NC STATE UNIVERSITY

JTATM

JOURNAL OF TEXTILE AND APPAREL, TECHNOLOGY AND MANAGEMENT

*Volume 4, Issue 3, Spring2005*

# Expanding Garment Functionality through Embedded Electronic Technology

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## ABSTRACT

*Electronic technology offers exciting new possibilities for functional clothing design. Technology allows a garment's functionality to become dynamically adaptable, changing in response to environmental or situational changes. However, there are many challenges to integrating electronic technology into a textile-based garment structure. This paper outlines some of the possibilities and challenges to apparel designers in this new field, and highlights the importance of the apparel design perspective in the successful design of wearable technology.*

*Keywords: Wearable technology, smart clothing, wearable computing, functional clothing, apparel design*



## 1 Introduction

Electronically augmented clothing has the potential to meet the user's functional needs in a dynamic, efficient manner. However, the use of electronic and computing technologies is a relatively new tool for apparel designers. While electronic components create new design variables for apparel designers, at the same time the integration of electronics into the body space creates new variables for technology designers. Many current prototypes suffer from the divide between these two perspectives. An iterative, aware design process can in theory help to form a complete design perspective, but in practice it is often difficult for designers to imagine influencing variables that lie outside their scope of experience.

This overview seeks to introduce to apparel designers some of the important and challenging new issues that arise in wearable technology design.

## 2 Textile Foundations

Historically, functional clothing has utilized mechanical means or passive textiles to achieve its functional goals. (Watkins, 1995) For instance, cold-weather clothing has relied on the textile's and garment's ability to retain the heat produced by the wearer's body by reducing conductive, convective, or radiant heat transfer. Such textile or mechanical solutions are effective in static or homogenous environments, where the user's needs and environmental conditions remain consistent over time. In variable environments or when presented with a diverse set of user needs, passive solutions are not always optimal. For instance, should the user of a cold-weather suit find him/herself in a warmer environment, the ability of the garment system to retain body heat would quickly become a negative feature.

New technologies have introduced ways to create dynamic functionality in clothing and textiles. One such method is the engineering of adaptive textile structures which react to environmental changes by altering their physical properties. Examples of this include phase-change materials, UV-reactive dyes, and shear-thickening fluid coatings (for more examples see Braddock and O'Mahony, 1999). Such textile advances can provide garment systems which are engineered to respond to specific changes.

While adaptive textiles are elegant solutions to the problems they address, this tactic requires custom engineering of a specific textile for every situational or environmental change. The alternative is to make use of textile and non-textile technologies whose properties change when exposed to an electric current. Electrically active materials, when combined with sensor networks, can be used to create many types of garment systems that can respond to input from multiple environmental or situational changes. For instance, an adaptive textile with a phosphorescent surface treatment responds to a single environmental change: presence or absence of ambient light. An electronically active garment system with the ability to generate a light source (Dunne, Ashdown, and McDonald, 2002) can be designed to respond to any number of contextual changes, providing the system with enough information to moderate the appropriate activation or suppression of the garment response (activation if the wearer is on a dark busy street, suppression if the wearer is in a darkened movie theatre).



## 3 Background: Wearable Technology

As seen in Figure 1, the scope of wearable technology overlaps with that of functional clothing. Wearable technology itself contains two sub-groups of interest here. The first is *wearable computing*, body-mounted devices traditionally more focused on assuming the kind of information-processing tasks performed by desktop or portable computers. The second is *smart clothing*, garment-integrated devices which augment the functionality of clothing, or which impart information-processing functionality to a garment.

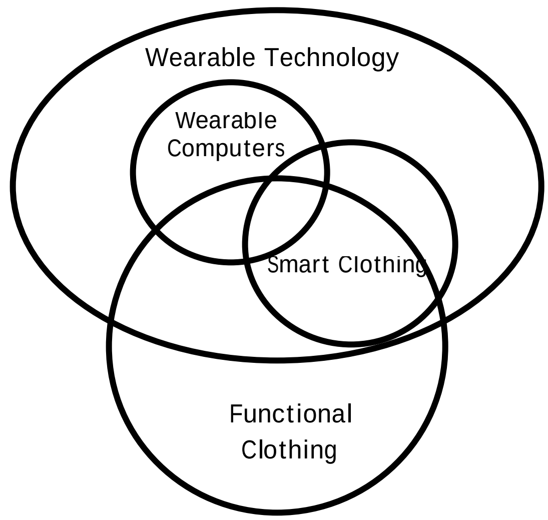


**Figure 1: Relationships among clothing technologies**

The field of wearable technology itself is a sub-set of the larger field of ubiquitous or pervasive computing. Ubiquitous computing refers to computing devices that are embedded in everyday objects, environments, and individuals. (Weiser, 1991) They can be anything from simple sensors to high-powered computer systems. These devices can be designed to monitor their environment or selectively activate their host device based on sensor input, and are incorporated into objects as basic as a thermostat or as advanced as smart appliances. Distributed and ubiquitous computing devices result in a flow of information that pervades our living spaces. This may seem like a 'futuristic' concept, but in fact most of us interact with ubiquitous technologies every day: from automatic door openers to self-flushing toilets. We also interact with personal body-worn computing devices on a daily basis: cell phones, PDAs and portable music players are all often mounted on the body; in pockets, bags, or carried by hand.

Mobile body-mounted devices take a variety of forms:

- *Carried devices*, which are placed in pockets or bags, and are not designed to be worn continuously.
- *Body-mounted devices*, which are designed for constant wear but do not necessarily take the form of a traditional garment, and are instead strapped on or otherwise affixed to the body (see Bodine and Gemperle, 2003 for two examples)
- *Garment-integrated devices*, which are designed for constant wear and are embedded into a garment; these often function only when the user is wearing the garment, but may also be removable (Barfield et al., 2001)
- *Implanted devices*, which are implanted directly into the user's body; these are usually not intended to be removable (Holland, Roberson, and Barfield, 2001).

This review will focus primarily on garment-integrated devices, as these are the most relevant to apparel-based research.

## 4 Wearable Technology: A New Design Challenge

As with any attractive new technology or concept, one major design problem is over-application. There is a tendency on the part of designers and developers to create wearable technology for the sake of wearable technology. This results in the "because we can" application, or applications in which a problem is sought which fits a pre-existing solution. Unfortunately, this kind of reverse design process often leads to applications or products that are inefficient or unattractive to users. In wearable technology specifically, this is often seen in the integration of existing portable or mobile technologies into a garment. While the hands-free approach can be effective, garment-integration is often not the best solution.

The reason for this springs from the disparity in product cost, expected lifespan, and situational appropriateness between garments and complex electronic technologies. A garment is developed in a few months, produced in a season, and expected to be worn anywhere from a few months to a few years. Portable technologies like cell phones, mp3 players, PDAs, or laptop computers are developed in a year or more, produced in a similar time frame, and expected to last 3 years or more. Therefore, when the two are integrated, their cost and life cycle must be reconciled. Consumers are not willing to pay for an expensive technology (such as a personal computer) every time they purchase a jacket, and the producer of the jacket will have difficulty shifting a product line from producing new models every 3-6 months to producing new models every 1-2 years.



More significantly, the device and the garment are expected to function in a different set of environments. Most garments are situationally specific in some way: they are designed for specific environmental conditions and social environments. Portable devices, on the other hand, are generally required in a broader set of situations. If an mp3 player is permanently integrated into a garment, then that specific garment must be worn any time the user wishes to make use of the device. Either the garment must become as versatile as the device, or the device must become inexpensive enough that the user may own as many devices as situational garments.

In the design of wearable technology, the designer must continually ask: why is this device wearable (or garment-integrated)? Would the device function better as a portable device? Better yet, the design process should start from an existing problem, and technology only be applied when it is the best possible solution.

## 5 New Parameters for Design

Most current wearable technology research is driven by the computer science/electrical engineering disciplines. Therefore this research often reflects the traditions, logic, and common practices current in those disciplines. These practices differ from the norms of apparel research in their narrow focus on the information space versus the body space. However, many body-centric wearability issues such as weight distribution, movement and mobility, sizing and fit, thermal management, and moisture management are crucial to the comfort and functionality of a wearable device. As functional apparel designers know, an uncomfortable or badly designed protective garment loses its protective abilities completely when the user alters the configuration or refuses to wear it. In mass-market wearable technology, this problem is magnified. An average user will not tolerate discomfort (physical or social) or difficulty of use in a device which provides only marginal benefit or slightly increased convenience, as is the case with many non-niche-targeted wearable technologies.

While apparel designers are accustomed to taking into account the physical impact of a garment on the human body, the integration of electronic components into apparel introduces many new variables to be addressed by the designer. Among these are bulk/weight/stiffness, thermal and moisture management, flexibility/durability, sizing and fit, and device interface.

### *5.1 Bulk/weight/stiffness*

Electronic components, while ever decreasing in size and weight, are generally relatively stiff and solid. Because off-the-shelf computer components and circuitry are generally designed to minimize their physical size by centrally locating all components on a single board, the result is often a blocky, rigid object of considerable size relative to the planar surfaces of the human body). Most available power sources are similarly constructed as rigid blocks, adding even more bulk, stiffness, and weight.

Careful distribution of these solid elements over the body surface can reduce their perceptibility and discomfort. Gemperle et al. address this issue in determining optimal shapes and body locations for wearable technology (Gemperle et al., 1998.) The shapes in that study, however, must be held close to the body in order for their comfort to be preserved. In a garment-integrated paradigm, the garment structure may not permit objects to be maintained in contact with the body surface. Gemperle's parameters can still be used to guide object placement, but in the garment-integrated case, existing garment structures must also be taken into account. Bulk and stiffness of electronic components can often be incorporated into a garment in places where bulk or stiffness already exists: in areas of garment padding or interfacing. Figure 2 illustrates body areas where garments are often padded or stiffened: blue areas represent padding; grey areas represent stiffening. Exploiting pre-existing volumes or areas of stiffness will be easier in more structured garment systems. The business suit, for example, provides a good deal of available real estate for incorporating electronic components, and is also worn in many situations and environments which may present a need for wearable devices (Dunne, Toney, Ashdown, and Thomas, 2004).

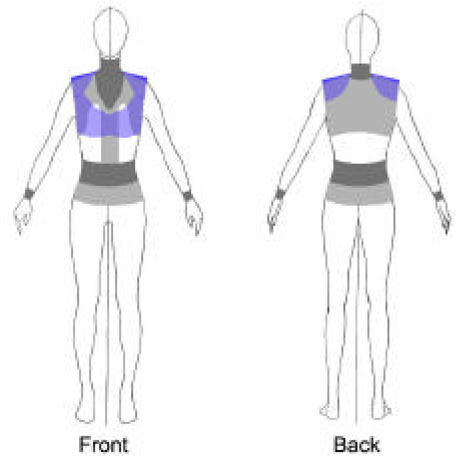


**Figure 2: Common Areas of Garment Padding or Stiffening**

*5.2 Thermal and Moisture Management*

Clothing comfort is closely related to the transport or conservation of heat and moisture throughout the garment system. Computing and electronic components are all resistive to some degree. In a resistive device, a portion of the electrical current is lost as radiant heat. Thus, electronic components produce heat, some more than others. This heat can be damaging to the computer system and heat dissipation is often a priority in system design. Microprocessors and other complex chips must be cooled in order to prevent malfunction of their fine circuitry. This is usually accomplished using a heat sink or a fan.

Excess heat can also be a problem in a garment system. In cooler environments, the user may not experience discomfort from the heat generated by the device. The user's body itself can then operate as a heat sink to absorb excess heat. However, in warmer environments both the user's body heat and the device's heat must be removed or diffused. Depending on the external temperature, this task can be difficult. It is important for the apparel designer to take into account the specific areas of a device which may produce heat. The smaller the area over which electronic components are distributed, the smaller the area over which their heat is initially distributed. Recent advances in miniaturization have not been paralleled by similar advances in component power consumption. As a result, for a consistent level of functionality smaller components generally are hotter. Locating heat-producing elements in such a way that their heat is diffused away from the body into the environment or dissipated by body areas of high circulation and heat transfer (such as the limbs) can promote user comfort (Starner and Maguire, 1998).

Currently, almost all electronic circuitry is constructed on some sort of printed circuit board (PCB), made up of layers of impermeable resin. The body, however, continually produces moisture which is often used as a means of conductive heat transfer. Placing an impermeable, heat producing device over the body surface can both prevent evaporative heat loss and add to the trapped heat. Additionally, as trapped moisture builds up, it may pose a threat to the device itself—excess moisture may create a short circuit or corrode interconnections.

*5.3 Flexibility/Durability*

Standard solid PCBs are often difficult to integrate into clothing or body-mounted forms because of their inability to conform (statically or dynamically) to the contours of the body. Flexible PCBs are available with optimal bend radii of 1-2 millimeters. However, the flexibility of a populated board is dependent on the layout of its components. Boards are only flexible outside of the regions populated with components. Aggressive flexion or torsion in a populated region will weaken electrical connections and could cause components to be ripped free of the circuit board.

Flexibility and durability are trade-offs in wearable electronic design. In general, more flexible circuitry is less durable, and vice versa. However, it is not necessarily the individual components that are the issue—fine-gauge wires and conductive fibers used for connectors are very flexible and durable, for example. More often the interconnections between elements pose durability problems. Weak points such as pin connections and solder joints must be strain-relieved to promote durability, and this strain-relief is often not flexible.

In order to create flexible PCBs for garment integrated wearable electronics the component layout must be designed with components clustered in areas that can be stabilized against bend and torsion Stabilized areas can then be connected together by unpopulated (and thus still flexible) boards. Alternately, the design may be segmented with components distributed over many small inflexible PCBs joined together with ribbon-like flexible interconnections.

*5.4 Sizing and Fit*

Multiple concerns related to issues of sizing and fit are introduced when technology is incorporated into a garment. As previously discussed, wearable technology often incorporates bulky or solid areas, which must be situated at specific locations on the body in order to preserve comfort, mobility, and wearability. In some cases, device functionality is dependant on components being located in very specific body areas in order to operate as designed, such as sensors or actuators.

Most current wearable technology research involves the production and testing of a very limited number of research prototypes. Consequently anthropometric variation in the subject pool is generally small, and issues of sizing and fit are not addressed. Similarly, anthropometric differences between the sexes have rarely been addressed: for instance, the male upper chest is a planar surface that is appropriate for distribution of rigid objects. Rigid objects placed in the same location on the female chest would not be comfortable.

*5.5 Interface*

The user interface of a standard garment is usually limited to closures, adjustment points, and/or pockets. In an intelligent garment, the user interface can range from no physical interface at all (automatic or sensor-driven interface), to a complex keyboard/mouse based interface. The issue of user interfaces in wearable systems is a heavily researched area (for many examples, see ISWC, 1997-2004). Interfaces must be useable while mobile, in a variety of environments, and often while involved with other tasks. From the garment perspective, they must be accessible, comfortable to operate (ergonomic), and not create mobility or comfort restrictions. While these issues are complex in the physical domain (issues of ergonomics, wearability, comfort, and ease of access), there are still more issues in the cognitive domain. The structure of an interface has a significant impact on the user's ability to successfully accomplish tasks and attend to other input.

**6 Introducing the Information Flow**

Computing and communication technology introduces a new modality to apparel functionality: managing the flow of information. In the wearable sector of ubiquitous computing, the potential for almost limitless informational functionality is introduced into the body space. However, in such a system the management of demands on the user's attention and cognitive processes is essential. Imagine a wearable system with the ability to provide the user with unlimited and uninterrupted access to the world's knowledge base. The utility of such a system is obvious, but how would the system function? Requiring the user to actively query the system for information drastically reduces the potential utility. The system then would be limited by the user's cognitive capacity for active queries. At times the user may have need for information but lack the time or ability to query the system. Should the system then be designed to actively provide information based on, for instance, conversational cues, the situation becomes reversed: one can imagine the user inundated with information, only a portion of which would actually be useful.

Since wearable technology is ever-present and part of the user's immediate body space, it has the potential to make far more obtrusive demands on the user's attention than ambient or environment-based technology (like desktop computers or smart appliances). Wearable technology is more pervasively present in many more environments and situations than stationary technology. It also enters into social interactions to a much higher degree than peripheral technologies: this is commonly experienced when a portable telephone rings, interrupting a face-to-face conversation.

*6.1 Cognitive Ergonomics*

As the functional possibilities of wearable technology expand, the designers of such technologies must come to understand cognitive patterns and design the information flow around these needs. This field of study is known as Cognitive Ergonomics. The scope of the field is large, covering issues such as problem-solving strategies, attentional abilities, social negotiations, and trust or mistrust patterns. In the same way that physical ergonomic principles guide the design of successful physical structures, cognitive ergonomic principles guide the structure of the information flow (Long and Whitefield, 1989).

*6.2 Context Awareness*

In order to reduce the user's cognitive load and tailor the information flow, wearable technology can make use of sensor input. Many different types of sensors can be used to build a concept of the user's context: their physical location, social situation, and cognitive/emotional needs. There are three steps to context awareness, as illustrated in Figure 3. First, information about the user's specific context must be collected via discreet sensors or sensor networks. Second, that raw data must be processed, and synthesized into a conceptual model of context on which a decision is based. Third, some action must be initiated (or not) within a device based on the context model.

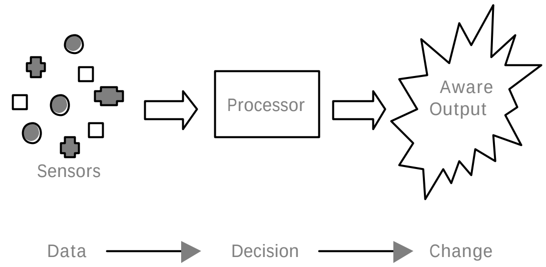


**Figure 3: Context Awareness**

The first step, sensing, can take many forms. From direct sensors that detect simple changes such as light levels, temperature, or presence of a specific chemical to less direct sensors that detect more complex changes such as microphones or cameras. Any given contextual cue may be detectable using several different methods: for instance, location can be established using global positioning systems (GPS), infra-red detection, radio-frequency (RF) tags, or simply with a password-protected door. Depending on the complexity of the contextual element and on the directness of information gathered by the sensor, the signal processing may be quite minimal or very elaborate. Data from a switch may require very minimal processing, where determination of conversational patterns from a microphone or face recognition using a camera are far more complex processes. Once the cue is extracted from the sensor, it may need to be incorporated with other sensor data into a conceptual model of the user's context. For example, a light sensor in a wearable system can be used to detect the ambient light levels of the user's environment. However, that data alone may not be sufficient to distinguish between a dark outdoor space where light is required and a dark indoor space (such as a movie theatre) where light is not desirable. Temperature, sound, location, and movement data could inform a more accurate and detailed model.

Once the contextual model is generated, it can be used to inform the operation of a system through various types of actuators. These range from those which control information flow (alerting the user to new information at a time when it is convenient to attend to it) to those which control the physical environment (altering the garment's temperature, color, structure, or function).

*6.3 Sensing the Body*

One of the most compelling needs for wearable technology is in the continuous monitoring of the human body, be that for medical monitoring or to inform the operation of a context-aware computerized application. While many technologies that are often made wearable (such as music players or telephones) function nearly as well (or sometimes better) as portable devices, almost all continuous body-sensing technologies must be worn to be effective. However, because of their ubiquitous, constant-wear nature, such technologies must prioritize the effects of the technology on the user's physical comfort as well as social comfort. Traditional sensing technologies are rarely designed for continuous, on-body use: those that require skin contact are generally designed to be used in a hospital or doctor's office, and those that do not are generally designed for use in stationary devices. Consequently, the achievement of certain design goals for existing sensors (such as durability) is ultimately detrimental to the user's comfort when applied to the wearable environment. For example, durability often equals stiffness, which results in a solid device that can cause discomfort by localizing pressure. Textile-based sensors offer a compromise solution to this problem, by retaining the tactile characteristics associated with comfort and wearability. Many textile-based sensors are actually sensing materials used to coat a textile or sensing materials formed into fibres and woven or knitted into a textile structure (DeRossi et al., 2003).

## 7 Challenges of Manufacture

Although wearable technology has recently emerged on several occasions from academia into commercially-available products, such products are few and far-between. Besides the problem of effective product design, there are also many difficulties in physically integrating electronic components into textile structures. To minimize these difficulties, a common approach in commercial garment-integrated devices has been to maintain (to the extent possible) the integrity of both garment and device by incorporating the device into a special pocket in the garment. However, this approach centralizes the device's bulk and weight, adds unnecessary volume and stiffness, and necessitates the incorporation of the entire device into one garment. If the device is broken down into its component functions (sensing, input, output, processing, power, etc), then it becomes possible to incorporate only the necessary components into each garment structure. The sensors, for instance, can be placed in an undergarment, or an input/output device in an outer layer. Processing and data storage can be left in a portable device that can then be used in many situations or with different garments. Integration of only garment-appropriate technology reduces the physical presence of wearable technology but also minimizes the added cost to a garment, making it much more accessible to the consumer.

Distributed integration, while often optimal for wearability and added cost, presents significant production challenges. The stability and durability of electronic components, as previously discussed, is compromised by integration into a flexible substrate. And unlike pocket-based integration techniques which preserve the integrity of garment and device, the manufacturing processes of textile, garment, and device must be much more closely integrated. Figure 4 outlines an example of an integrated production scenario, where the product moves between apparel/textile and electronic processes.

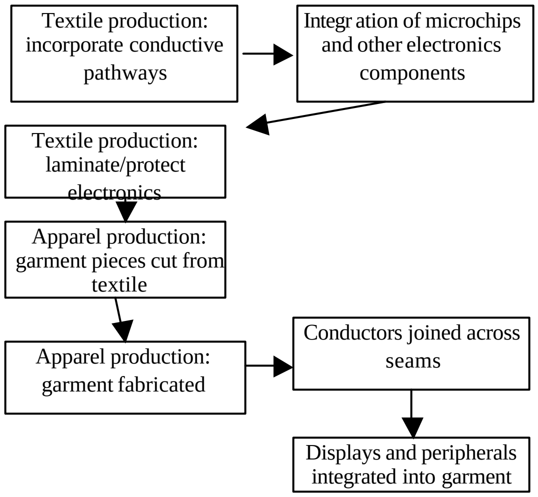


**Figure 4: Example Distributed Technology Productio n Process**

The integration of the production processes of electronics and apparel may be assisted by cutting-edge apparel production methodologies. Digital textile printing technology and CAD patterning software, for instance, may assist in the layout, attachment, and interconnection of conductive pathways in a cut-and-sewn garment.

Many recent commercial forays into wearable technology have involved products of considerable computational complexity (for examples, see Adidas, 2004 and Infineon, 2002). Products of this level of complexity require significant development and production costs. Consequently, the product price increases. Simpler devices rarely hit the market, perhaps because companies wish to present a more "impressive" offering. But simple electronics can often provide considerable increase in functionality at little cost. The knee sleeve developed by Munro et al (2004) uses a textile-based elongation sensor to sense the angle of the knee joint. Rather than use extensive technology to alter that angle, the device simply provides the user with direct feedback about the joint's movement. For instance, the sensor can integrated into an analog circuit containing only a few components that outputs an audible tone that varies as the knee bends. Slightly more complex circuitry gives the user a tone only when the knee is in a good landing position.

This type of simple device requires much less commercial development than a garment-integrated cell-phone. The component pieces are much less expensive, and much less numerous, yet the benefit to the wearer is clear.

## 8 A Case Study: Activity monitoring using soft sensors

Monitoring of a user's basic level of physical activity is often of use in context awareness. Such information can be useful in determining whether a user is walking, standing, or running, where the user is pointing or looking, or how long a user's body has been in one position.

As previously discussed, monitoring the body often imposes a certain level of discomfort on the user. In particular, many mechanisms for recording motion or position are intrusive, constrictive, or bulky, and can require skin-tight garments or skin-adhered elements. However, these same cues can be monitored using textile- and garment-based solutions.

As the body moves within a garment, dynamic forces are generated between the body and the garment. Equipping the fabric of the garment to respond to these forces can make it possible to gather data directly from the garment without altering its tactile and visual properties, or requiring the user to don new garments or wearable devices. In this way, the user's body movement can be deduced from the movement of his/her garments. One method for accomplishing this task is to coat a textile or foam with a conducting polymer, such as polypyrrole. The polymer coating has little effect on the substrate's hand, flexibility, or elasticity, and the coating is durable and resistant to laundering. When stretched, bent, compressed, or deformed, the coated structure becomes more conductive, and that change can be electronically monitored (Brady, Diamond, and Lau, 2005). Through selective coating of specific garment areas, forces created by joint movement, external pressure (sitting, leaning, lying or standing, carrying a bag, etc), or even physiological functions such as breathing can be monitored (Dunne, Brady, Diamond, and Smyth, 2005a). Combinations of sensors can be used to detect complex information such as joint angle (Dunne et al., 2005b).

The advantage to embedding sensing intelligence into the garment itself is that the sensor and the technology become minimally invasive for the user. There are no separate devices and no tactile discomfort for the user: from the user's perspective, the garment remains the same. Returning to the issues discussed in section 5, it is clear how such a textile-based sensing device could aid in problems of thermal and moisture management, as well as stiffness, by retaining a soft, breathable textile structure.

## 9 Conclusion

The perspective and knowledge base of apparel design is crucial to the design of successful wearable technology. However, just as the technology designer's perspective is incomplete with respect to apparel, so is the apparel designer's perspective with respect to technology. While collaboration removes the need for one person to be an expert in all of the fields that influence successful design in this arena, it is very helpful in facilitating collaboration if all team members have some working knowledge of all the variables involved; both of textiles and user needs and of technology capabilities and functions.

As a developing field, the inter-disciplinary components that make up wearable technology are still relatively isolated from each other. Dialogue is crucial, between apparel and technology designers and especially between apparel and technology producers, to identify and resolve the problem areas. The potential of technology to expand the functionality of apparel is immense, and by no means a futuristic possibility. The technology exists, and needs only to be adapted to the apparel environment.

## 10 Acknowledgements

This material is based on works supported partly by the College of Human Ecology at Cornell University and partly by Science Foundation Ireland under Grant No. 03/IN.3/I361.
Thanks also to Susan Watkins for invaluable assistance in the development of this work.

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