003.

[15] Nakad, Z. Jones, M. and Martin, T. " Communication in Electronic Textile Systems," to appear in the Proceedings of the International Conference on Communications in Computing, August, 2003.

[16] Park, S., Gopalsamy, C., Rajamanickam, R., and Jayaraman, S., "The Wearable Motherboard™: An Information Infrastructure or Sensate Liner for Medical Applications," in Studies in Health Technology and Informatics, IOS Press, Vol. 62, pp. 252-258, 1999.

[17] Parker, R., Riley, R., Jones, M., Leo, D., Beex, L. and Milson, T "STRETCH - An E-Textile for Large-Scale Sensor Systems," *International Interactive Textiles for the Warrior Conference* pp. 592002.

[18] Pillai, U. *Array Signal Processing*. Springer-Verlag, New York, 1989.

[19] Post, E.R., Orth, M., Russo, P.R., and Gershenfeld, N. “*E-broidery Design and fabrication of textile-based computing,”* IBM Systems Journal, Vol. 39, Nos. 3&4, 2000.

[20] Ptolemy Project, Heterogeneous Modeling and Design. UC Berkeley, http://ptolemy.eecs.berkeley.edu.

[21] Randell, C.; Muller, H. “Context awareness by analysing accelerometer data,” Proceedings of the Fourth International Symposium on Wearable Computing, Oct. 2000, pp. 175 – 176.

[22] Ressler, S. "AnthroKids - Anthropometric Data of Children," National Institute of Standards and Technology, http://ovrt.nist.gov/projects/anthrokids/.

[23] Riley, R., Thakkar, S., Czarnaski, J. and Schott, B. "Power-Aware Acoustic Beamforming," Proceedings of the Military Sensing Symposium Specialty Group on Battlefield Acoustic and Seismic Sensing, Magnetic and Electric Field Sensors, September 2002.

[24] Spinks, G.M., Kim, B.C., Wallace, G.G., and John, R. "Electroformation of conductive polymers in a hydrogel support matrix," *Polymer* vol. 41, pp. 1783-1790, 2000.

[25] Van Laerhoven, K.; Cakmakci, O. “What shall we teach our pants?” Proceedings of the Fourth International Symposium on Wearable Computing, Oct. 2000, pp. 77 - 83

[26] Van Laerhoven, K., Aidoo K.A. and Lowette S. "Real-time analysis of data from many sensors with neural networks," *Wearable Computers, 2001. Proceedings. Fifth International Symposium on* pp. 115-122, 2001.

[27] Wild Ginger Software, Inc., “PatternMaster Website,” http://www.wildginger.com/PRODUCTS/patternmaster.htm