Garment Integrated and Deployable Technology

by

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Glossary

Affordance is a term borrowed from psychology, where it is used to describe the "action possibilities" that an object presents the individual. For example, a doorknob affords grasping and use in opening. Psychology's use of Affordance is idiosyncratic to the individual. Stairs, for example, afford climbing to the able bodied but not to individuals in a wheel chair. When describing human-machine interactions, an object's affordance represents the usage an object offers the user based on both physical context and the user's experience interacting with similar objects.

Anthropometry is the study of the size and proportions of the human body.

Deployment is a new usage context for mobile devices, advanced in this thesis as a way to ensure a mobile user's ubiquitous computing coverage (Toney and Thomas 2006; Toney and Thomas 2007). Deployment is the act of a user temporarily instrumenting their environment by meaningfully placing a device. When devices are deployed overtly, the act of deployment can act as a social cue to all parties that support technology is in use. For example, a businessman using a mobile device to capture the content of a meeting might place the device on the table before him. Not only would this better position the device for the task of capturing information about a meeting, it also discreetly signals all participants that recording technology is in use. In a more overt usage, the deployed device could project data or track object immediately in front of the businessman instrument his immediate environment with displays and tangible user interfaces. As part of the user moving on to a new environment the deployed devices are collected so the can be redeployed.

Direct Manipulation User Interface Direct manipulation and direct touch user interfaces have user interface elements that require being physically touched by the user as part of their use (Toney and Thomas 2006). For the work of this thesis, direct manipulation and direct touch user interfaces refer to interfaces that present their elements on large touch sensitive display surfaces.

Direct Touch User Interface Another term used to refer to the same class of interfaces as Direct Manipulation User Interfaces.

Dyad refers to something consisting of two elements.

Dyadic interactions are interactions between two or more individuals. Dyadic interactions specifically refer to social interactions.

FCB is an acronym that stands for Fabric Circuit Board. Fabric circuit boards are similar to conventional printed circuit boards, only instead of fiberglass housing electrical circuit paths in copper; an FCB uses layers of conductive fabric sandwiched between nonconductive insulating fabrics to provide the electrical circuit paths. Components mounted to an FCB are electrically connected to exposed pads of conductive cloth, similar to the exposed areas of the top and bottom layers of conventional circuit boards.

Graspable User Interfaces were first proposed in Fitzmaurice et al's paper "Bricks: Laying the Foundations for Graspable User Interfaces" (Fitzmaurice, Ishii et al. 1995). Graspable user interfaces use artifacts that are "…tightly coupled or 'attached' to virtual objects for manipulation or for expressing action." (Fitzmaurice 1996), using "movement in real physical space to control navigation in the digital information space" (Small and Ishii 1997). Two years later, the same group proposed the extended concept of tangible user interfaces, which has largely eclipsed graspable user interfaces in the literature.

Pervasive Computing is a branch of the field of Ubiquitous Computing.

Physical Presence is a subjective measure of how noticeable the presence of a device is. The physical presence of a device is not a constant attribute, for example the physical presence for a phone contained in its user's pocket jumps dramatically when it uses an audible ring to notify its user. (Toney, Mulley et al. 2002; Toney, Mulley et al. 2003). Physical presence is also highly dependent on context, the ringing phone in would experience a much smaller jump in physical presence if it rings in a loud informal environment like a sporting event, then it would at a quiet or formal even like the theater or a business meeting (Toney, Mulley et al. 2003).

Smart Garment is the term used in this work to refer broadly to any article of clothing with integrated electronics including a microprocessor (Toney, Thomas et al. 2006). This differs from other researchers in the field, who tend to use the term smart clothes or smart clothing in a similar capacity. Smart clothing has the drawback that it is an inherently plural term, referring to multiple garments. The distinction was made as this work deals with both individual prototype garments and collections of smart garments or smart wardrobes. The term smart clothing is only convenient for referring to the special clothing in the plural, as the singular used awkward wording such as "an article of smart clothing".

Smart Garment Management Systems (SGMS in the singular) provide their user with a central common interface for maintaining their clothing (Toney, Thomas et al. 2006). Primarily the SGMS provides a single interface for the user to maintain their smart garments, effectively allowing them to treat all of their smart garments as a single device. As an ancillary benefit of having a system managing their garments the SGMS can guide the user's choice of clothing ensuring their chosen day's outfit always provides in aggregate a pre-specified level of functionality. As part of guiding the daily choice of clothing, the SGMS also handles other garment management functions such as ensuring appropriate attire for scheduled functions or weather, managing dry cleaning schedules, or home shopping.

Smart Wardrobes offer a means of smart garment management advanced in this thesis. The term wardrobe can either refer to a cabinet in which clothing is stored, or to an individual's entire collection of clothing (Toney, Thomas et al. 2006). Within this thesis, the term smart wardrobe refers exclusively to a cabinet, which is part of a smart garment management system.

Social weight was a concept proposed in this thesis to measures the social consequences of technology use. For an item of technology, Social weight is formally defined as the measure of the degradation of social interaction that occurs between the user and other people caused by the use of that item of technology.

Tangible User Interfaces were first proposed within the academic community at SIGGRAPH in 1998 in the presentation of the “mediaBlocks: Physical Containers, Transports, and Controls for Online Media” (Ullmer, Ishii et al. 1998). Tangible User Interfaces (TUIs) are “…a genre of human-computer interaction that uses spatially reconfigurable physical objects as representations and controls for digital information.” (Ullmer 2002). The concept of tangible user interfaces evolved out of the group’s earlier work on graspable user interfaces, and has subsequently eclipsed it in the literature. The work identified simple tangible interactions occurring for block based physical user interfaces, demonstrating those interactions as part of a video-editing suite. A refined version of this work was more formally presented two years later in the IBM Systems Journal (Ullmer and Ishii 2000), and has since become the benchmark for tangible user interfaces.

Transitional environment is used in this thesis to refer to environments in which a mobile user has temporarily stopped and is using technology. A coffee shop in which a businessman stops for a few minutes to review a presentation before visiting a customer site would be an example of a transitional environment. For the purposes of user interface design, I formally define transitional environments to be any place where a person is acting outside of a formal support infrastructure, usually for short periods of time, and is limited to whatever support bring with them and the locally discovered resources that they are willing to trust.

Two-point threshold is term referring to the minimum distance between two points of tactile stimulation before they can be perceived as separate. The two-point threshold on the body varies with the location of the stimulation, and the stimulation channel tested.

Ubiquitous Computing is a term coined in the early 1990s by Mark Weiser (Weiser and Brown 1995), as part of describing the coming age of “calm technology”, or an age “…when technology would recede into the background of our lives.” The initial focus of Ubiquitous Computing applications was making sure that tools were always available to the user. The “tabs”, “pads”, and “boards” systems developed at XEROX PARC[1] under Mark Weiser are some of the earliest, and best-known, examples of ubiquitous computing. These systems took the approach of providing ubiquitous computing support by littering the environment with cheap interchangeable tools. As the field has matured it has spawned subfields such as Pervasive Computing. Disciplines which seek to provide ubiquitous support of the user by making the objects in the user’s environment more intelligent.

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[1] Xerox PARC – 3333 Coyote Hill Road Palo Alto, CA 94304 USA

Abstract

The Research conducted for this thesis was focused on supporting mobile users, developing "bring your own support" solutions in order to ensure that minimum levels of computational support are always available to the user. Research contributions were made along three distinct lines.

The first line of research developed ways to minimize the negative social consequences arising from technology use. Mobile technology will only be used when the user perceives that the benefits of its use outweigh its costs. Being able to minimize the negative consequences arising from use eases the user adoption for any new device. When developing technologies the user is intended to always have with them, it is critical to minimize any negative consequences associated with the technology. Any negative attributes for devices can build up over time and in aggregate can overwhelm the benefits of the technology, at which point the user will stop using the device or deviate from its intended use.

Research into garment integrated devices, their use construction, and management of smart garments formed the second line of research. Garment integrated devices have a unique perspective from which to observe their user, a perspective that is perfectly suited to implementing the sort of "bring your own support" solutions that are of interest to this thesis. By bringing the technology that they are going to rely on with them, the user can rely on a minimum level of support being available. Any discovered local resources only act to increase the level of support of the user.

Device deployment formed the third line of study pursued in this thesis. Deployed devices are another aspect of the "bring your own support" approach to supporting the mobile user. Deployed objects are temporarily placed in their user's environment in order to instrument them with additional coverage. Formal models were developed the space in which a user could deploy an object, the space usable by tangible inputs for the deployed object, and predict how the working surface will be segmented. After a number of studies ratifying the developed models, a small trial was run observing how users interacted with a simulated deployed application.

Declaration

I declare that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge it does not contain any materials previously published or written by another person except where due reference is made in the text.

Aaron Toney ....

Signature: ______________________________............. Date: ___________

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The hardest part about going to schools overseas was the distance from my family. As loud and passionate as we are, I love you all, and your love and support has emboldened me to pursue my dreams, even when doing so scared the hell out of me. Mom, dad, and Joe—I love you and I owe you more then I can articulate. Grandma K, you are one of the strongest people I know and have always been one of my biggest role models. Bubbie, I am sorry you did not make it to see me graduate. I love you and will miss you.

When I initially arrived at the Wearable Computer Laboratory it was for a three-month "working vacation" that would turn into the next four and a half years of my life. As fortunate as I was to find a position in a lab like the WCL, my true luck was in finding a group of people that I am proud to consider close and hopefully life long friends. You all were always there and supporting me with seemingly infinite patients while time and experience all too slowly blunted my ignorance and obstinacies.

As the visitor, I got paired with Barrie Mulley, and I am sorry to say probably made Barrie's life a royal pain for about a solid month and a half. Barrie, thank you for your friendship these past five years, and for talking through problems. You and Peter's constantly encouraging me to get out of the lab and get a life are what kept me sane and able to finish.

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Aaron Toney, August 2007

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The work of this thesis involved multiple collaborations. These collaborations shaped the work of chapter on Chapter 3 on Social weight, and the work of chapters Chapter 4 through Chapter 6, on Garment Integrated User Interfaces, Integration of Technology, and Smart Garment Management respectively.

Chapter 3 and Chapter 4 describe aspects of the e-SUIT's construction and social weight (Toney, Mulley et al. 2002; Toney, Mulley et al. 2003). The e-SUIT is a prototype garment with integrated technology that allows its user to surreptitiously adjust scheduling information. Mr. Barrie Mulley designed software running the e-SUIT's PDA, a Compaq H3660[2] series iPAQ^{TM}. This software provided the microcontroller integrated into the e-SUIT with access to, and the ability to alter, the user's Microsoft[3] Outlook Scheduling information.

Chapter 4 presents research on shoulder pad vibrotactile displays (Toney, Dunne et al. 2003). This research was conducted in collaboration with Miss Lucy Dunne and Dr. Susan P. Ashdown of Cornell University's Department of Textiles and Apparel. Both Miss Dunne and I collaborated on the design of a user study examining the potential of the shoulder as a location for garment integrated vibrotactile display. Miss Dunne constructed the shoulder pads and ran the subject in the study, while I constructed the hardware used to drive the display and the software used to conduct the user study.

Chapter 5 presents the mechanics of garment integration and manufacture. As part of this work a series of Smart Tags were constructed to demonstrate the modular design and assembly of the components of a smart garment. This work was conducted in collaboration with Mr. Wynand Marais of the University of South Australia, and Miss Leah Buechley of the University of Colorado at Boulder's Department of Computer Science. The Smart Tags were inspired, by Miss Buechley's e-textile kit construction kit (Buechley 2006; Buechley, Elumeze et al. 2006). I designed and laid out the required electronics, which were then assembled by Mr. Wynand Marais prior to being shipped to Miss Buechley. The electronics where then shipped to Miss Buechley, who constructed fabric circuit boards for the electronics, and then used them to retrofit one of her existing garments demonstrating Smart Tagging.

As part of Chapter 5's reviewing the design considerations surrounding wearability, I present material on considerations for wearability previously published (Dunne, Toney et al. 2004) by Lucy Dunne, Dr. Susan P. Ashdown, my advisor Dr. Bruce H. Thomas, and myself at the First International Forum on Applied Wearable Computing.

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[2] Compaq has subsequently been purchased by the Hewlett-Packard Company,

Hewlett-Packard Company – 3000 Hanover Street Palo Alto, CA 94304-1185 USA - Phone: 650 857 1501

[3] Microsoft Corporation – One Microsoft Way, Redmond, WA 98027-6399 – Phone: 800 642 7676

Chapter 6 presents smart hangers and a smart garment management system. The mechanics of how to reliably integrate conductive contacts into the shoulder of a garment was influenced by collaboration with Lucy Dunne, who had since moved to the Advanced Information Cluster University College Dublin. The relevant collaboration is not presented as part of this thesis but it generated correspondence, which influenced the design. Miss Dunne was originally supposed to be an author of the paper on Managing Smart Garments (Toney, Thomas et al. 2006), but chose to withdraw prior to the papers submission.

Wynand Marais was a co-author of the Smart Garment Management work (Toney, Thomas et al. 2006), that was the basis for Chapter 6. Mr. Marais worked under my supervision for two summers as part of scholarships offered for promising undergraduate students. Most notably Marais was solely responsible for the clever design of the spring-loaded hanger connection with a recessed bus terminal, the physical construction of the Narnia cabinet (pictured in Figure 50). Under my direction, Mr. Marais developed a demonstration user interface for Narnia, and then extended my original communications code, which enabled Smart Tags and Smart Hangers to communicate over the systems one-wire bus.

Chapter 8 concludes its presentation of the phenomena of table usage and segmentation with a discussion of device deployment. Since deployable devices with the functionality envisioned by the work of this thesis do not yet exist, testing usage of a deployed user interface required simulating both the deployed application and the deployed hardware providing the display. Mark Rebane and Vanessa Towers helped produce a simple user study to observe the usage of a deployed application. Miss Towers was a summer student working in the Wearable Computing Laboratory over the summer of 2006, and developed the testing software under the supervision of Mr. Mark Rebane and myself. Mr. Rebane is a member of the WCL and helped guide Miss Towers in the development of the graphical components of the deployment simulation software.

1

"I would have written a shorter thesis but I did not have time."
A Ph.D. Student blatantly ripping off Pascal.

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Chapter 1 Introduction

The goal of both ubiquitous and pervasive computing is to ensure the user is always supported. Ubiquitous computing attempts to provides this support by making formal tools plentiful and easily available - placing literally "…hundreds of wireless computing devices per person" (Weiser 1996) in the user's environment. Pervasive computing is an offshoot of ubiquitous computing, that attempts to support the user by making the objects already found in their user's environment more intelligent.

User mobility presents significant challenges to both ubiquitous and pervasive approaches for supporting the user. To date ubiquitous and pervasive computing research has focused on strategies instrumenting the user's primary environments, such as their home, car, and office, with tools and infrastructure. By instrumenting the environments in which users spend the majority of their time, researchers have been able to provide ubiquitous and pervasive support to the user the majority of the time. Unfortunately, while this approach provides support the majority of the time, it totally fails when the user leaves one of the preinstrumented areas, resulting in intermittent gaps in coverage throughout the day.

The obvious solution to supporting mobile users when they are traveling through areas where local support may be unavailable, insufficient, or untrusted is to take a "bring your own support" strategy. The rapid adoption of pagers, cellular phones, and general connectivity tools that provide access to email, scheduling information, and other resource, reflects how desirable users find this level of coverage. The coverage mobile devices are currently able to provide only represent relatively simple functionality in comparison to what their users will soon expect. Pervasive and ubiquitous infrastructures will be increasingly called upon to fill the deficits between the functionality users expect while mobile, and the functionality their mobile devices are able to deliver. The core of a "bring your own support strategy" is the user prioritizing the functionality they desire while mobile and ensuring that they carry mobile devices sufficient to provide that coverage. In this way the user is assured a desired level of support even when there is insufficient pervasive and ubiquitous infrastructure.

A "bring your own support" approach can also be used to increase trust in available pervasive and ubiquitous support when it is present. For example, when using local resources to provide high speed network access during a negotiation, periodically independently verifying the integrity of their connections using a slower network connection supplied by their mobile device, increases the users overall trust in the available local resources.

While it is currently common for an individual to carry multiple mobile devices, there is a strong trend towards the convergence of the different mobile devices. The work of this thesis postulates that this convergence trend will result in future mobile technology being structured around a single, user-worn, personal server (Want, Borriello et al. 2002; Want, Pering et al. 2002; Intel 2007) and a small number of accessory devices. High end smart phones and PDAs already have many of the features and capacity of simple personal servers: these small pocketable devices allow the user to carry trusted computational resources, file storage, and access available network connectivity. The personal server itself has only a minimal user interface, relying instead on discovered accessory devices and pervasive and ubiquitous computing resources, to provide the user interface elements. My research has focused on the development of accessory devices, carried with the user to provide their personal server with user interface elements.

1.1 Problem Statement

The accessories developed for the personal servers will themselves be carried with the user throughout much of their day, and be frequently used when the user is in social situations. This prolonged and frequent use necessitates that the negatives associated with device usage be minimized, so that the aggregate experience of prolonged device usage will not be a negative one. Socially this requires that the negative social consequences arising from device usage be minimized. Ergonomically this requires the developed devices be comfortable to wear or carry, and be physically unobtrusive when not in use.

Two different classes of accessory device were researched, garment integrated device and deployable devices. Garment integrated devices provide the personal server with a known set of user interface elements, detected when the server is initially activated and present throughout the day. Deployable devices allow the user to carry more powerful user interface elements. They fill the gap between the level of support suitable for garment integration, and the resources possible from a fixed ubiquitous or pervasive infrastructure.

Clothing needs to be functional, clean, and attractive. The importance of personal appearance necessitates that any garment integration of technology faces the constraint that it must not negatively impact the appearance, or fit of the garment. Maintaining garment function requires that the integrated technology meet a number of requirements, such as being light, soft and flexible, allow inner layers to breathe, and generating minimal thermal waste. Maintaining the garments as a wardrobe requires the garments remain washable, and that some management system be used so that a wardrobe full of smart garments does not become dozens to hundreds of new devices for the user to maintain.

Device deployment can provide user interface elements in many ways. This work focuses on using deployed devices to provide projected direct manipulation displays on temporary working surfaces. This requires answering a number of fundamental design questions such as: How much space is usable by the deployed user interface? Where should interface elements be initially placed, and to what degree should they be scaled to optimally make use of the available working surface? and, How can gross table segmentation be predicted from knowledge of the participating user's position and physical anthropometric parameters?

Answers to these various questions form the contributions of this thesis.

1.2 Contributions

My research has lead to a number of contributions to the state of the art in the design, construction, and use of mobile technology. Broadly, the contributions are as follows:

Social weight: The concept of device social weight has been developed in this thesis as a way to describe the negative social consequences associated with technology use (Toney, Mulley et al. 2002). A formal mathematical model of social weight has been developed, including techniques for numerically quantifying observed behavior and social interaction for use as components of the model. Therese tools were shown to have a role in the design process. Being able to quantifiably evaluate the social weight of a device or interface enables developers to iteratively refine their design in order to minimize their social weight. The designs themselves can use run time evaluation of social weight models to guide usage, directing their user to use strategies such as device or interface escalation to control their device usage (Toney, Mulley et al. 2003).

Garment integration of technology: A number of garment integrated prototypes were constructed for this thesis. The complexity of the garments necessitated making a number of advancements to the state of the art in garment integration. The three primary contributions made were; the technique of bedding, using cloth conduits internal to the garment, and integration into existing interfacing. The technique of "bedding" wires to form a fabric backplane bus was developed to integrate a bus for distributing power and data within a garment (Toney, Mulley et al. 2002). The technique of using cloth conduits to run a conductive bus within a garment without altering its fit or hang (Toney, Mulley et al. 2002; Toney, Mulley et al. 2003). Finally, the technique of integrating technology within pre-existing volumes created by padding and stiffening agents within the garment was developed as a way for integration to minimally alter the hang and fit of the garment (Toney, Dunne et al. 2003; Dunne, Toney et al. 2004). By prefabricating the interfacing elements, the integration process is also compatible with the existing garment production processes.

Garment integrated user interfaces: A number of prototypes for covert garment integrated user interfaces were developed as part of this thesis. As a whole these devices significant contributions to garment integration, demonstrating for the first time the design of garment integrated devices designed to minimize resultant social weight arising from their use (Toney, Mulley et al. 2002; Toney, Dunne et al. 2003; Toney, Mulley et al. 2003). In particular, a series of garment integrated vibrotactile display prototypes were constructed and formally evaluated with a user study (Toney, Dunne et al. 2003). The formal development and evaluation of these displays provided an initial pad sizes, actuator layouts, and pad construction suitable for use in developing garment integrated multi actuator vibrotactile displays.

Smart Garment Management: My research was the first to recognize that for a wardrobe consisting of mostly if not exclusively intelligent garments to be usable, it will require a smart garment management system (Toney, Thomas et al. 2006). The smart garment management system developed in this thesis consisted of a collection of smart hangers and a smart wardrobe. The work is the first to use intelligent hangers as a tool for managing smart garments. Augmented the existing form of a hanger enabled a single management system to take care of a wardrobe consisting of a heterogeneous mixture of conventional and smart garments, providing its user with a single interface for managing all of their smart clothing.

Available on table space: This research demonstrated that existing models of reach used for industrial design could also be applied to the design and evaluation of on table user interfaces (Toney and Thomas 2006). A new statistical model of user reach was developed for application to on table user interfaces (Toney and Thomas 2006; Toney and Thomas 2007). The developed model contained previously unavailable data describing user preferred table working heights, and working distances from the working surface, required for accurate model applications. Collectively the adaptation of existing models from other domains, along with the derivation of new models under more appropriate conditions, enables the development of tangible and direct touch user interfaces that dynamically scale and respond to their current users reach (Toney and Thomas 2006; Toney and Thomas 2007).

Algorithmically predicting table segmentation and territoriality: Preferred segmentation and territoriality on the working surface was show to be predictable by applying models of reach (Toney and Thomas 2006; Toney and Thomas 2007) . These predictions are shown to explain both observations previously observed in the literature, and the results of several user studies and trials conducted for this thesis. Applying models of reach to predict utilization of the working surface enables the creation of applications that dynamically tailor their user interfaces to their users (Toney and Thomas 2006).

Device deployment: Device deployment is a new usage context my work proposes for mobile devices. Deployed devices fill the gap between the functionality that can be garment integrated or worn, and the level of functionality expected from preinstalled ubiquitous computing infrastructure. Collectively the developed models of reach and predictive use of the working plane were researched as part of answering the question “where and how can a user deploy?”

1.3 Dissertation structure

After this first introductory chapter, chapter two provides the background material needed for the readers to familiarize themselves with the general context of my research. The background chapter contextualizes the work of this thesis, explaining its evolution and relevance. More detailed background information required for understanding specific work is summarized at the beginning of each chapter.

The overall dissertation structure is divided along three distinct lines of research focused on supporting the mobile user; minimizing the negative social consequences of using mobile technology, supporting mobile users through garment integration of technology, and deployment of devices to temporarily instrumenting the user’s environment with additional resources to support the mobile user.

The research concerned with the negative social consequence of device usage is presented in Chapter 3. The concept of device social weight (Toney, Mulley et al. 2002; Toney, Mulley et al. 2003) is presented. The chapter presents techniques for measuring the social weight of an existing device and for applying models to predict the social weight of a new device or interface.

Chapters 4-6 present the line of research focused on the garment integration of technology. Specifically, Chapter 4 covers the use of garment integrated technology to provide low social weight user interface elements for a personal server. Chapter 5 presents research into the commercial construction and manufacture of garment integrated of technology. Finally, Chapter 6 presents smart garment management, or tools for maintaining a wardrobe full of garments containing integrated technology without requiring the user to individually maintain each garment as a separate device.

Device deployment is a new context for using mobile devices advanced in this thesis. Chapter 7 and Chapter 8 focus on problems requisite to developing deployable devices. Chapter 7 introduces the idea of formally considering user anthropometry, kinesiology, and reach in user interface design. Several exploratory and formal studies of reach are presented culminating in a model predicting the space reachable by a user, based solely on directly observable anthropometric characteristics for that user. Chapter 8 demonstrates how models of reach can be applied to predict high-level table usage. The technique is demonstrated with the models developed in Chapter 7, as well as those found in the literature. The developed techniques predict the table usage for both individuals and collocated groups of users. Simulations of table use under similar conditions, varying only a single specific design conditions such as table size and shape, are used to determine the sensitivity of table usage to the tested condition. Chapter 8 concludes with a small study of the use of a simulated deployed user interface used to determine usage phenomena for deployed devices warranting further study.

Closing remarks and a review of this dissertation’s research contribution conclude the thesis in Chapter 9. The following appendices provide statistical results, equations, and schematics for all hardware constructed for the thesis for researcher interested in applying the developed techniques.

2

Forgetting the past does not mean we are free from its direction.
Lost and confused Ph.D. Student

Chapter 2 Background

The research of this thesis investigates ways the mobile user can always bring a persistent level of support with them into any new environment. Investigating this problem required researching a broad range of topics. This background chapter provides an introduction for the reader to familiarize themselves with the general topics touched upon by the thesis work as a whole. Each chapter of this thesis focuses on a different area researched as part of this thesis's work. A detailed presentation of the relevant background information is provided as part of the beginning of each chapter.

2.1 How technology is shaped by the past

Developers of new technologies often deliberately seek inspiration from existing and well-established technologies. Borrowing conservative elements from a familiar design allows for portions of the new technology to be immediately familiar to users and afford their usage. The experience of the designers themselves also inadvertently brings context to their creations. Even the most radical designs are built from elements ripped from the familiar, and re-imagined. As a result, modern technology often has roots of unexpected historical depth. For example, computers borrowed their keyboard from typewriters, an influence that is reflected by the fact that the most common keyboard layout today, the QWERTY configuration, dates back virtually unchanged to the 1870's (Sholes 1878). Similarly, the revolution of handheld computing began with the release of the Apple[4] releasing the Newton Message Pad in 1993, a device inspired in name and function by small spiral bound pads of paper, and earlier electronic organizers (Apple-history.com 2007).

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[4] Apple - 1 Infinite Loop, Cupertino, CA 95014 – Phone: 408 996 1010 – URL: http://www.apple.com

Figure 1 Replica waxed tablets pictured with Apple Newton Message pad
Image Credit: Greg Priest-Dorman[5]

Many aspects of recently emerging mobile devices were spookily foreshadowed by devices literally thousands of years old, and quite clearly show that mobile technology has been an integral part of human life for a very long time. Moreover, whether or not the similarity is inherited or unintentional a device's predecessors directly shape its design. For example, waxed tablets, or pugillares, like those pictured in Figure 1 and Figure 2, indirectly inspired modern hand held devices. While they obviously did not organize schedules and send and receive emails, for thousands of years waxed tablets provided the educated and the wealthy with a mechanism for mobile information and storage and retrieval. At a time when paper was

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[5] The pictured wax tables were made by Greg Priest-Dorman, and are pictured against a backing of hand died yellow cloth weld by Carolyn Priest-Dorman. The text carved into the wax tablet reads "Nihil sub sole novum" which translates to [There is] nothing new under the sun. -- Ecclesiastes 1:10 (Vulgate edition)

an expensive rarity, waxed tablets provided an erasable writing surface. Simply warming a tablet by the fire for a few minutes would erase it, making it ready for another use once it had cooled. The tablets served an important organizational and note taking role, similar to the note taking functionality of the modern PDA.

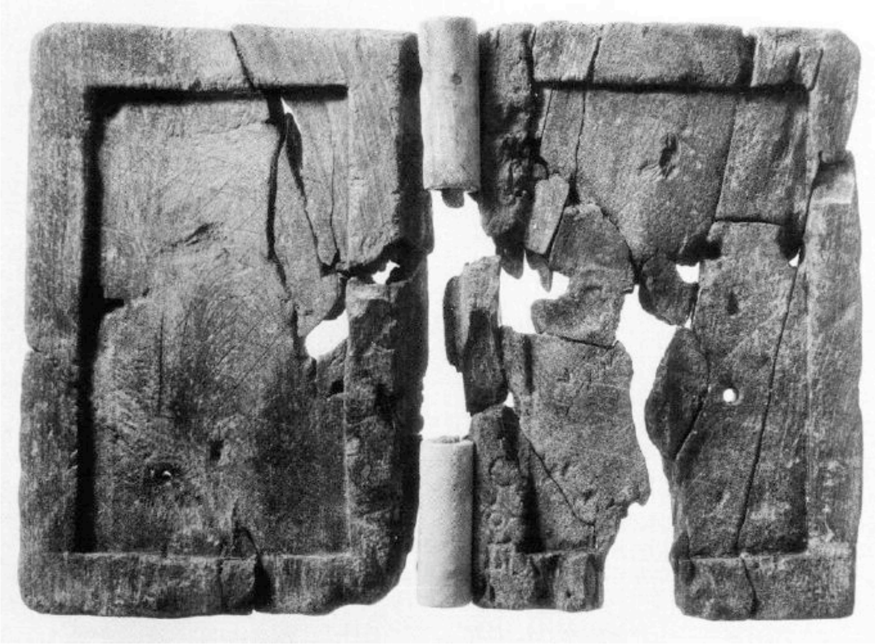

Figure 2 14th century B.C.E. Waxed Tablet or Dipstytch
Image Credit: Dr. Cemal Pulak and Dr. George Bass

The oldest known wax tablet, pictured in Figure 2 (Bass, Paulak et al. 1989), was recovered from a shipwreck which based on Mycenaean ceramic evidence was dated broadly to the 14th century B.C.E (Paulak 1988), or at a minimum 3,400 years ago. Perhaps not surprisingly the recovered tablet is remarkably similar in form factor to modern handheld computing devices "consisting of two rectangular wooden leaves, 6.2 cm wide by 9.5 cm high".

Even having established that waxed tablets were used for thousands of years, it is easy for a reader familiar with their modern day digital counterparts to underestimate the importance of the waxed writing tablet prior to industrialization providing cheaply available paper. In their time, tablets were an essential tool for the scholar. So much so that *The Rule of St. Benedict*, Chapter 55 (Fry 1981), which dates to the sixth century C.E., lists waxed writing tablets as indispensable for a monastic life. A life, which at the time was to be, focused solely on theistic and scholarly pursuits. The specific reference is:

> "…et ut hoc vitium peculiaris radicitus amputetur, dentur al abbate omnia quae sunt necessaria, id est cuculla, tunica, pedules, caligas, bracile, cultellum, graphium, acum, mappula, tabulas...."

Which Fry (Fry 1981), translates as (pg 110-115):

> "In order that this vice of private ownership may be completely uprooted, the abbot is to provide all things necessary: that is, cowl, tunic, sandals, shoes, belt, knife, stylus, needle, handkerchief and writing tablets...."

When paper became readily available due to industrialization, the wax tablet inspired the paper notebook. Paper based tablets and notebooks where in turn a partial inspiration for the first PDA, Apple computer's Message Pad, and indirectly the PDAs that followed it. Figure 1 shows the Apple Newton Message Pad pictured next to several replica waxed tablets. The inspired and inherited traits of the devices descended from waxed tablets highlights how general purpose personal mobile technology is not new, and that inspired and derived elements of ancestor devices can persist through many changes in technology.

2.1.1 Garment Integration

Since clothing is one of the humanity's oldest technologies (Kittler, Kayser et al. 2004), which has evolved to its current form over thousands of years, any integration of technology into the garment is restricted by many deeply rooted and long-standing social conventions and expectations about its form and what constitutes acceptable dress. These conventions and expectations are idiosyncratic to the diverse contexts of human life, such as regional, cultural, social, gender based, religious and functional expectations. As an example, many orthodox religions have expectations of modesty that specifically address what constitutes acceptable attire for both genders, such as Orthodox Judaism's *tzniut* (Fishman 2000), some orthodox sects of Christianity, such as the Mormons and the Opus Dei, requirements for modest dress[6], or Islam's requirements of modesty (Syed and Ali) and the wearing of a veil (Read and Bartkowski August 26th, 2007) or *hijab* (Windle 2004). Similarly, many cultures also have integrated concepts of modesty governing acceptable dress and behavior, such as the Hispanic concept of *pudor* as it applies to clothing, or the Chinese concept of *mapagpakumbaba (Andrews 2006)*. As a result garment integrated technology is unusual as an emerging class of technology, as it already has a large volume and range of extension social conventions.

Regional and geographic differences have also fostered differences in traditional attire. For example, the clothing traditionally worn in hot countries such as India or Southeast Asia are very different from those typically worn in colder climates such as the far northern parts of North America, Scandinavia, and Europe.

The work of this thesis demonstrates two distinct approaches for respecting the cultural and historical context of clothing, while developing garment integrated systems. Use of generic modules for garment integration of technology, as advocated in Chapter 5, enables integration of the same technology into a number of different garment forms spanning cultural, gender, religious, social, and geographic expectations. Applied cultural anthropology has been revealing that differing cultures respond differently to the same technology, often integrating it into their lives in ways unexpected and unintended by the manufacturer (Bell 2004; Biddlecombe 2004). Integration using generic modules also allows different modules to be intermixed by regional manufacturers, producing smaller targeted runs of garments. As a result, this approach to garment integration provides garment developers greater freedom to innovate new and unexpected applications driven by customer response. Competitive market pressures amongst competing garment manufacturers using this approach will result in garments that avoid violating the relevant regional and cultural expectations where it is marketed, maintaining the garments general situational appropriateness.

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[6] http://www.lightplanet.com/mormons/daily/modesty.htm

The other approach for developing garment integrated systems advocated by this thesis is basically to embrace the fact that historical context will be inherited by new technology, using the current devices and user behavior patterns as the framework for new development. This approach respects existing cultural and historical context of clothing, using it to inspire new designs. Chapter 6, which advocates this method of development, uses the existing user behavior and form factor of a closet and hanger as the basis for building a management system for maintaining and storing clothing with integrated technology. Building the system using the form of the conventional hanger enable it to ensure that a garment was ready for use, without altering how an individual interacts with their clothing. Hanging a smart garment one of the developed hangers was demonstrated running self-diagnostics on the clothing, charging integrated batteries, and synchronizing data.

2.1.2 Device deployment

The current trends in mobile device evolution are towards a conversion of functionality into a single mobile device and a small number of accessories. The modern hybrid PDA phone used with a Bluetooth headset is an example: a single device containing the majority of the processing power and user interface, and accessories are used to position audio the audio components near the user's mouth and ear. While hybrid devices are emerging from the very young arena of mobile devices, they and their accessories will not be without historical precedent. Mobile devices of all kinds already enjoy widespread use have well established, though not always consistent, societal expectations of what constitutes appropriate and socially acceptable use. As a result, emerging convergence devices will inherit established cultural and societal expectations regarding appropriate usage.

The goal of deployment is to instrument the user's environment with sensors, providing a minimum level of coverage when the available local ubiquitous resources are insufficient. Integration of sensors, such as cameras, into the deployable device allows for powerful user interaction techniques by tracking the user's position, gaze, or gesture. Many applications would benefit from the system also building up knowledge of the user's environment and collaborators.

Deployable devices will have to be designed to be sensitive to existing cultural expectations that they inherit. For example, the integration of cameras into mobile devices has inspired a wide range of cultural responses. For example, in some predominantly Muslim countries like Saudi Arabia, since cameras in embedded devices can be used to take pictures of women without their knowledge they were initially banned as spreading obscenity in Muslim society. While the blanket ban was eventually lifted, camera phones remain banned in many areas In Saudi Arabia, such as schools and gyms, and are closely monitoring camera phones for abuse by police and religious authorities (Akeel 2005). The devices are often confiscated or smashed if an abuse is suspected, the principal reported abuse being taking pictures of others without their knowledge. In the United States camera phones are also starting to be banned in some locations, such as schools to curb cheating, in class distraction caused by ring tones, and inappropriate use of the integrated cameras (CBS News 2007).

The problem of culturally appropriate design is further complicated by the fact that within any given culture there is not a single consistent set of beliefs as to what constitutes acceptable device usage. For example in a survey of 383 college students from Colorado, Connecticut, Louisiana, and North Dakota, Lipscomb et al. (Lipscomb, Totten et al. 2007) observed a wide range of beliefs about the appropriateness of using cellular phones in public spaces such as movie theaters, restaurants, or public restrooms. Other research seems to indicate that what is perceived as acceptable behavior is quickly altered when a person starts using technology themselves (Palen, Salzman et al. 2000). The problem is further complicated in that the addition of a single feature, seemingly innocuous from one cultural perspective, can have a radical influence in how a device is perceived by other cultures. The most popular feature of mobile phones in the Muslim world and one a major selling point, prayer calendars, is only a minor feature in the west. Mobile phones with integrated direction finders and scheduling applications have enjoyed tremendous popularity in the Muslim world as a whole, as they can their users of prayer times and indicating the direction of Mecca (Biddlecombe 2004).

The precedents currently being established for existing mobile technologies will have ramifications for future mobile devices. Once established, cultural attitudes towards technology determine how and where it is acceptable to use both that technology and visually similar technology. Once established, cultural precedent shapes what constitutes an acceptable device design. This makes it especially important for the early generations of a new technology to be well researched and culturally sensitive in design to avoid wherever possible cultural For example, deployable devices targeted for use in cultures sensitive to embedded cameras will need to include a feature addressing those concerns - such as a privacy shutter capable of physically blocking the lens of any integrated cameras.

The concept of device social weight influenced the work of this thesis. Measuring the degradation of social interaction caused by the use of mobile technology, social weight provides developers and designers with a way to assess the influence of cultural, religious, and regional factors on their designs. As the concept of social weight is refined, it will provide application developers the means to evaluate the social costs of individual design features that they are considering across cultures. As an exhaustive and generic treatment of factors that influence this type of design would require many theses in their own right, a set of constraints, enumerated in Chapter 3, were placed on the work of this thesis. In abstract, the research problem is constrained to interactions taking place in homogeneous western cultural context, with users interacting in a formal to semi formal business environment. Constraining the research problem enabled this thesis to address the purely technical and mechanical aspects of device deployment. While Chapter 7 through 8.8 focuses broadly on the questions of what space is available for the user interface issues of internationalization will not be addressed in depth.

2.2 The evolution of garment integrated and deployable devices

Both wearable computers and commercially available mobile devices have been experiencing trends in convergence with more functionality and better performance in increasingly smaller devices. The work of this thesis is predicated on the belief that the destination for these trends is two classes of mobile devices; either, devices that are either garment integrated or worn by the user, or single convergence device that acts as a personal server (Want, Pering et al. 2002) for the user and a few optional accessories carried and deployed by the user.

Garment integration provides a convenient way for mobile users to surreptitiously bring a minimum level of support with them into any environment. Device deployment complements garment integration by providing a way the user can easily increase the level of trusted support in an environment in which they have stopped. For example, deployment of the device allows it to project information onto environmental surfaces such as tables or walls, track other objects deployed on the table potentially making them part of the user interface, and track its user with integrated cameras in order to identify position, gaze, and gesture.

A garment integrated device has a unique perspective from which to observe its user, one that is particularly suited to monitoring biometric and medical information (Rossi, Carpi et al. 2003; Brady, Dunne et al. 2005), and this is indeed where most of the initial development work on garment integration has focused. Devices unobtrusively integrated into the garment also benefit from being socially acceptable while being carried with their users. While the same medical monitoring functionality could be integrated into a mobile accessory such as a watch or a Bluetooth™ earpiece, these devices have a much higher social profile than devices unobtrusively integrated into a garment.

While requisite technical background material will be presented in the relevant chapters, a brief description of the evolution for deployable and garment integrated systems is provided in the rest of this subsection. This thesis is the first to apply the term "deploy" to mobile devices, using it to describe the act of temporarily introducing the technology into the user's environment. The envisioned emergence deployment as another way for the mobile user to interact with their technology contextualizes the work within the rest of this thesis. While garment integration is an active area and already commercially used for military (Linderman, Sibert et al. 2004; Winterhalter, Teverovsky et al. 2005) and medical (Edmison, Jones et al. 2002; Rossi, Carpi et al. 2003; Linz, Kallmayer et al. 2006) applications, the research the work of this thesis is predicated on the belief that it will be adopted for mainstream commercial use. A brief discussion of how garment integrated devices are emerging is also presented in the following subsection.

2.2.1 Wearable Computing up to 1997

The release of Reflection Technologies' Private Eye displays in 1989, provided the first commercially available high resolution head mounted display that was ruggedized and safe to use for daily wear. The commercial release of the private eye head mounted display (HMD) jump-started early research into wearable computers. The availability of standardized HMD enabled standard designs to evolve fostering early community of wearables researchers.

By 1991 Carnegie Mellon had demonstrated the VuMan 1, a task specific belt mounted wearable computer for examining plans in the field, and in that same year Dough Platt developed his more general purpose "Hip-PC". Both systems were belt mounted, used a chording keyboard for input and a Private Eye display for their display. Speaking at MIT's Media Laboratory, Doug Platt and his "Hip-PC", inspired Dr. Thad Starner as an undergraduate. Eventually the pair went on to develop what would become, after many iterations, MIT's "Tin Lizzy" wearable computer design (Rhodes 1997). By June of 1993 Dr. Starner was wearing his computer full time as part of his research and building a community of other researchers at MIT interested in wearable computing. The period of 1993-1997 was significant as during that time a number of students began experimenting with wearable computers and wearing their computers for a large fraction of the day.

Wearing a computer required it be small and have sufficiently have sufficiently low power requirements that the combined weight of the system and the batteries required to power it for the better part of a day would not hinder the user. The few commercially available wearable computers played a surprisingly small role in the wearables research of the mid to late 1990's. Targeted at specific industrial and military tasks commercially available wearable computers, like those marketed by Xybernaut[7] or ViA[8], were prohibitively expensive, rarely reflected the state of the art, and often difficult or impossible to expand to the level required for a particular research problem.

The early wearable computers were of necessity hand built prototypes, composed of a collection of commercially available components. As commercial electronics decreased in price, size and required power wearable computers became increasingly more accessible. By 1997 enough researchers and hobbyists had started using wearable computers that 365 people were in attendance at the first conference on wearable computers - the International Symposium on Wearable Computers (Kirsner 1997).

By this time, the research on wearable computers had stated to bifurcate into two distinct groups. The first group used wearable computers as a powerful mobile infrastructure from which to simulate the resources that would be available on future generations of mobile devices, while the second group sought to develop wearable computers into a new class of devices that could be persistently worn throughout the day hosting agency software. The Herbert I wearable computer created by Greg Priest-Dorman, and pictured in Figure 3, gives an excellent example of the state of the art of wearable computers targeted at daily wear circa 1997.

Figure 3 GPD and Herbert I in use – 1997
Image Credits: Greg Dorman

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[7] Xybernaut Corporation - 5175 Parkstone Drive, Suite 130 Chantilly, Virginia 20151-3832 - Phone: 703 480 0480

[8] ViA Technologies, Inc. – 940 Mission Court Fremont, CA 94539, USA – Phone: 510 683 3300

Mr. Dorman suffered from back problems. He began constructing wearables in order to have a computer that could be used while standing, walking, or lying down in order to remove pressure from his back. As a result, his wearables are significant in that they were constructed for, and sustained daily usage over a number of years. The system Mr. Dorman is pictured wearing in Figure 3 was used for over 10 hours a day, five to six days a week, from 1994 until mid 1998 (Dorman 2007). The system, the Herbert I, is pictured both in and out of its custom carrying case in Figure 4.

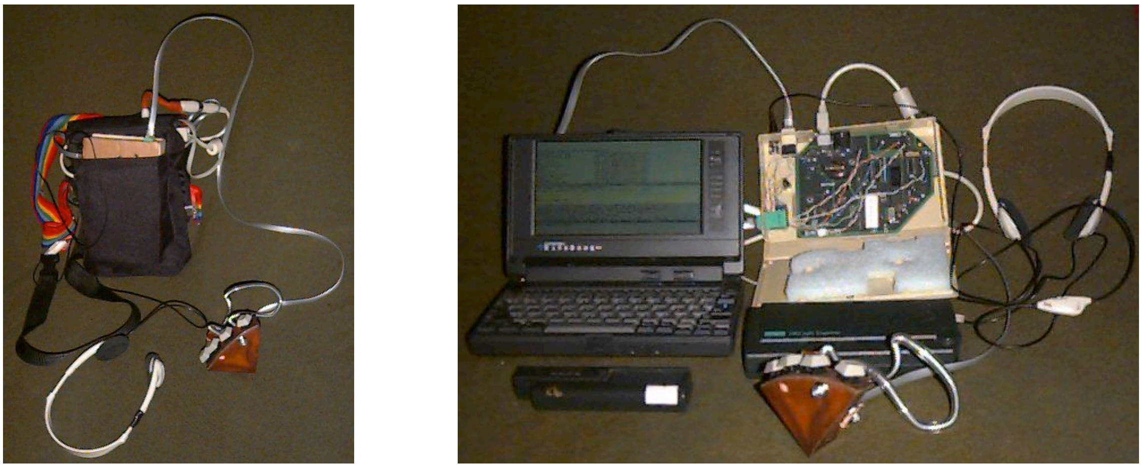


Figure 4 Herbert I in and out of its case
Image Credits: Greg Dorman

2.2.2 Wearable Computing from 1997 to the present

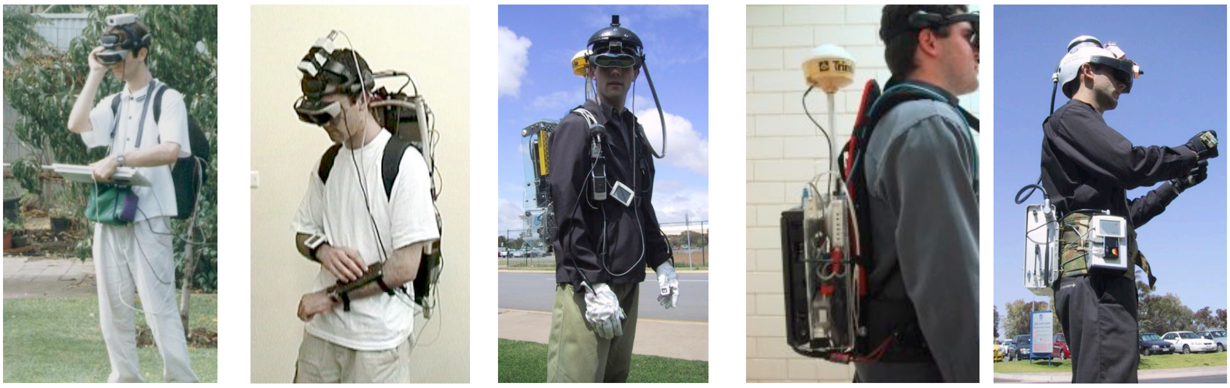
Researchers prototyping applications available on future mobile devices require an extremely powerful infrastructure in order to simulate the resources that will be available. For example, researchers in outdoor augmented reality require a mobile computer platform that can determine where the user is located, where they are looking, and then overlay meaningful data about their environment onto what the user is seeing. At a minimum, this requires building a system with an integrated camera and head mounted display that can detect the position of the user, and the body relative position and orientation of their head. Outdoor augmented reality is representative of a large number of wearables research problems in that no single commercially available device exists that possesses all of the features required by researchers. As a result, wearables researchers are commonly forced to build their own prototype research platforms from a collection of custom prototypes and commercially available components.

Hard Framed Backpack Wearable Bag Wearable

Figure 5 Example of early backpack wearable computers

Image Credits (left): (c) 1997 S. Feiner, B. MacIntyre, T. Hoellerer,
and A. Webster, Columbia University.
Image Credits (right): (c) 1998 Bruce H. Thomas, University of South Australia

The first two outdoor augmented reality systems were respectively Feiner et al.'s "Touring Machine" (Feiner, MacIntyre et al. 1997), the hard framed backpack wearable pictured in Figure 5, and Thomas et al.'s "map-in-the-hat" system (Thomas, Piekarski et al. 1998), the bag based wearable pictured in Figure 5. Both of these systems demonstrate the common practice for early researchers using wearables computers, building backpack based systems. These early systems either tended be a bag or backpack full of all of the individual part of the system (e.g. GPS, Digital compass, single board computer, batteries, power regulation, HMD driver board, etc), that was literally strapped to the user during use.



(A) 1998 (B) 1999 (C) 2002 (D) 2004 (E) 2006

Figure 6 Evolution of backpack systems
Image Credits: Dr. Wayne Piekarski & Ross Smith

The backpack-based approach to wearable computers has evolved, and continued to shrink along with available technology. Figure 6 depicts the development of the TINMITH system from 1998 until the present. The TINMITH system is unusual in that it is both one of the earliest backpack based wearable computers, and that has is has been under continuous development and refinement since that time. As a result, the evolution of the TINMITH system reflects the evolution of the state of the art in wearable computing over the last decade. During this time the state of the art in the most powerful wearable systems has shrunk from the early bags of parts and open frame backpack systems similar to the those shown in Figure 6 cells (A) and (B), through custom-built backpacks such as those shown in cells (C) and (D), and finally shrunk to the point where they were belt mounted computers like that show in cell (E). One of the foundation beliefs driving the work of this thesis is that this trend will continue, and that the next stage will be objects that are carried or worn by their users.

Concurrent advances in commercially available technology have driven the evolution of custom-built wearables. Devices such as portable music players, high-end cellular phones, personal digital assistants (PDAs), and electronic organizers, have all become increasingly common in the last decade. A thriving market in accessories has accompanied these devices such as the now ubiquitous in ear Bluetooth earpieces, used to allow hands free use of the phone. These devices and their accessories have enabled increasingly powerful custom-built wearables to be developed in ever shrinking form factors. As commercially available mobile devices continue to evolve, developing ever-increasing functionality and social acceptance, they are eliminating wearables researcher's need to develop custom prototypes to have a platform with the functionality required for their research. Eventually these trends will lead to commercially available wearable platforms.

2.3 Summary

This chapter has provided context for the work of the rest of this thesis. Examples of how the past can influence product design are presented, and used to highlight the difficulty of working with garment integrated devices, due to the deeply rooted expectations people, cultures, and religions have of clothing. The design issues that deployable devices face because of inherited beliefs is also discussed. Finally, the chapter concluded with a brief history discussing how both deployable and garment integrated devices are evolving as a result of long term development trends in both wearable computing and commercially available devices.

3

"Cell phones, PDAs, Laptops… does anyone else see the irony of engineers being the ones building the tools that are revolutionizing acceptable social behavior?"
Confused Ph.D. Student

Chapter 3 Social weight

Using mobile technology has social consequences. Where and how someone chooses to use mobile technology reflects on him or her socially, just like any of his or her other actions. When those actions are situationally inappropriate, they can negatively influence the user's current and future social interactions. The overall goal of this thesis is the exploration of emergent mobile technology; specifically garment integrated and deployable technology. As these types of technologies are mobile, they are frequently used within social settings. The work presented in this chapter was undertaken in order to find ways to minimize the negative social consequences arising from the use of mobile technology. The concept of social weight was developed as the first step towards a quantifiable model of the negative social consequences arising from the use of a particular piece of mobile technology.

Minimizing social consequence requires a means of quantifying the impact of a specific item or use of technology so that it is comparable against other possible implementations. The social weight (Toney, Mulley et al. 2002; Toney, Mulley et al. 2003) for an item of technology is defined as the measure of the degradation of social interaction that occurs between the user and other people caused by the use of that item of technology.

Use of consumer mobile technologies are elective and will only occur when the user perceives the benefits of using the technology as outweighing the costs. Models of social weight allow application and device developers to minimize the overall social weight of their designs, and create applications that deliberately offer the user multiple interfaces each with distinct associated social weights.

Social weight has influenced the designs and provided constraints for the work of this thesis. After defining social weight and its accompanying research problems, the constraints placed on the research of this thesis by considering social weight are presented. Then device and interface escalation are presented as strategies for the user to control their technology use and its resultant social weight.

3.1 The Research Problem: Defining social weight

The work on social weight presented in this chapter began with the observation that the use of mobile technology often degraded the social interactions within the user's current social group. The use of mobile technology in the early social weight research (Toney, Mulley et al. 2002; Toney, Mulley et al. 2003) was informally observed impacting both the user's interactions with others in the group, and how the other members of the group interacted. These observation were supported by the available literature (Dryer, Eisbach et al. 1999; Sheridan, Lafond-Favieres et al. 2000). While mobile technology makes new means of remote connectivity possible, overall the informally observed impact of technology on concurrent collocated social interaction was negative.

Formalizing the observations of social weight into a formal model required measuring the degradation of social interaction that occurred between the user and others due to the user's use of technology. In order to build a quantifiable model of a complex social phenomena I chose to use the established techniques which Murray and Gottman (Gottman, Murray et al. 2003) developed for modeling marital interactions. Lacking the rich sources of data available to Murray and Gottman, this research began by compiling our informal observations about mobile technology use, breaking down the key components that were observed contributing to social weight, and then clustering the observed elements. Clustering revealed three (Toney, Mulley et al. 2002), and then later four (Toney, Mulley et al. 2003), clusters observed by all authors. These clusters identified the primary components of social weight to be cognitive load (CL), physical presence (PP), technology apprehension (TA), and social convention (SC). The working hypothesis for the work of this thesis is that social weight (SW) can be treated as a function of these four independent variables; $SW = f(CL, PP, TA, SC)$. Frequency and duration of device usage concurrent to social interaction influences the cognitive load, physical presence, and social conventions forming a devices social weight. Sections 3.1.1 through 3.1.4 describe each of these variables.

3.1.1 Cognitive Load

Building a quantitative model of social weight required developing a means of scoring observed components of social weight. This meant a means of scoring observed cognitive load was required as part of building a model to describe social weight. For the work of this thesis, the Model Human Processor as described in (Card, Moran et al. 1983) is used to gauge cognitive load. The forced loss of eye contact during social interaction is generally undesirable. The lost eye contact forces the user's attention to the device and not at their social group. Excessive lack of eye contact also has negative social implications. For interactions taking place within the social context of this thesis, the loss of eye contact with the social partner that a device causes is being used as an indirect measure of the cognitive load that device places on the user.

3.1.2 Physical Presence

Physical presence is a measure of the space that something subjectively appears to occupy. While all other features being equal a larger object will naturally tend to have a larger physical presence, physical presence is a measure of subjective appearance and not physical size. Physical presence is both a subjective and dynamic property, and many non-physical properties may impact physical presence. For example, a watch will tend to have a smaller physical presence than a phone or PDA, and a phone or PDA will tend to have a smaller physical presence than a palmtop or tablet PC. A loud alarm going off on the watch in a quiet room or at a socially inappropriate time will cause a spike in the devices physical presence. As another example, a laptop sitting on a table with its screen closed will have a much smaller physical presence then a PDA that is being held and used.

For the purposes of this thesis, physical presence can be thought of as the social space a device appears to occupy. Consider a phone ringing and interrupting an important speaker at a business meeting. Ringing dramatically increases the phone's physical presence. As an alternative example, consider a camera. Despite the camera's small size, as soon as the little red light appears on the camera, indicating by social convention that the device is recording, the physical presence of the device increases enormously. These examples illustrate an important point, that physical presence is not the same as form factor.

In calculating the resultant social consequences arising from technology use, the physical presence of a device is measured from the perspective of others interacting with or observing the user. The attributes of physical presence measured from the perspective of the user are considered as parts of the calculation of cognitive load, and are reflected in how much thought is required for the user to perceive and decode the signals being presented.

The actions of the user of a device also alter the devices physical presence. For example, the social weight of a timepiece is proportionate to the frequency with which it is checked. Consider the social difference between glancing at a watch once while someone is talking and glancing at a watch repeatedly. The more frequently the timepiece is checked the higher its social weight, due to its increased physical presence. Checking a timepiece increases the physical presence for both a timepiece and its owner. Similarly, as time elapses after checking a timepiece its physical presence decays back to a baseline level.

3.1.3 Social Convention

The work of this thesis is predicated on the belief that technologies too young to have evolved social conventions of their own will inherit the conventions of existing familiar technologies. For example, when mobile phones were first introduced they were conceived of as mobile versions of the familiar landline based phones, and inherited social conventions accordingly. While cell phones were still novel, it was socially unacceptable to loudly have one half of loud private conversation in a public place – something that is common place today. This change in socially acceptable social behavior for mobile phones illustrates how social conventions are subjective and dynamic; evolving out of society's prolonged contact with a technology. With increased adoption of mobile phones it became increasingly common to encounter people using them in every area of public life. Eventually, exposure and convenience made public mobile phones use socially tolerated in almost all aspects of modern life. Oddly, the inheritance of social conventions is illustrated by the youth markets tendency not to inherit established conventions. As the demographic with the demographic least burdened by prior experiences with casually similar technologies - the youth market is the most likely to innovate new and novel conventions about where and how it is acceptable to use a newly introduced technology.

3.1.4 Technology Apprehension

Technology apprehension is highly idiosyncratic. Rather than measure the impact of an individual's technology apprehension on social weight, the approach used in this work was to try and minimize the amount and volatility of technology apprehension. The models and prototypes developed for this thesis were constructed under the belief that when technology is invisible to a user's social partners, its resultant technology apprehension will be minimized. When introducing new technology that will be visible to its user's social partners, designing the new technology to resemble a well-established existing technology, such as a wristwatch, provides a means of minimizing the technology apprehension the new technology will engender.

The specific context of the interaction and the background of its participants influence social weight. Unfortunately, this means that a number of factors, each with high volatility, influence social weight, especially for the mobile user. In order to build an initial model of social weight, restrictions were made to constrain the contexts in which social weight was being studied and modeled. Constraints were selected to stabilize the volatility arising from participant-dependent rather then device-dependent factors. The selected constraints were placed on the research determining the number of individuals present, the environment where the studied interactions take place, the expected cultural context in which the interactions would take place, and the implementation details of the devices used to study social weight.

The material following in this section discusses the self-imposed constraints, adopted to narrow the problem scope to the point where initial models could be constructed and tested. Future work can expand the model by iteratively removing these restrictions and refining the model.

3.1.5 What is missing

The presented model of social weight is a first order mathematical model, developed as a tool for researching social interactions in the presence of technology. The model is far from exhaustive, instead being designed to be both simple to apply and easily extended. As a consequence the presented model is not exhaustive, and many familiar aspects of social interaction are not represented in the parameters of social weight as presented. For example, when a high social weight technology such as a laptop is used in a meeting the presented model lacks the ability to account for any feelings of outrage, insult, or neglect that it would be understandable for others present to feel.

The social weight research conducted as part of this thesis was published in two venues, a conference publication and in a longer more formal journal publication (Toney, Mulley et al. 2002; Toney, Mulley et al. 2003). The longer format of the journal publication allowed for a more involved discussion of social weight, including a discussion of the nonlinearity of more involved social models consisting of a greater number of terms. As much of this more detailed work was speculative, I chose to not publish it as a contribution of my thesis. Interested readers are directed to the referenced journal publication.

3.1.6 Mobile users

This thesis focuses on supporting mobile users, or users away from one of their primary working spaces such as their home or office.

3.1.7 The business environment

One of the self-imposed constraints placed on the social weight research conducted for this thesis restricted the research to the business environment. Social interactions within a business environment are frequently of high personal and economic impact. As a result, the business environment presents a well-defined conservative social foundation, possessing well-defined social conventions. The explicit nature of the social conventions within the business environment removed much of the subjectivity from scoring adherence to social convention. This made the business environment ideal for developing models of social weight, which require repeatedly quantifying adherence to social convention in order to generate and test functions of social weight.

3.1.8 Location and physical context

For the work of this thesis, social weight is researched only within a homogenous set of non-industrial settings commonly frequented by a mobile businessperson. Offices, vehicles, and coffee shops are all areas in which mobile professionals commonly conduct business, and which were considered for the research of this thesis.

3.1.9 A western cultural context

While the business environment offers a conservative social foundation within a given culture, the specific expectations of acceptable behavior differ dramatically between cultural contexts (Bell 2001; Bell, Gaver et al. 2003; Forest and Arhippainen 2005). More than that, what constitutes socially acceptable behavior is complex in every culture, and evolves over time (Anderson 1996). When collaborating or doing business over seas, the businessperson is frequently operating across cultural lines. The cultural expectations in regions such as China or Russia are in many cases very different then in the west (Gangemi 2007; Goldsmith 2007). Each culture has a unique set of cultural expectations and social affordences (Bell 2001; Bell, Gaver et al. 2003).

In order to be able to score adherence to social conventions, a western cultural context was assumed for all social participants. Specifically, all the models, hypotheses, and prototypes of this thesis were developed and tested within either an American or an Australian cultural context.

3.1.10 Dyadic interactions

Within a group, each member brings with them a different context. To minimize possibly confounding factors while developing the initial model of social weight only dyadic social interactions, or interactions between two individuals, were considered. The model of social weight was not constructed to account for multiple social partners or observers of the social interaction.

3.1.11 Serial technology interaction

Only one of the dyads was considered to be using technology at a time. The developed model of social weight would be applicable for calculating the social weight of one of a pair of individuals interrupting a social interaction, with an action such as checking a PDA or watch. The current model is not suitable for calculating the resultant social weights when both parties concurrently use technology; such as if one party checked their PDA and the other used the opportunity to check their watch.

3.2 Scoring the components of social weight

In order to apply a model of social weight its elements need to be quantifiable in measurable units. The techniques used in this thesis scored each identified component of social weight into one of five unit-less equally weighted values; none, small, medium, large, and very large. This allowed for mapping of relatively subjective phenomena into a numeric scale of five equally weighted values ranging from zero for a value of "none" to four for a value of "very large". In this way, each of the physical and psychological components of social weight can be evaluated against a common scale, providing quantifiable data suitable for generating or evaluating mathematical functions of social weight. Consistent scoring enables multiple measures of social weight to be compared as four-dimensional vectors with a shared set of basis vectors. Even using this low granularity quantization for its components can generate a rich measure of social weight. A function of social weight where each of the components ranges has five possible states is capable of predicting 625 different graduations of social weight.

Technology apprehension is a purely subjective and idiosyncratic factor contributing in the formation of social weight. Developing models of social weight that for example can factor in the technology apprehension of an elderly person is an important open research problem. All the research conducted as part of this thesis observed individuals who regularly used a variety of mobile technology and whose technology apprehension is "none" (numerically scored as zero) for all subjects. Since technology apprehension is a form of phobia, subjects with nonzero technology apprehension were avoided. Deliberately exposing individuals with a strong apprehension of technology to different technologies was deemed to require too much work in meeting the significant burdens of the required psychological oversight required by the human subjects comity.

Adherence to social convention presents a scoring problem similar to technology apprehension. Even with the self-imposed restriction to a specified cultural context and environment, adherence to social conventions is subjective depending on both the user's and observer's perception of what the governing rules are. This perceptive dichotomy presented a significant problem for accuracy of scoring. Research has shown a high degree of agreement between the assessment of self and of others even at zero acquaintance (Zebrowitz and Collins 1997). Ultimately, I decided to use an external scorer's subjective evaluations of the observed behavior to provide a scoring of adherence to social conventions. In this way, all subjects behavior were scored against the same standard, the scorer's perception of social convention.

Physical size for a mobile device provides a estimate of its baseline physical presence. For physical devices, this work quantified the physical presence of a mobile device based on how the device is carried when not in use. Devices that are not visible to others are considered to have no physical presence. Non-garment integrated worn devices, such as jewelry or a watch, are classified as having a physical presence of “small”. Devices carried in existing pockets or straps within the user’s garments, are classed as having a “medium” physical presence. Devices requiring special pockets or wiring conduits to the garment are classed as having a “large” physical presence. Devices that require a specialty harness or straps have a “very large” physical presence.

Physical presence increases relative to this baseline established by device size if the device is performing a display action, such as making a noise or flashing a light. Visual displays increase the baseline physical presence by one level (on the scale of 3.2), while audio displays increase the baseline by two levels. A large value is given for the physical presence of sound due to its large disruptive nature in the social situation. While coarse, this scale proves sufficient for evaluating commercial products, which to be marketable are designed to have a minimal physical presence. It needs to be noted that this scale does not account for pathological cases, such the use of a bullhorn. All weightings are assumed to be applied to devices that would be commonly carried and used by mobile users.

Repetition also increases physical presence of the displaying device. A repeating audio alarm would has a “large” accompanying physical presence. A continuous display action increases the estimated physical presence by three levels. A mobile device will increase its physical presence from a baseline of “small” to “medium” while it flashes a light to signal the user. While the device repeatedly signals the user with both a light and an audio alarm, it will have a “vary large” physical presence.

This work treats estimated social weight as additive. Devices have zero physical presence when not perceivable by others. If LEDs integrated into the cuff of a shirt or jacket so as not to be visible by others, begin flashing; they give the garment a perceptible but “small” physical presence. If the device escalates to using an audio alert in conjunction with the LEDs the resultant total physical presence is “medium”.

The “model human processor” (MHP) model and “loss of eye contact” (LOEC) are jointly used to quantify observations of device or interface usage and generate quantitative measure of cognitive load. Both MHP and LOEC are measured using elapsed time. The following groupings quantified time consumed in seconds: *none* <1; $1 \leq$ *small* < 2; $2 \leq$ *medium* < 5; $5 \leq$ *large* < 15; $15 \leq$ *very large.* As previously mentioned, these values are estimations to provide a means of grouping the social weight values of different devices. These assumptions were based on a reading rate of 4.35 words per second (five letters per word). A base reaction time of 0.38 seconds is assumed; this is the time to perform the task of seeing a visual stimulus, access an information chunk from long-term memory to make a decision about the stimulus, and respond by pushing a physical YES or NO button (Card, Moran et al. 1983).

3.3 Escalation – Strategies for managing social weight

Device and interface escalation are two strategies that enable users of mobile devices to control the level of technology use exposed to others. Device escalation is a well-established way that consumers have developed to deal with the current generation of mobile devices. The strategy of interface escalation is commonly seen in commercially available mobile devices, which contain an increasing array of interface options. Using device escalation the user carries multiple devices, each with a distinct social weight. The user selects the desired compromise between functionality and visibility of technology use by selecting the device used to interact with an application. For example, a user may choose to check and respond to their email with a PDA or with a laptop. The laptop provides greater screen space and processing speed, but at the cost of socially isolating the user. Figure 7 illustrates a user progressively escalating (from left to right) through a series of common and increasingly higher social weight devices.

The technique of interface escalation is similar to device escalation; only the user's choice is amongst multiple interfaces presented by a single device, rather then amongst multiple devices. For example, a user checking their schedule on a watch could choose to use a very simple text display (Toney, Mulley et al. 2002; Toney, Mulley et al. 2003), or to project their schedule onto a convenient vertical surface in their environment (Blasko, Coriand et al. 2005). Choosing to project a display into their environment provides users with access to a larger higher resolution display then could be integrated into one of their devices, but at the cost of having a much higher social weight and less privacy (Tan and Czerwinski 2003).

Figure 7 Device Escalation

Either the user or the application drives the choice of what device or interface is used. User driven escalation provides the user with distinct choices over the devices and interfaces and relies on the user to pick the most appropriate device and interface for their current context. Letting the user select the tier of social weight appropriate for their current social context leverages the user's social knowledge. Unfortunately, the technique is of little help to users with poor awareness of the social consequences to improve their usage experience.

Application driven escalation allows the social weight for the user's constellation of mobile devices to be adjusted without requiring user action. A simple example of application driven escalation would be a user's messaging software overriding a device's silent-mode setting if a trusted third party has set the incoming message as an emergency. The user may not know if they were about to lose big on the stock market or if their wife has just gone into labor early, but the increasing peripheral display will immediately signal the magnitude of the emergency. If the warning goes unacknowledged, the alert can escalate from using a peripheral to a focal display of the magnitude of the emergency. The user is immediately aware of the magnitude of events, and can decide on the most appropriate response.

Research has demonstrated the use of wearable sensors to detect a user's social context through both video (Singletary and Starner 2001) and audio analysis (Basu 2002; Madan and Pentland 2006) of their immediate environment. User driven escalation leverages the user's social knowledge to ensure proper use of technology usage. The long-term potential for application driven escalation is the promise that one day the system will be able to warn the user when they are potentially using an inappropriate level of technology, or when their technology use appears to be incurring a higher social weight then expected.

3.3.1 Device Escalation

Device escalation relies on the user carrying multiple different devices each with a distinct social weight. Figure 7 presents a typical device escalation commonly observed with currently commercially available mobile devices. In the figure, the user starts by using a single-handed device such as a phone, and escalating through bimanual use of a PDA, a tablet, and finally a laptop. With each escalation in social weight, the user in increasingly engaged and functionality available to the user increases. Increasing their engagement with the device they are using bears a corresponding cost, as the user becomes increasingly unavailable for social interaction. The device escalation pictured in Figure 7 illustrates the user's increasing social unavailability. Initially the user is looking at their device and not their social partners. Then with an escalation to bimanual interaction, the user is interacting with their device and their body posture is concentrating on the device rather then their social partners. Escalation to larger mobile devices also requires that the user find a place in which to deploy the devices before they are used. For example, the user of a laptop needs to find a high counter, table, or a place to sit in order to use the device effectively. The last two escalations have the highest social weight, isolating the user and making their interaction with collocated social participants subordinate to their use of technology. While device escalation has the potential to isolate a user socially, this is as a result of providing access to more powerful resources not concurrently accessible with social interaction.

Device escalation does not necessarily require a change in interface. Emerging user interfaces can span multiple devices with the same interaction techniques. While taking advantage of a device escalation from a watch to a smart phone in order to obtain a greater amount of screen real estate, an application supporting device escalation can offer the user a contiguous user interface spanning the device escalation. For example using the tilting of a device to enter text has been demonstrated for both watches (Partridge, Chatterjee et al. 2002) and on larger devices such as PDAs and mobile phones (Wigdor and Balakrishnam 2003).

3.3.2 Interface Escalation

Interface escalation relies on a device having multiple different interfaces, each with a distinct social weight. An example of interface escalation is entering of text on a mobile device. Previous research has demonstrated that for a single handed interaction with a mobile device, the detection of finger tapping (Fukumoto and Tonomura 1999), gestures (Rekimoto 2001), and tilt (Wigdor and Balakrishnam 2003) can all be used to enter text. All of these techniques provide the user with a channel of unimanual input for their mobile device. Bimanual interfaces provide a generally higher bandwidth, higher social weight, means of entering data for mobile device. Current commercially available devices demonstrate several bimanual methods for input, pushing buttons while holding the device like the RIM[9] Blackberry and many modern smartphones, or holding the device while using a writing stylus as with the Palm[10] Treo and the Compaq iPAQ™ PDAs.

Gabor Blasko et al.'s investigations provide another example of interface escalation within the form factor of a watch. Their work developed several new interfaces for use interacting with a watch form factor, each possessing a distinct social weight.

Working with the IBM watch pad, (Narayanaswami and Raghunath 2000; Kamijoh, Inoue et al. 2001) Drs. Blasko and Feiner (Blasko and Feiner 2004) demonstrated a mechanism for navigating a complex menu of options using a touch screen that was only slightly larger then the user's finger. Their navigation technique uses pressure and direction of the figure during strokes to quickly navigate a complex tree of options. They demonstrated their technique on a display the size of a watch screen, only 3 to 4 times the area of the finger pad being tracked. Their technique required the user to press on the screen of their watch and to move their finger in a series of strokes of less then a centimeter each. For a short series of strokes, it is reasonable to believe that this navigation technique would have a low social weight similar to a user referencing a feature of a conventional watch that required bimanual action such as pressing a button. Figure 8 depicts an example of using this interface.

Figure 8 Blasko's stoke based interface being used on the IBM watchpad
Image Credit: (c) 2004 Gabor Blasko and S. Feiner, Columbia University.

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[9] Research in Motion - 295 Phillip Street, Waterloo, Ontario, Canada Phone: 519 888 7465 – URL: http://www.rim.com

[10] Palm, Inc. – 950 W. Maude Ave. Sunnyvale, CA 94085 – Phone: 408 617 7000 – URL: http://www.palm.com

Blasko also demonstrated a prototype for a string based display interface for a watch (Blasko, Narayanaswami et al. 2006). By pulling the retractable string from the watch the angle and orientation of the string with respect to the watch, and depth to which the string is retracted, act as inputs to the watch. The idea is similar to using the tensioned string as a joystick for the watch with the length of the string acting as another point of data about the scale. The string was able to act as a display by illuminating differing colored dots to convey data about a list of menu items. Dr. Blasko's implementation fixed the position of the watch, anchoring it to the table, and optically tracked the string. Their system was created for modeling and testing novel interaction techniques and was not an interface prototype. A ceiling mounted camera determined position, length, and orientation of the string by tracking a retro-reflective dot attached to its end. A ceiling mounted projector illuminated the string with the colored dots.

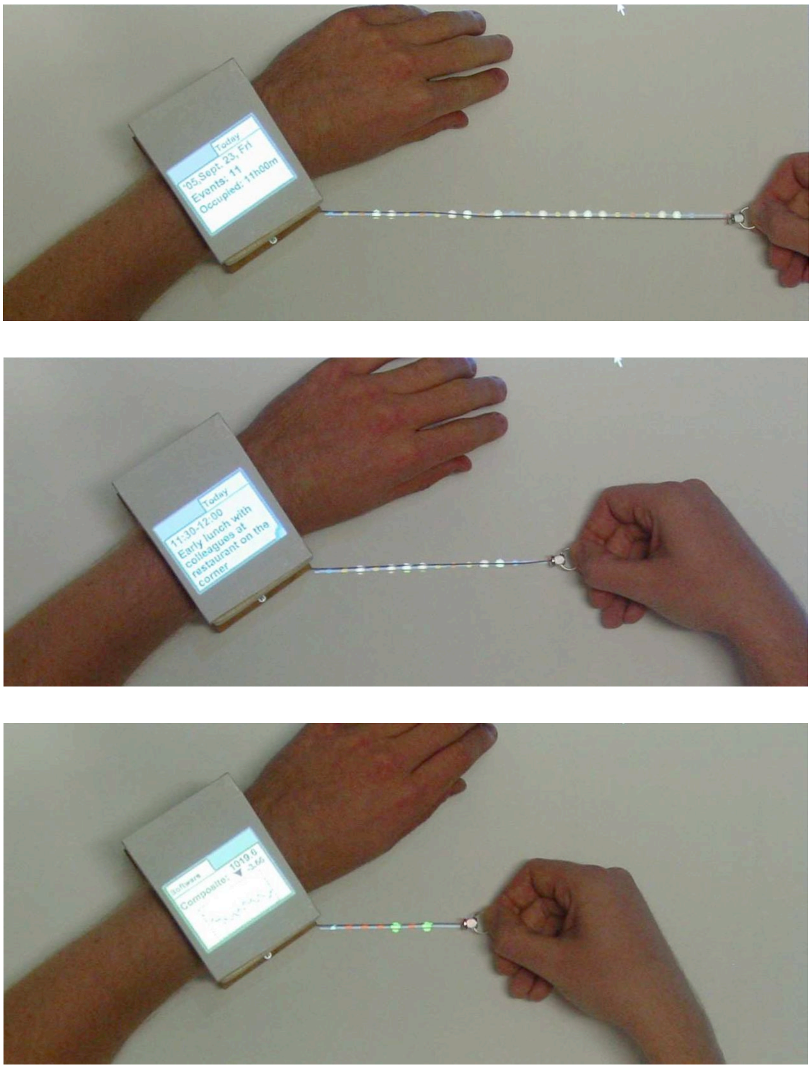

Figure 9 Blasko's string based user interface
Image Credit: (c) 2006 Gabor Blasko and S. Feiner, Columbia University

The specific example which Blasko's Ph.D. work demonstrated was a stock broker pulling the string out to quickly glance at a string of red and green lights displayed on the string. The interface is illustrated in Figure 9. The colors would indicate the current health of his stock portfolio. By feeding the string back into the watch, the "string of pearls" metaphor representing the stock portfolio appears to disappear back into the watch. Adjusting the string's length so the current "pearl" represents a desired stock enables the broker to obtain information about any particular part of his portfolio. So for example, they pull the string out and glance at their portfolio. Seeing, amidst the green, a bright red light indicating an unhealthy stock, they let the string reel back into the watch until it swallows the red light. At this point, the watch displays the current stock information for the stock in question. This type of interaction not only extends the functionality of a mobile device but also allows the user to use interface escalation to control his interactions social weight. The user can always glance at the watch, being indistinguishable from a normal timepiece. Then if they need additional information, the user can quickly glance at a more detailed view of the overall health of their portfolio by pulling out the string and glancing at it. A slightly higher social weight but more detailed view, can be obtained by using both the string and the watch to display more detail, the string acts as a joystick to dynamically control what data is displayed, and how that data is rendered.

3.3.3 Hybrid Escalation

Device and interface escalation are not mutually exclusive strategies for managing social weight. Each strategy presents the user with a number of distinct tiers of social weight with in which to interact with technology. Combining these strategies enables the user to choose not only the appropriate device for their current social setting, but the appropriate way to use that device. Hybrid escalation enables the user to make fine-grained compromises trading social weight for functionality.

Consider the case of a user sitting in a meeting and using a collection of garment integrated and mobile devices to covertly reschedule an event being added to their calendar. To minimize its social weight the scheduling process should be accomplished with minimal awareness by others at the meeting. By using a vibrating alarm, similar to a cellular phone's vibrating while in silent mode, a garment-integrated device can covertly notify the user of an appointment or incoming message.

Either device or interface escalation can be used to convey further information about the priority of the pending appointment. Using interface escalation, the intensity of the vibration can be used to signal the marked priority of the appointment. Alternatively, using device escalation the user can escalate to using another device, such as a watch or a visual display integrated into the jacket cuff. A visual display can map priority onto immediately readable visual characteristics such as color. Both escalation strategies offer the user the ability to immediately read the priority of the incoming information, either by feel or at a glance.

Context will often determine the most appropriate strategy. For example, a visual display would be better suited for use in quiet environments where a vibrotactile display may be overheard, and a vibrotactile display may be better suited for environments where the user is being observed since both the display and the action of reading the display are potentially visible to others. If the user determines that the priority is sufficient to warrant further escalation and interruption, the user can further use device escalation, casually checking their watch for both the time and a short description of the proposed appointment.

Device and interface escalation, and subsequently hybrid strategies of escalation, and not restricted just to displays. However, in the scenario under consideration the user has access to a simple potentially low social weight means of controlling the application by manipulating garment integrated buttons on the inside cuff or hem of their jacket. When controls that require higher bandwidth and that warrant a higher cognitive load are needed, the user can escalated their device usage to the buttons on their watch or the pen input of a PDA.

Using a garment integrated keyboard allows the user to decide to accept the appointment as proposed or to move it by a specified time. Alternatively, the user can choose to escalate their device usage employing their watch. The watch offers the user several interface choices ranging from conventional buttons to the touch screen and string of pearls interfaces discussed earlier. If the user still feels the need for a higher bandwidth device they can escalate their device usage to a PDA.

3.3.4 Priority escalation

Programmatic priority progression is a strategy used to minimize the social weight of alerts. The technique divides the potential notification channel for the alert into distinct user distinguishable intensity level. Changes in the intensity of the alert can then be used to reflect changes in the alert priority.

As an example of priority escalation consider the case of the user standing having an important conversation when a garment integrated vibration alarm goes off indicating an appointment or incoming message. As discussed earlier the perceived intensity of a vibrotactile display's vibration can be used to signal the priority of the incoming appointment or message. The knowledge of relative urgency that this type of signal provides allows the user to choose either to finish their current interaction or to wait for an appropriate time to interrupt their interaction, before responding. As the expiration for the unaddressed message or scheduling event approaches, the vibrotactile display can covertly indicate the approaching expiration by increasing its vibration intensity. Escalation of the vibrating pattern from gentle and intermittent to intense and frequent, signals the user of the increasing priority of the message about to expire.

Priority escalation increases the social transparency of mobile technology use by enabling the user to choose when to interrupt their social interactions to service alerts non-critical alerts. When used in a system that allows the caller to flag the priority of the call, escalation enables the user to always be immediately available in an emergency to individuals trusted not to abuse the privilege. At all other times, priority escalation provides the user with control over both the timing and degree of social disruption caused by responding to alerts raised by their mobile technology.

3.4 Conclusion and Contribution

This chapter has presented social weight as a measure of the social consequences arising from technology user. Social weight is presented as a concern for the developers of future mobile devices and applications. Four components of social weight were identified in the chapter, cognitive load, physical presence, social convention, and technology apprehension. Then the constraints places on the context of the research of this chapter and their ramification on social weight discussed. Research was limited to dyadic business interactions between mobile users taking place in a western cultural context.

Next, a set of tools for quantifying the components of social weight were presented, demonstrating deriving quantitative measures from the largely subjective components of social weight. After defining a process by which the social weight of a device or interface could be evaluated strategies for managing the social weight of an interface are discussed. Three strategies are presented providing the user with control over the level of social weight they experience, device escalation, interface escalation, and hybrid escalation.

4

New worlds are built from pieces ripped from older, familiar, worlds.
Ph.D. Student

Chapter 4 Garment Integrated User Interfaces

A central premise of this thesis is that mobile carried and worn devices are evolving into a hierarchy of accessory devices supporting a single personal server (Want, Borriello et al. 2002; Want, Pering et al. 2002). The personal server ensures that the user always has access to trusted computational resources, data storage, minimal sensor coverage of their environment, network connectivity where coverage is available, and a means of discovering additional pervasive infrastructure. Garment integrated user interface elements ensure that the mobile user always has a potentially low social weight user interface available for interacting with their personal server.

Under their envisioned use, a personal server will be pocketed by a user in the morning after they have made their day's wardrobe selection and dressed. When initially pocketed the personal server dynamically detects the available resources offered by the user's garment integrated and carried devices. Discovered garment integrated and body worn devices offer the personal server a persistent set of potentially low social weight user interface elements available throughout the mobile user's day. Chapter 6 will present strategies for automating the daily outfit selection to ensure that a day's chosen outfits collectively offers a persistent set of features from day to day.

This thesis's investigation into garment integrated user interfaces required the construction of a prototype garments and garment inserts with integrated user interface elements. All of these prototypes were constructed under the same constraints established for researching social weight in Chapter 3.

The first prototype presented in this chapter, the e-SUIT, is a prototype suit jacket constructed to research social weight for emerging garment integrated devices. In general the scenarios investigated with the e-SUIT investigates ways to allow a user of a piece of technology to strike a balance between the amount of functionality provided by a device the social weight of incurred by use of that device. After a general discussion of the merits of the business suit and the role of the tailor in garment integration the components and envisioned usage of the e-SUIT is presented.

The following two sections present the development of a garment integrated keypad and a garment integrated tactile display respectively. The keypad presented was developed for use in the e-SUIT. The garment integrated display refined the design of the e-SUIT's integrated tactile display. Refining the display provided research into construction techniques, and user study to determine optimal display location, optimal number and layout of actuators, and the simultaneous use of multiple vibrotactile displays.

The remaining section revisits the concept of social weight, presented in Chapter 3, specifically focusing on the social weight of garment integrated user interface elements.

4.1 Research collaboration

The initial e-SUIT work was conducted as part of a project conducted by the author, Barrie Mulley, Wayne Piekarski, and supervised by Dr. Bruce Thomas. The work (Toney, Mulley et al. 2002) of constructing the e-SUIT was divided between Mr. Mulley, who wrote the software that ran on the iPAQ$^{\mathrm{TM}}$, and myself, developing the rest of the electronics, hardware, and software used.

The development of the vibrotactile displays presented in this chapter was conducted as part of a research collaboration between the Wearable Computing Laboratory at the University of South Australia and the Department of Textiles and Apparel in Cornell University's College of Human Ecology. The collaboration was conducted between myself, my advisor Dr. Bruce H. Thomas, Lucy Dunne, and her advisor Dr. Susan P. Ashdown, and broadly studied the design of garment integrated vibrotactile displays. Both Miss Dunne and her adviser brought to the project expertise on garment constructions and the functional requirements of clothing and apparel. Previous research by both groups had revealed challenges with garment integrated vibrotactile displays (Dunne, Ashdown et al. 2002; Toney, Mulley et al. 2002). The collaboration was undertaken to generally research the design of garment integrated vibrotactile displays. The collaboration resulted in the paper "A Shoulder Pad Insert Vibrotactile Display" (Toney, Dunne et al. 2003). Both Miss Dunne and I guided the research testing display designs, developing prototypes, and designing and running a user study to test actuator placement. Physical labor was divided with Miss Dunne handling the construction of all sewn prototypes and running the subjects, and with myself handling the construction of the electronics and software used to conduct the study.

4.2 The e-SUIT

Researching social weight for garment integrated user interface elements necessitated the construction of a garment containing multiple user interface elements, each possessing a distinct social weight. The same constraints used in developing this thesis's models of social weight constrained the development of the required garment. These constraints necessitated that the garment be able to function within semi-formal to formal western business environments without violating any of the predominant cultural expectations of clothing. It was imperative that wearing the garment in the testing environment did not bring the user under scrutiny. The business suit is the uniform of western executive. The suit jacket was chosen as the garment type to use in researching social weight within a business environment. Collectively the system developed was called the e-SUIT.

In addition to its garment integrated elements the e-SUIT also used a wristwatch and PDA. As both of these devices and their respective user interfaces have been heavily researched by others they were not studied as part of this thesis outside their use in studying social weight.

4.2.1 Components of the e-SUIT

The e-SUIT was built primarily upon commercially available technology. The initial research application demonstrated by the e-SUIT was a calendaring program specially designed to facilitate communication between a mobile user and their human personal assistant (Robinson, Kovalainen et al. 2000) in a manner with minimal social weight. The application ran on a Compaq H3660 series iPAQ^{TM} running Microsoft Pocket PC 2000, a Windows CE 3.0 variant. The wireless connectivity enabled the application running on the PDA to interact with Microsoft Pocket Outlook to set and check the mobile user's schedule.

The PDA was also connected to a custom bus connecting all of the devices integrated into the e-SUIT. The e-SUIT's integrated bus connected the PDA with the garment integrated and carried user interface elements contained in the e-SUIT. The components of the e-SUIT are pictured in Figure 10.

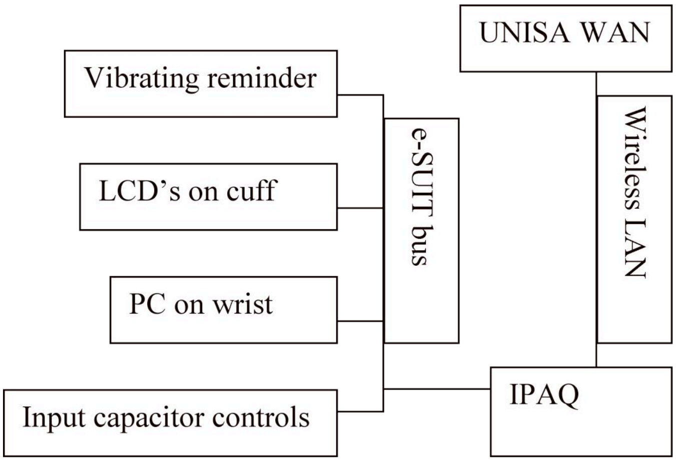

Figure 10 Basic configuration of the e-SUIT's components

4.2.1.1 Software

In addition to being designed to minimize social weight, the e-SUIT's software design was guided by the belief that interacting with commercial personal information managers (PIMs) is critical to making new mobile technologies useful to the business community. A design that does not support the user's existing technologies actively discourages its own adoption, and the general dissemination of the device.

Building its calendaring applications on top of Microsoft Pocket Outlook enabled the e-SUIT to host aggregate applications that provided the user with access to the functionality of a commercial grade PIM package capable of managing contact, task and appointment data across multiple, synchronized devices. Synchronization ensures consistency across data stored in multiple environments, and was specifically chosen to give the e-SUIT the potential to be used in exploring mobile user interfaces used across multiple locations. For example, an "in office" scenario that starts off using a PC in the user's office can be continued in an "out of office" scenario with the user using the e-SUIT to control an application at another location such as a remote job site, a factory floor, customer site, or coffee shop.

In terms of the e-SUIT's software architecture, graphed in Figure 11, the mobile device acts as the user's personal server, communicating with the e-SUIT's Master Bus Controller (MBC). Communication was conducted via a custom communications protocol communicating over a RS-232 serial connection. As discussed earlier my research collaborator Mr. Barrie Mulley designed software running on the PDA that communicated with the e-SUIT's MBC, labeled as "MBC Software" in Figure 11. This software interfaced with Microsoft outlook using the Pocket Outlook Object Model (POOM). My contribution was to design a custom communications protocol, a simple custom real time operating system (RTOS) to support the system, and drivers to support the custom protocol. The e-SUIT's MBC was built around custom hardware, at the core of which was a Ubicom[11] SX18 microcontroller. Due to the high volume, timing-critical workload placed on the microcontroller the e-SUIT's RTOS and its requisite communications drivers were written and optimized in hand coded assembly.

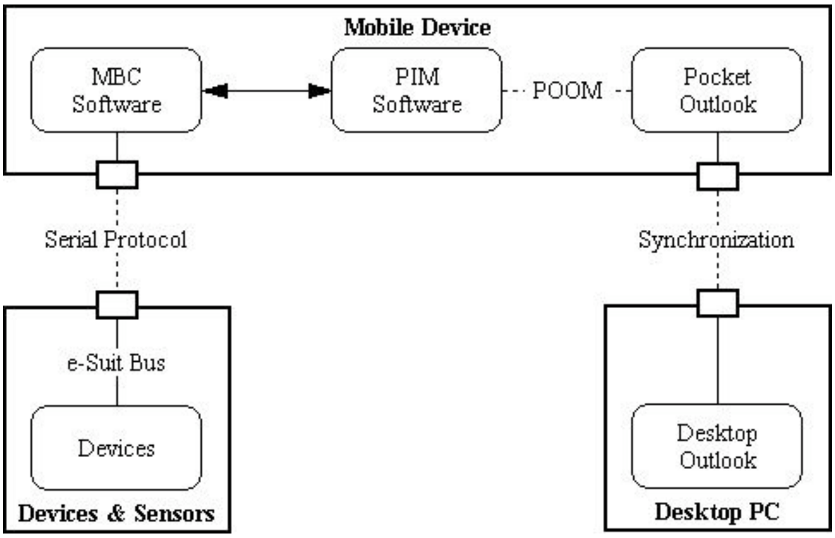

Figure 11 e-SUIT software contexts

4.2.1.2 Inputs

The e-SUIT's user interface used three different devices as user inputs. A keypad is integrated into the jackets hem providing both buttons and slider functionality. A Matsucom[12] onHand PC watch provided additional buttons coupled with a small display. The watch is shown in

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[11] Ubicom Inc - 635 Clyde Avenue, Mountain View, CA 94043-2213.

[12] Matsucom Inc. 1801 Broadway, Suite 1650 Denver, Colorado 80202

use in Figure 15. The iPAQ^{TM} PDA also provides an input coupled with a larger higher resolution display, offering both buttons and stylus input. The watch and iPAQ^{TM} both enable traditional button and stylus driven applications to use the e-SUIT.

Figure 12 The e-SUIT's keyboard in use

The keyboard is shown in use and located on the right hem of the suit jacket in Figure 12. The keypad itself is shown in Figure 13. The buttons and slider used a garment integrated capacitive sensors. The five buttons, pictured in Figure 13, were formed from fine metal wire embroidered into the garment to form the buttons. Embroidered wire was used since at the time, suitable conductive fabric was not yet commercially available and conductive thread was deemed to have too high a resistance. The embroidered patterns could easily be replaced with many of the currently available conductive fabrics.

The keypad was designed so that it could be read either as discreet buttons or to interpolated analog finger position implementing a slider. When touched, the capacitive value of the embroidered pad increases: potentially by several orders of magnitude. This change in capacitance can be used for the pads to measure proximity, contact, touch pressure, gross finger motion and gesture (Baxter 1997; Post, Orth et al. 2000; Rekimoto 2001). A combination of software and simple hardware filtering is then performed to filter out spurious environmental triggers.

As discussed later in 4.3.2, while the keypad was intended for use inside of the garment along the hemline, it was designed to be testable at a number of locations in the garment. As can be seen in Figure 12 the user’s fingers would curl around the hemline and over a long bar-like key. In this position, one button was presented to each of the user’s four fingers. The keypad layout is shown in Figure 13. Since the keypads buttons were capacitive the proximity of the hand around the large bar like key signaled that they keypad was in use. Depending on the application context, the four remaining buttons acted as either discreet buttons or as a slider. When used as a slider seven states are possible with a single finger either pressing a single button or being detected mid way between two of the buttons.

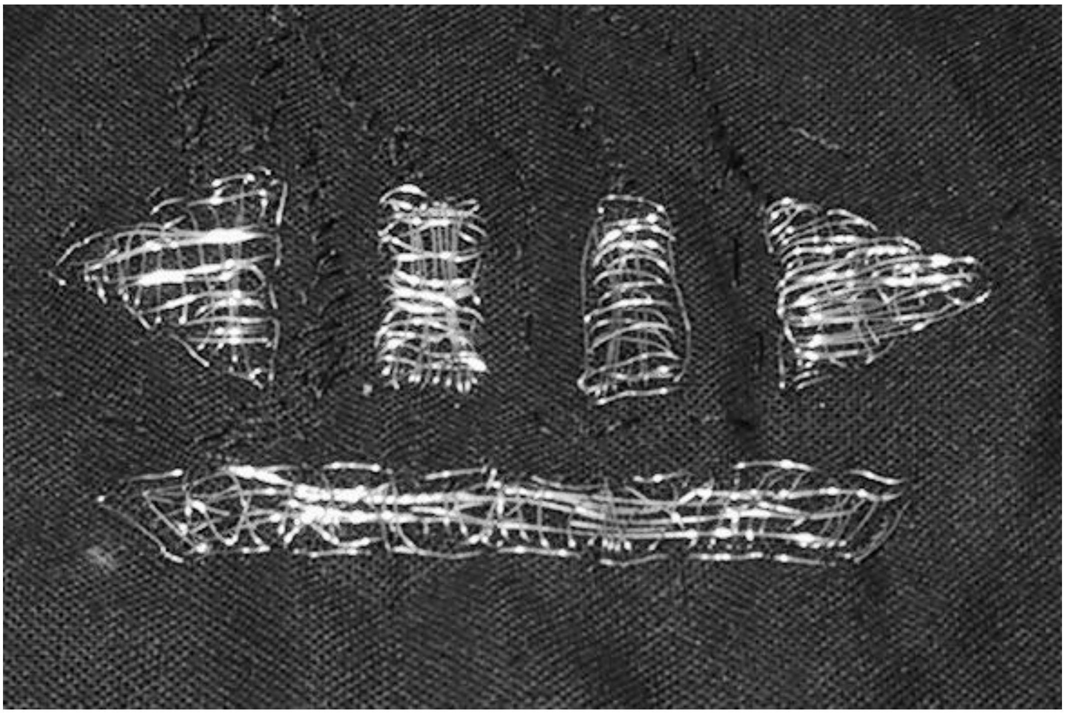

Figure 13 e-SUIT keyboard buttons

4.2.1.3 Displays

The e-SUIT contained four displays; two garment integrated displays, a body worn display device, and a carried display device. These devices were respectively; a vibrotactile actuator and a set of LEDs integrated into the suit, a watch was worn by the user, and a PDA carried by the user.

4.2.1.3.1 Vibrotactile display

The e-SUIT's vibrotactile display was low bandwidth single bit display, formed by a pager motor sewn into the jackets shoulder. In addition to the signal conventionally used with a pager motor to notify the user of a message of a 50% duty cycle vibration, six other simple signals are encoded in the duty cycle, duration, and repetition of the vibration pattern. The next six coded signals are shown in Table 1, and indicate duration of time. The e-SUIT's demonstration application used the patterns to specify the length of time to move an appointment forward or the length of snooze.

The presented patterns are encoded in seconds with the symbol ↑ indicating the motor is on, and ↓ symbol indicating the motor is off. The patterns demonstration a single actuator vibrotactile display of covertly displaying information more complex than a simple "A message has arrived." Gemperle et al. proposed a similar idea, with a tactile display incorporated into an earpiece (Gemperle, Ota et al. 2001). These initial patterns were chosen as they appeared distinct to the researchers. No subsequent formal testing was done to determine if these single actuator patterns were optimal as the ensuing research, which is presented later in this chapter, focused on tactile displays using multiple actuators.

5 mins	0.5s ↑, 1s ↓
15 mins	0.5s ↑, 0.5s ↓, 0.5s ↑, 1s ↓
30 mins	0.5s ↑, 0.5s ↓, 0.5s ↑, 0.5s ↓, 0.5s ↑, 1s ↓
1 hour	1s ↑, 1.5s ↓
2 hours	1s ↑, 0.5s ↓, 1s ↑, 1.5s ↓
Next day	1s ↑, 0.5s ↓, 1s ↑, 0.5s ↓, 1s ↑, 1.5s ↓

Table 1 Tactile display patterns

4.2.1.3.2 Cuff integrated LEDs

Constructed for a right-handed user, the e-SUIT's jacket contained a red, yellow, and green LED display in the cuff of the right sleeve. Since the watch is worn on the non-dominant hand, the LEDs are integrated into the sleeve opposite the user watch. These LEDs are pictured in Figure 14. The LEDs used were selected to have a very narrow viewing angle so that the display would only be visible when viewed straight on.

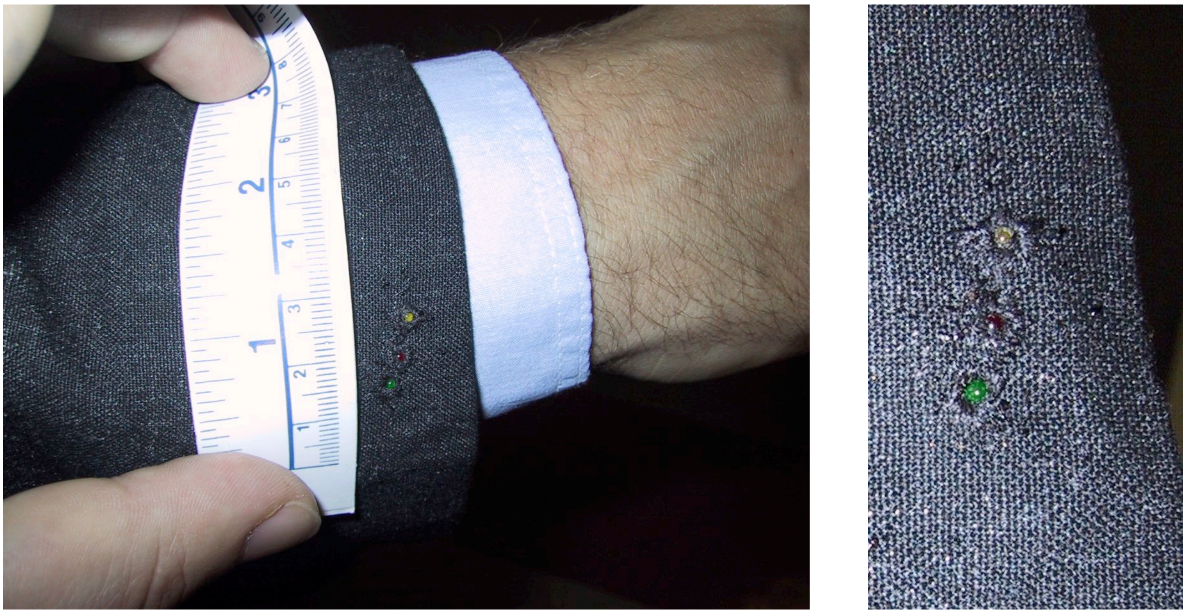

Figure 14 LED's on the e-SUIT cuff

The light emitting diodes (LEDs) integrated into the cuff of the e-SUIT were used to display the priority of the incoming information. Priority level was initially set by a trusted third party and was encoded by color with red indicating a high priority, yellow indicating a medium priority and green indicating a low priority.

The e-SUIT also demonstrated automatic priority escalation, where the initially assigned priority was escalated proportionate to the duration of time elapsed to since the user was initially notified of a message. The escalation demonstrated by the e-suit switches from low to medium priority, switching from the green to the yellow LED, after two minutes of inactivity. If the user takes no action after an additional five minutes, the priority is escalated again from medium to high priority, switching from using the yellow to the red LED. These times were set nominally and do not reflect derived optimal values.

4.2.1.3.3 Watch

The e-SUIT’s watch was an onHand Matsucom watch computer. The onHand watch contained four buttons and a 102 by 64 dot-matrix LCD display. The display supported five lines of 16 character wide text. The notification application developed for the watch provides its normal timekeeping function, and two lines of text overlaid on the top portion of the display. An example message warning of a pending meeting in five minutes with a VP or marketing about the budget depicted in Figure 15. The top line of the display signals the time of the warning “5M”, and scrolling a line of text describing the event ““Meet w/ VP Marketing”. The second line displays a scrolling text message providing additional information about the warning, “re: budget”.

Figure 15 The e-SUIT’s watch display

4.2.1.3.4 PDA

In addition to providing a sound display using its speaker, iPAQ$^{\text{TM}}$ PDA provides the user with the option of a higher resolution display at the cost of removing the device from the suits pocket. While this functionality was added to the e-SUIT it was not the focus of any of the research of this thesis as human computer interaction has been so thoroughly studied by other researchers.

4.2.2 Scenario using the e-SUIT

A user is in a meeting; a vibration alarm in the shoulder of the user’s jacket goes off indicating an appointment or incoming message to the user. The user then surreptitiously views a set of LEDs in the cuff of their suit jacket to determine the priority of the information.

Determining that the incoming information is of sufficient priority, they casually read a short message off their watch informing them of an important appointment at 2:00 pm that afternoon. The user decides to accept the appointment, but needs to move the appointment two hours forward from the original starting time. The user controls the application by manipulating the capacitor slider controls on the inside of the hem of their suit jacket. The user slides his fingers along the slider until the e-SUIT informs him the appointment has been moved two hours into the future. This change in starting time is signaled to the user via a coded pulsing signal from the vibration alarm device.

The user may decide to increase the social weight of the interaction by reading their PDA to give them a more complete description of the appointment. They then may move onto using more intrusive technology, such as a notebook computer or desktop workstation.

4.2.3 Trust

When used to convey highly subjective information such as priority ratings, the efficacy of the displayed information is proportionate and highly sensitive to the user's level of trust in the assigned subjective values. As part of its demonstration calendaring application the e-SUIT used a trusted human personal assistant (Robinson, Kovalainen et al. 2000) to assign priority to information in the system, enabling the users to trust the priority ratings assigned to the incoming material. Unfortunately, due to its human elements this solution does not generally scale. Developing automated systems that the user can trust to automatically prioritize incoming information is a major research challenge facing both academic researchers and mobile applications developers.

4.3 Developing a garment integrated keypad

Buttons and keypads were chosen as the type of input device to integrate into the e-SUIT in order to study social weight. The choice was made under the hypothesis that a familiar type of input technology would have a lower cognitive load and technology apprehension. Buttons and keypads are the most common, and thus familiar, type of input device. Consequently, a garment integrated keypad was chosen as the type of input integrated into the e-SUIT, and as one of the device with which social weight was studied. More exotic types of garment integrated inputs, like using gesture (Rekimoto 2001; Mazé and Margot 2003), posture (Kern, Schiele et al. 2002), biometrics (Vuorela, Kukkonen et al. 2003), or detected emotional affect (Picard 2000) to control an application, were avoided so as their exotic nature would not confound observation of the artifacts of social weight.

4.3.1 Previous garment integrated keypads

A number of garment integrated button pads and keyboards have been demonstrated in previous research. While not necessarily garment integrated, the earliest relevant keyboard that the author is aware of is the in pocket chording keyboards used by the secret service and other protection agencies. A reproduction of this type of keyboard[13] is pictured in Figure 16. The keyboards are intended to be used while remaining in the wearer's pocket. Being used while in a pocket obscured the use of the keyboard from others observing the security professional, minimizing the risk that the use of the keyboard would tip off hostile parties of action being taken by security personnel. This class of chording keypads is relevant here as a device that used garment integration, or containment, to obscure its use from others. Some of the keyboards even supposed to contain a cover for the key area into which the fingers were slipped. The cover prevented the fingers from disturbing the surface fabric of the pocket.

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[13] http://www.cs.vassar.edu/~priestdo/wearable.pics.html

Unfortunately, due to their niche exclusively by intelligence agencies it is almost impossible to find detailed descriptions of the keyboards.

Figure 16 GPD's In Pocket Keyboard
Image Credit: Greg Priest-Dorman

One of the earliest garment integrated keypads, and the first to use embroidered conductive fibers to form the keyboard, was the MIT Media Lab's Music jacket (Orth, Post et al. 1998; Post, Orth et al. 2000), pictured in Figure 17. The music jacket had a twelve key keypad positioned on the left breast of the wearer. The keypad, pictured in Figure 17, was connected to a MIDI "Boat" synthesizer board and enabled the jacket to be played as a simple musical instrument. Both the keypad and its use were plainly visible to people interacting with the wearer.

Figure 17 Keypad composite - denim E-broidered keypad and mating circuit board
Image Credit: E. Rehmi Post / MIT Media Lab

As a result of the explosive growth in the market for portable digital music players, garments that have integrated controls for common devices, like Apple's iPOD^{TM}, have become commonplace. As an example, Burton's[14] Audex collection of jackets (Burton 2006) have an integrated interfaces for Motorola's cellular phones and Apple's iPOD^{TM} devices. The jacket provides the music playing functionality of the iPOD^{TM}, and lets groups of people stay in touch on the ski slopes by offering "push to talk" functionality.

Kaho Abe's work on creating discreet interfaces for wearable technology (Abe 2005) provides prior work relevant to both social weight and garment integrated user interfaces. At the International Symposium on Wearable Computing in 2005, Abe displayed the four prototype garment integrated keyboards pictured in Figure 18. The demonstrated keyboards were integrated into the sleeves of four very different types of garment. From left to right the keyboards pictured in Figure 18 were implemented within the sleeve of a blouse, a jean jacket, an outdoor pullover, and a "punk" garment. The different garments called for different types of keys. The blouse used push buttons, the jean jacket used touch sensitive snaps, the outdoor pullover used squeeze tabs, and the punk garment used touch sensitive spikes. Abe demonstrated the keypads controlling a music application. The buttons along the edge of the table selected one of the four display sleeves, and the four keys on the sleeve provided the functionality for "volume down", "volume up", "skip song", and "play song".

The most relevant part of Abe's work was that it provided an early example of how to deliver persistence of interface for garment integrated devices. In the demonstrated example, the user can change their outfit and layering of garments from day to day and still have the same interface available to them. In Abe's words the user is "…able to change to a new outfit every day without having to change technology". This shows how same garment integrated user interface can span multiple garments without imposing itself on the form of the garment.

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[14] Burton Snowboards USA, 80 Industrial Parkway Burlington, VT 05401, Phone (800) 881-3138,

URL: http://www.burton.com/AudexCollection.aspx

Figure 18 Kao Abe's sleeve buttons

4.3.2 Keypad Locations

Thomas and Grimmer (Thomas, Grimmer et al. 2002) showed that the efficiency of a cursor controlling device was directly effected by its location on the body of the mobile user, and the user's posture while using the cursor. These results suggested that the location of the integrated keypad could impact its efficacy. Further, not all keyboard locations are socially acceptable. The e-SUIT's keypad was developed using the "Pinning" technique discussed in Chapter 5, to enable testing of the keypad at a number of locations on the "inside" of the garment facing the user's body.

The final location settled upon for the e-SUIT's keypad was inside the jacket sitting opposite the hip and just below the dominant hand. A right-handed user is pictured using the keypad in this location in Figure 12 (the layout of the keypad being used is shown in Figure 13). This location was located near a relaxed resting place for the user's hand. This placement lets the user typically interact with the suit with a minimum of extra motion and thus has a reasonably low social weight. It was observed from using the suit that the keypad needs to be located ventral to the coronal plane of the user's body (NASA 1995), keeping the keypad and the user's hand clearly away from the buttocks to avoid negative social weight associated with prolonged hand position in that area. Previous research supported this choice of location from a functional stand point when the user is standing (Thomas, Grimmer et al. 2002).

Another possible position for this type of keyboard, more suitable for use when the user is seated, is inside the cuff on the non-dominant hand near where the watch is traditionally worn. In these locations, the impression the user gives when using the cuff buttons is that they are straightening their cuff or adjusting their jacket, while in reality they are controlling their computer. This location was not tested with the current keypad. Since the cuff has less available area for the keypad testing a cuff integrated keypad would require a different keypad layout and key size.

Placing the keyboard at these locations lets the business user interact with the suit with a reasonably low degree of extra motion, and thus should cause correspondingly low levels of additional social weight. The optimal position for suit-integrated keypads to both maximize efficacy and minimize social weight is an open research question that will require further investigation.

Several areas were considered and rejected for the placement of a keypad. The inside of the suit jacket's pockets was rejected as hard to reach and uncomfortable to use. The inside of pant pockets was similarly rejected for similar reasons as well as being both socially unacceptable in general, and physically awkward to use when the user was seated. Controls integrated into visible areas on the outer surface of the suit, such as a keypad located on the thigh, were rejected as their high level of visibility would lead to high levels of social weight.

4.3.3 Keypad implementation

Commercial solutions for implementing garment integrated buttons and keypads were unavailable at the time of the e-SUIT's construction. The e-SUIT's keypad was a custom built capacitive keyboard. The individual capacitive keys functioned by electrostatic coupling to their environment. When a finger makes contact or is in close proximity with a key the pads capacitance is changed.
A microcontroller monitored tank oscillation frequency counter was used to implement the custom capacitive keypad as it possesses both a low component count and the components are low cost and readily available. Each button on the keypad acted as part of a RC feedback path to a separate gyration oscillator (Baxter 1997) with capacitive dependent frequency. In essence the oscillator works by charging and discharging a capacitor, in this case the capacitive button. The frequency of this type of oscillator varies inversely proportionately to the capacitance of the pad. The greater the capacitance of the button pad the bigger the "tank" to charge up and the slower the frequency of the oscillator. Schmidt trigger inputs on a microcontroller debounce and digitize the output of each oscillator so that its frequency can be determined and the associated buttons current capacitance determined. A Ubicom SX18 microcontroller was used to measure each buttons capacitance, provide software filtering of the data, and transmit it to the e-SUIT's internal bus.

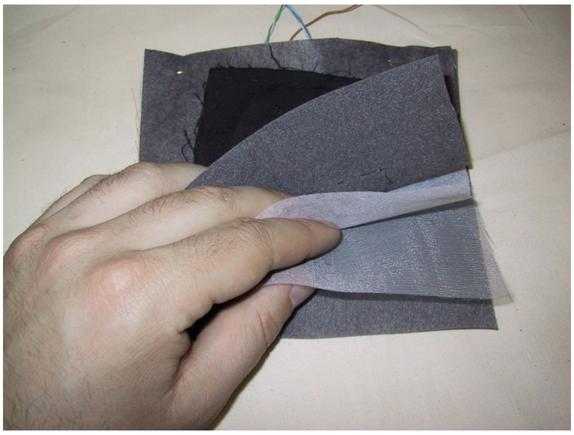

Figure 19. Layers of cloth

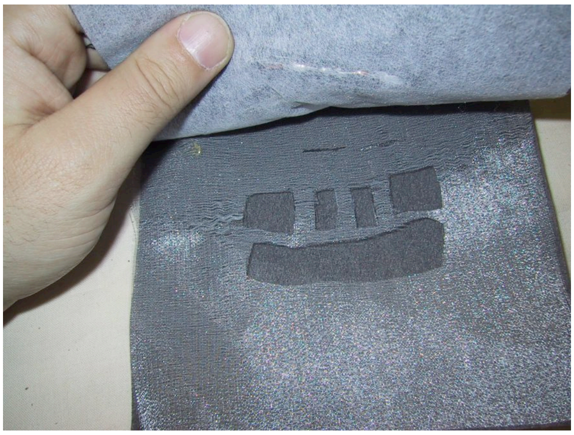

Figure 20. Button outline

The buttons themselves, as can be seen from Figure 19, are constructed in four layers. Two of the layers have electrical significance for our purposes. The first is the top layer. Metal wire was embroidered into this layer in order to form the button pads. The second layer is a metal organza. The organza sits separated from our button pads by a layer of non-conductive interfacing to keep the conductive buttons from electrically shorting to the organza. Cut into the metallic organza is a pattern outlining the buttons, as shown in Figure 20. The organza helps to terminate electrostatic field lines between buttons and is used to help minimize button AC coupling between the buttons.

4.3.4 Discussion and observations

At the time of the e-SUIT's construction commercial solutions for implementing garment integrated keypads were commercially unavailable necessitating the construction of a custom keypad. Several methods of capacitive button detection were tried. While better then the alternatives, all capacitive approaches tried experienced the plethora of problems for which capacitive circuits are famous. The problems associated with capacitive detection circuits are exacerbated when used on the body; an environment, which has by its very nature, has a strong coupling to the circuit, which is in a near constant state of flux. To obtain reasonable performance, both hardware to provide hysteresis on the microcontrollers input and software low pass filtering were required. Subsequently, available commercial field based technologies have countered these problems with inbuilt auto calibration.

Despite being relatively simple in comparison with the keypads that have subsequently become commercially available for garment integration, the keypad integrated into the e-SUIT successfully met it's primary design goal of demonstrating that a keypad could be both covertly integrated into the garment and remain concealed during use. This enabled observing the usage of a covert garment integrated user interface. These observations helped formalize the concept of social weight presented in Chapter 3.

4.4 Developing a garment integrated tactile display

While the e-SUIT integrated pager motor was excellent for covertly notifying the user of one to two bits of information, as a single actuator vibrotactile display both the cognitive load and latency of the display increased significantly in response to an increased message length. Displaying a message of even modest length required the user to stop and consciously decode the pattern of vibrations. As a result the displays social weight quickly escalates with the increased cognitive load required to decode longer messages. Despite its problems the e-SUIT's display successfully demonstrated the promise of using vibrotactile displays to minimize social weight.

The work presented in this section details the research following up on the primary shortcoming of the e-SUIT's display, its use of a single actuator. Several multi actuator prototypes were constructed and formally evaluated as part of this follow up effort. This section begins with a presentation of requisite background information before presenting the details of the designing and then formally evaluating a shoulder mounted vibrotactile display.

4.4.1 Cutaneous display channels

All of the user's skin can perceive cutaneous information. This frees tactile displays to be located on areas hidden from view under the user's clothing. As a result, displays built using cutaneous sensory channels have the potential to provide high levels of privacy with low levels of associated social weight.

Mechanoreceptors contained within the skin provide the cutaneous sensory channels, which collectively are known as the sense of touch. This section reviews the different mechanoreceptors that provide the sense of touch. Table 2 outlines the seven tactile mechanoreceptors and their sense modality. An analysis of each modality reveals different levels of appropriateness for use in clothing insert based tactile displays.

Receptor	Sense modality
Meissner Corpuscle	Stroking, fluttering
Merkel Disk Receptor	Pressure, texture
Pacinian Corpuscle	Vibration
Ruffini Ending	Skin stretch
Hair follicle	Stroking, fluttering
Hair	Light stroking

Table 2 Human mechanoreceptors and corresponding sensory modalities

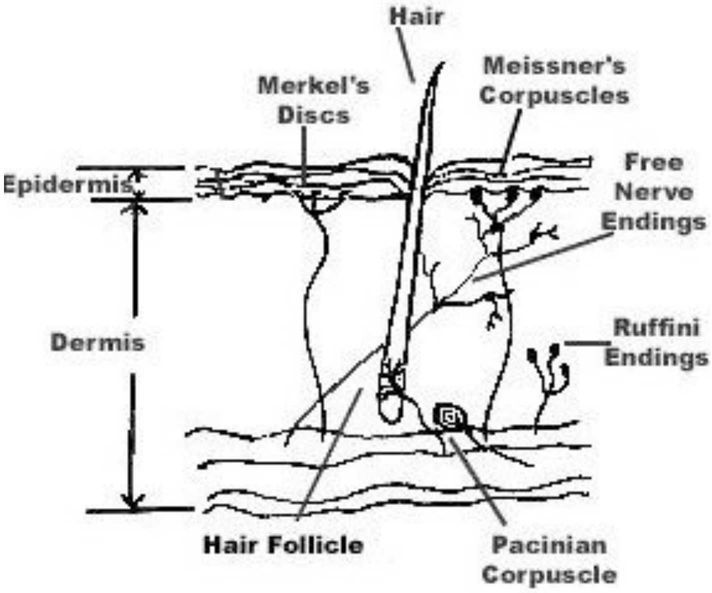

Figure 21 Sensory Anatomy of the skin

4.4.1.1 Vibration

Vibration is a sensory channel suited for use in clothing insert based tactile displays. Both the scale and geometry of vibrotactile actuators device facilitates easy integration into small garment spaces. The Pacinian corpuscles are the mechanoreceptors responsible for most detection of vibrational stimuli. Pacinian corpuscles are some of the deepest mechanoreceptors in the dermis, and are the largest touch receptors. They are the fastest adapting of the class of fast-acting receptors, meaning they respond quickly to changing stimuli. They have optimal sensitivity around 400 Hz, and have difficulty detecting frequencies below 50 Hz or above 600 Hz (Wilentz 1968).

4.4.1.2 Pressure and Stroking

Although vibration is merely the time variance of pressure about an equilibrium level, it remains a distinct dermal sensory channel from both pressure and stroking. Pressure and stroking communication channels both require the accurate generation of static or low time variant pressure distribution across the skin surface. For most garments, hang weight alone will not supply enough static counter force for actuators to support reliable pressure or stroking stimulus. Further fluctuations in hang weight resulting from user movement or changes in posture would vary the channel sensitivity. While these problem can be overcome in specialty garments that can use straps to maintain a constant location and pressure for the actuator they are not generally suitable garment integration.

4.4.1.3 Skin Stretch

While displays using the perception of stretch have been demonstrated (Hayward and Cruz-Hernandez 2000), they inherently require at least two points of firm contact with the skin to operate, which are drawn apart to stretch the skin that they are in contact with. Any fabric between the skin and the actuator may cause the contact points to slip. Consequently, stretch makes a poor mobile or garment integrated communications channel.

4.4.1.4 Texture, Stroking, and Fluttering

The sensations of texture, light stroking, and fluttering are subtle sensations that are only perceptible directly on the skin surface. As these tactile channels are all severely muted when felt through clothing they are not an appropriate foundation for a wearable tactile displays in garments that are not directly in contact with the users skin. For example, a jacket sitting over a shirt and possibly an undergarment will have one to two layers of fabric between the actuator and the wearer’s skin muting the signal.

The subtle nature of these sensory channels also makes it unclear how suitable they would be for use in garment that may be worn under another garment. For example a tactile display integrated into a shirt that attempts to use light fluttering on the skin as a communications channel, would need to be designed to handle a heavy coat being donned over the shirt, pressing down on the display elements. Similarly, a display integrated into a blouse or shirt that attempts to use stroking would need to deal with changes in garment mobility resulting from the user carrying a purse or bag using a shoulder strap.

The suitability of all of these sensory channels needs to be the subject of further study.

4.4.2 Selecting a vibrotactile display location

The smallest of situational changes effects sensory perception, including factors such as amplitude or frequency (Verrillo, Fraioli et al. 1969), and location on the body (Verrillo 1966; Verrillo and Chamberlain 1972). Since garment integration is such a recently developed area of research little to no work has been done studying the impact of most of the variables of garment integration on the perception and discrimination of displayed tactile patterns. For example, no information was available on the impact of layers of textile being present between the user’s skin and the garment integrated actuator. Almost no research has been conducted examining how the fundamental measures of the cutaneous communications channel, such as the two-point threshold or the minimum distance needed between two points of stimulation before they can be perceived as separate, is effected by simple things like movement of the garment of integration of the actuator.

Locating a vibrotactile display in the shoulder area of a garment helps to minimize the variability of the changes encountered during normal garment use. The hang of most garments is somehow anchored at the shoulder, where fabric running over the shoulder acts to holds up the rest of the garment. The weight of the garment presses down on the shoulder weather the user is seated or standing. Garment integrated vibrotactile displays located in the shoulder area of a garment can be designed use the hang weight of the garment to firmly yet gently press the displays actuators onto the user’s skin.

The work of this thesis represents some of the earliest formal work examining garment integrated vibrotactile displays, and to the author’s knowledge was the first to examine the potential of placing garment integrated displays in the shoulder area.

4.4.3 Selecting a vibrotactile actuator

A number of factors that determine the appropriate type of vibrotactile actuator to use with a given garment integrated context. The following subsections evaluate different commercially available actuators. The considered types of actuators are solenoids, speakers, piezoelectric actuators and electromagnetic motors. After a review of the properties of each, my research collaborators and I chose to use a pager motors, a type of electromagnetic motor, as the actuator for the constructed prototypes.

4.4.3.1 Solenoids

Generally, solenoids are not suitable for implementing tactile garment integrated displays. Solenoids small enough to be garment integrated have been commercially demonstrated in devices like Braille displays (Akamatsu and MacKenzie 1996) or the TrakPoint pointing deice on the IBM laptop keyboards (May and Selker 2001). While small in size, these solenoids require a mounting that will keep their actuator aligned with the wearers skin and are thus only suited to a few types of garments and locations within those garments.

The use of solenoids to implement a vibrotactile display also suffers from sensitivity problems. The mechanical travel of the solenoid “slug” limits the maximum firing frequency of the solenoids. As a result, small solenoids are not able to impart significant mechanical energy over the full cutaneous vibrotactile sensitivity range of 50-600 Hz. To function properly these small solenoids rely on a small sharp contact surface (one with a high degree of contrast) striking the skin, and garment layers between the solenoid and the skin heavily mutes contact.

4.4.3.2 Speakers and Piezoelectric Actuators

Speakers are unsuited for garment integration due to the minimum size and mechanical mounting requirements necessitated by their user of a voice coil. Piezoelectric materials have a number of desirable attributes for garment integration (Edmison, Jones et al. 2002). Actuators built from piezoelectric material can be light, thin, flexible, and have a stimulation frequency range appropriate for vibrotactile perception. Piezoelectric actuators have previously been demonstrated in wearable applications (Gemperle, Ota et al.; Edmison, Jones et al. 2002; Gunther, Davenport et al. 2002) and are generally suited for the implementation of vibrotactile displays (Edmison, Jones et al. 2002). Unfortunately, piezoelectric actuators have the drawback of requiring high driving voltages. The required voltages present a significant risk to the user and needs to be addressed before piezoelectric actuators would be suitable for garment integration.

4.4.3.3 Electromagnetic Motors

The ability to deliver significant vibrational force at low voltages in a robust package has made motor based tactile actuators a very appealing option to wearable researchers. The wide scale use of motors in pagers and cellular phones has provided an economy of scale for electromagnetic actuators making miniaturized low power actuators available and affordable. As a result they have already been used in numerous wearable designs to provide vibrotactile stimulus (Tan and Pentland 1997; Tan, Ertan et al. 1998; Morikawa 1999; Rupert 2000; Toney, Mulley et al. 2002).

Motor based electromechanical actuators were used in the prototypes developed for the research of this thesis. In initial subjective evaluations motor based actuators were able to provide substantially more vibrational force then comparably priced and sized piezoelectric actuators. Positioning a garment integrated actuator on the shoulder maximizes the hang weight of the garment pressing the motors into the skin. The tested motor based actuators demonstrated sufficient force to operate under the hang weight of the garment.

Motors also benefit from being easy to drive as they are activated by the simple application of voltage. The voltage signal applied can be digital, merely to spin the motor up, or analog for more subtle control. Motors generate a relatively high level of vibration when compared to other vibration generating technologies. Small counterweighted electromagnetic motors are packaged in two different configurations: cylindrical and pancake motors.

The cylindrical motors are miniature DC brush motors with a cam shaped counterweight. These motors typically range from 4-6 mm in diameter, 15-20 mm in length, and draw 60-120mA at 1.5-3V depending on vendor and type. Our initial proof of concept prototype was designed around the cylindrical pager motors that were quickly abandoned in favor of pancake motors that deliver a more appropriate signal for our use.

The pancake motors trade height for increased diameter, and provide a more radially uniform distribution of vibrational energy whereas the cylindrical motors distribute most of their mechanical energy along the central axis of their body cylinder. Both types of actuator were used in the developed prototypes, and while only informally tested the pancake motors appeared to generate less noise. All of the most recent prototypes used use the Sanko Electric[15] 1E120 pancake motor.

4.4.4 Previous shoulder mounted vibrotactile displays

Previous work of researchers of cutaneous perception has characterized parameters of most of the body with respect to its typical size, shape, and tactile threshold sensitivities (Verrillo 1963; Wilentz 1968). As a result, a wide variety of worn and carried vibrotactile displays have been developed to take advantage of cutaneous vibration sense. For example, vibrotactile displays have been demonstrated integrated into vests (Tan and Pentland 1997; Tan, Ertan et al. 1998), shoes (Bass 1985), belts (Tsukada and Yasumura 2004), bracelets (Hanson and Ljungstrand 2000), and the shoulder straps of bags (Gemperle, Ota et al. 2001). However, while some work has been done investigating optimal shape of shoulder based wearable modules (Gemperle, Kasabach et al. 1998), the shoulder has been largely neglected as a target area for a tactile communications channel. Similarly while a number of worn and carried vibrotactile displays have been demonstrated, there have been very few efforts to integrate vibrotactile displays within a garment.

Vibrotactile displays on parts of the body other then the shoulder have already demonstrated a wide range of cognitive aids to improve situational awareness, navigation (Tan, Ertan et al. 1998), balance (Wall, Weinberg et al. 2001), and decrease confusion about spatial and directional orientation (Rupert 2000). Investigations into assistive technology to provide wayfinding and navigation support to the disabled (Lee and Kwon 2000; Wall, Weinberg et al. 2001), have typically used a single vibro-tactile actuator located somewhere on the upper

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[15] Sanko Electric Company Ltd. 5-1167 Hirosawa-cho, Kiryu, Japan Phone: 81 0277 52 5816 URL: http://www.mitsuba.co.jp

arm. While not specifically addressing tactile arrays or the shoulder area this work has been significant in their setting of early precedence for a shoulder mounted displays.

Osamu Morikawa's HyperMirror (Morikawa 1999) used a shoulder worn single actuator display to provide videoconference participants a vibrotactile cue for getting another person's attention. This cue literally provided a videoconferencing participant at a remote location with the ability to tap another videoconference participant on the shoulder.

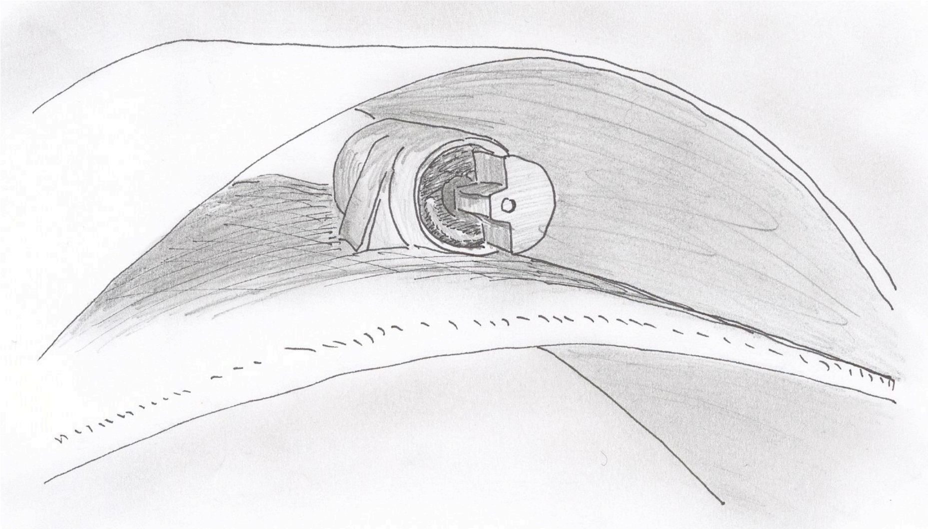

Figure 22 Morikawa's HyperMirror Actuator

Morikawa's "Shoulder Tapping" interface is the only work known to the author, other then his own, to have used a shoulder mounted vibrotactile actuator. Morikawa's actuators were not, however, garment integrated. His shoulder taping device, pictured in Figure 22, was composed of two curved sheets of plastic joined to form a shoulder mount. Set within the shoulder mount is a cylindrical pager motor. A significant feature of their work was their use of two such devices, which provided the videoconferencing participant with a stereo shoulder mounted vibrotactile display.

While vibrotactile arrays are uncommon they have previously been used to implement wearable technology. Wearable vibrotactile arrays have been demonstrated on the forearm (Verrillo and Chamberlain 1972), back (Tan, Ertan et al. 1998; Traylor and Tan 2002), and torso (Nakamura and Jones 2003). The few applications that have incorporated the shoulder as a tactile display space have almost exclusively investigated applications for assistive technology for the disabled (Lee and Kwon 2000; Wall, Weinberg et al. 2001).

The two most common applications of vibrotactile displays are as a grid of actuators located in the back of a vest or a chair. Examples of both types of interface would be the early work of Tan et al. (Tan and Pentland 1997; Tan, Ertan et al. 1998) integrating a display into a vest, and the work of Lindeman et al. (Lindeman and Cutler 2003) integrating displays into the backs of chairs. All of the cited example arrays are typical of the construction of the vibrotactile user interface arrays previously constructed by the research community. They arrays are implemented using either a 3 by 3 or 4 by 4 grid of pager motors. The implementation Lindeman et al's chair based array proved particularly instructional for the design of this thesis' shoulder pads. The configuration of Lindeman et al's Near-Field Haptic display used the same style motors that were chosen for the shoulder pad constructed for this thesis. Their actuator, or “Tactor”, pictured in Figure 23 used small foam blocks to increase the overall actuator area. For the paper “A Shoulder Pad Insert Vibrotactile Display” published at the International Symposium on Wearable Computers in 2003 (Toney, Dunne et al. 2003) my research collaborators and I also experimented with a foam construction for our shoulder pad. We abandoned the use of foam as our display was contained in the much smaller physical space of the shoulder, and initial testing made it appear that the foam’s mechanical coupling would blur the discreet actuator areas.

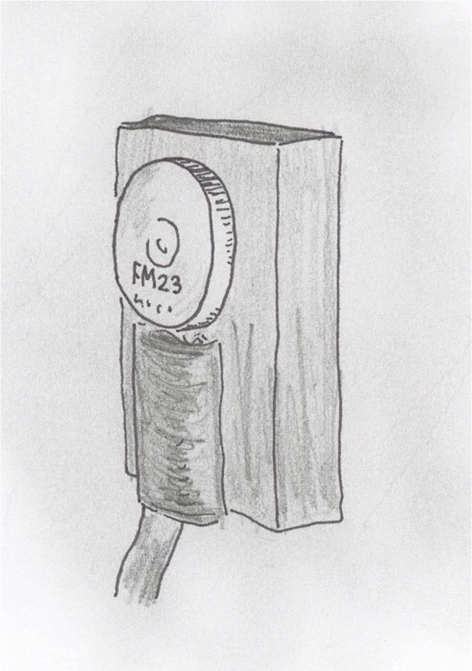

Figure 23 Lindeman et al's foam Tactor

4.4.5 Motivation & Objectives

The e-SUIT revealed a number of shortcomings of single actuator vibrotactile displays. A single vibrotactile actuator was sewn into the left shoulder of the e-SUIT. Displaying complex information with a single actuator required using patterns of vibration. For example, the scheduling application developed to demonstrate the e-SUIT used patterns of vibration in order to covertly display one of six different time intervals. After using the e-SUIT it quickly became clear that the use of serial vibration patterns of even modest complexity presented a significant bottleneck to the system. While they are potentially covert, single actuator vibrotactile displays are inherently low bandwidth since processing an incoming message requires the user’s attention for the time required to first perceive and then decode the message.

Three principle objectives guided the development of the new display. First, as the developed display was garment integrated its principle objective was that all of the display’s functionality be achieved while maintaining the shape, stability, and flexibility requirements of the area of the garment into which it was integrated. Second, as the display was eventually to be used by the general population another principle objective was that the display be usable by the majority of body types and sizes present in the general population. Finally, the new display needed to be capable of presenting several distinct stimuli in multiple locations at once.

4.4.6 Sizing and development of physical space

For the user's perception of a displayed pattern to be consistent despite movement or changes in position it is important that a vibrotactile display closely fit its user's body. Given the dramatic variation in size and shape of the population, it quickly became clear that a "one size fits all approach" would not provide an acceptable fit and function for a vibrotactile display. An analysis of the available area on the shoulder and the anthropometric variation of this area across the general population were conducted to determine the space available for a shoulder mounted vibrotactile display. Analysis of several measurements from the ANSUR (Gordon, Churchill et al. 1988) database of anthropometric measures (a survey of the body measurements of 3,982 subjects, 1,774 male and 2,208 female US Army personnel) provided the data required to determine the number of sized shoulder pads required to acceptably fit the majority of the population. Shoulder pads are shaped layers of padding sewn into many types of jackets and blouses to provide the garment with shape and structure. The pads can either be sewn permanently into the garment or removable.

Due to the size restrictions and fitness requirements of the military, the ANSUR database does not represent the anthropometric variation in the population as a whole; rather it is representative of the median 90% of the population that meets the military's size and weight requirements. As a result the derived sizes are representative of the majority of the general population but would not adequately fit either extremely large or small individuals.

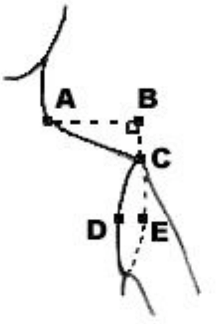

Figure 24: Desired dimensions for shoulder pad
Shoulder length A-C, vertical distance B-C, and curve length D-C-E

The specific measures derived from the ANSUR database were shoulder length, vertical distance from the horizontal plane, and shoulder curve length. These measurements are illustrated in Figure 24.

The ANSUR measurements for shoulder length, cervical height, acromial height and axilla height were used to derive the shoulder measurements. The derived measurements are illustrated in Figure 25. As part of Chapter 7's presentation of the physically reachable space Section 7.2.1 presents a more detailed anatomy of the shoulder complex, complete with figures more accurately locating the acromial landmark in relation to the bones and joints of the shoulder complex.

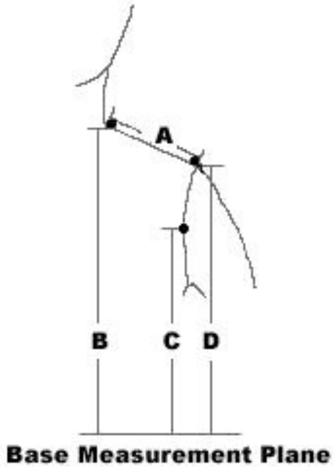

Figure 25 Available body measurements used A: Shoulder length, B: Clavicle height, C: Axilla height, D: Acromial height

The shoulder length measurement was the only measure available directly from the database; all other measurements were derived from related measurements. To derive the maximum vertical distance for a shoulder pad for each subject the acromial height was subtracted from the clavicle height measurement. This derived measure provided the vertical height that would produce a horizontal line from the base of the neck out to the end of the shoulder, or the pad height. For historical reasons shoulder pads are currently worn to square the shoulder, and this derived measurement provided a measure of the maximum thickness for the outer edge of the shoulder pad while still ensuring a squared look to the shoulder.

Data was unavailable on the thickness of the shoulder, or the depth from the front of the shoulder to the back. A linear measure of the acceptable pad curve length was used to approximate the curve length. (The curve length was approximated as two right triangle segments of known height.) A value of twice the difference between the axilla height subtracted from the acromial height (field C subtracted from D in Figure 25). The derived value is twice the difference in order to account for both the front and the back curve. The pad curve length is used as the acceptable underside length of the pad at the edge of the shoulder.

Using the above derivation, it was possible to estimate the ideal pad height and curve length for each member of the ANSUR database. Statistical analysis of ideal pad measurements determined the number of different pad sizes required to fit the population represented by the ANSUR data. The analysis compared the length and height to generate both the number of pads required to fit majority of the population, and the required pads sizes. Length was used in the correlation because it is the most important sizing measure in a shoulder pad. The thickness of the shoulder pad tapers a maximum thickness along its median to a minimum along its outer edge making the fit of the shoulder pad only grossly sensitive to the pad curve length. As long as the median thickness is unaffected, the shoulder will still look square fulfilling the visual requirements of the shoulder pad. An incorrect shoulder length measurement on the other hand has a significant visual effect. A pad that is too short results in a collapsed line in the silhouette of the shoulder. A pad that is too long results in a protruding edge at the sleeve cap.

Length was strongly correlated to height. A comparison of length to height resulted in a fairly strong relationship between the variables with a correlation coefficient is 0.667, significant at measurement differences of 0.01 mm. The scatter-plot is shown in Figure 26. Again, the pad length is measured in the direction from neck to shoulder, and the pad height is the measure from the base of the pads curve to its apex.

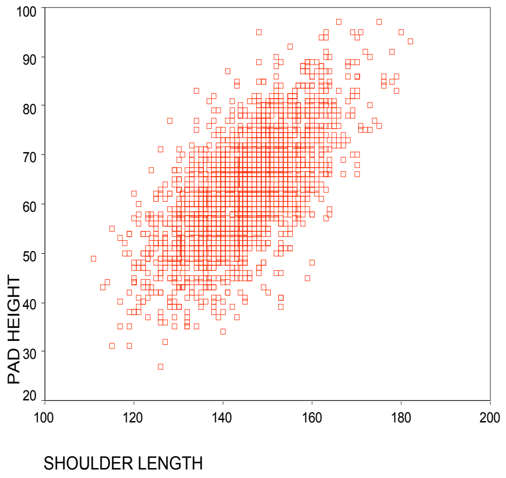

Figure 26: Scatter-plot of shoulder (pad) length versus pad height

Using the histograms of each measure, it was determined that the entire population could be effectively divided into 5 sizes. Eliminating the outlying extra small and extra large sizes left 3 sizes that could be expected to fit approximately 90% of the population. For the initial study, pads appropriate for testing the three sizes representative of the small, medium, and large segments of the population were constructed. These sizes are shown in Table 3. Small outliers represented approximately 6% of the population while large outliers represented less than 1%. The body sizes for each pad used to fit the population are shown in Table 3.

SIZE	LENGTH	HEIGHT	CURVE
1	13 cm	5 cm	22 cm
2	15 cm	7 cm	24 cm
3	17 cm	9 cm	26 cm

Table 3 Body sizes for shoulder pad grade

The actual shoulder pad dimensions were then determined by subtracting 2 cm from the shoulder length and pad curve length to allow for wearing ease, and 2 cm from the height to allow the shoulder line of the pad to slope down from the horizontal. A test of these sizes led to further reductions in height to create a more visually acceptable silhouette. The largest pad was reduced in height by an additional centimeter to further reduce the bulk of this pad. The resulting grade for the shoulder pads is shown in Table 4.

SIZE	LENGTH	HEIGHT	CURVE
1	11 cm	3 cm	20 cm
2	13 cm	4 cm	22 cm
3	15 cm	5 cm	24 cm

Table 4 Shoulder pad grade

4.4.7 Analysis of component materials and pad development

The padding present in an insert with integrated electronics must provide both the structure and support required to protect the electronics and conceal their shape. In developing a vibrotactile display integrated in a shoulder pad my research collaborators and I experimented with a number of different materials and techniques.

The first technique investigated built up padding and support for the integrated electronics out of layers of muslin soaked in latex rubber. A plastic form was created to the desired outer shape of the shoulder pad. Layers of muslin were added to the form and coated with latex. As the latex dried it firmed up portions of the muslin to permanently take the desired shape and size of the shoulder pad. Rails of latex coated muslin were then added to form channels for the electronics. The process of adding a new layer of muslin to a form, and the resulting latex muslin shell are shown in Figure 27. The AA NiCad battery that was intended to be the battery in this early shoulder pad design is shown in the figure for scale. The latex rails are visible to either side of the battery case holding it in place.

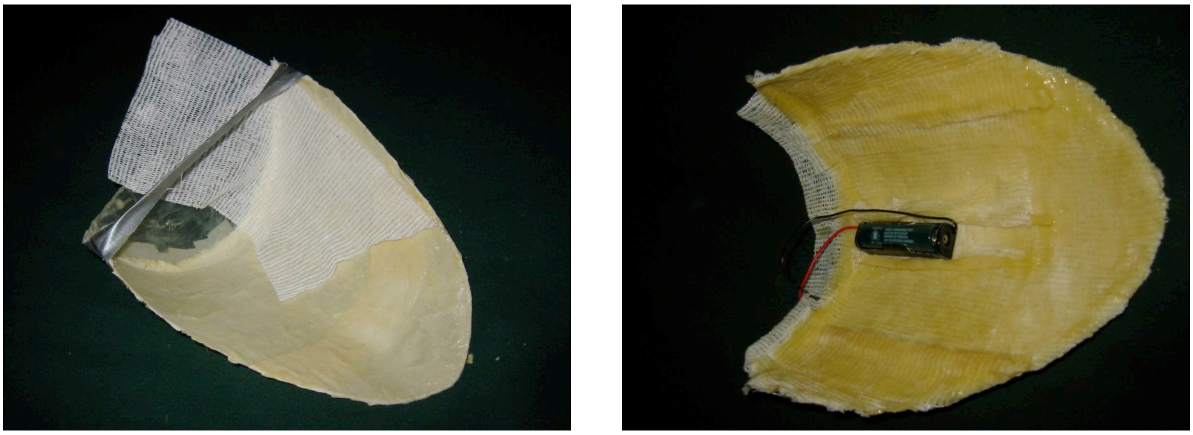

Figure 27 Latex Shoulder Pad

The use of latex and muslin was abandoned as the results proved too stiff and heavy. The iterative nature of the technique was also at odds with the long drying times required between adding layers of muslin.

Next the use of urethane foam as filler for a cloth shell containing the motors and electronics was investigated. Urethane foam is light, flexible, has a relatively short drying time, and had the advantage that it can be cast in place using a fabric shell. Two prototype pads were constructed to test the use of foam filled pads. One foam pad contained four actuators and the other seven. The prototype foam pads are shown in Figure 28. The foam used was Flex-foam from Smooth-on[16], which was chosen for its ability to be easily molded into a shape and for its similar physical properties to materials used in conventional shoulder pads.

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[16] Smooth-On, Inc. 2000 Saint John Street Easton, Pennsylvania 18042 Phone: 800 672 0744:

The use of foam filled shoulder pads was initially rejected for use in constructing the multi-actuator vibrotactile display prototypes. After constructing the initial foam shoulder pads, my research collaborator Miss Dunne statically tested the individual motors. Under static testing, it appeared that the foam mechanically coupled the integrated motors to the entire pad spreading the vibration imparted by individual motors over a much larger area then intended. The use of foam in shoulder pad construction was rejected because any spreading of vibration would have impaired the user's ability to distinguish individual motors and localize where a vibration initiated.

Figure 28 Foam shoulder pad prototypes

Unfortunately, it appears that the use of foam as a filling material may have been rejected prematurely. The rejected foam prototypes were shipped to Australia to be used in testing the hardware and software being developed for driving the shoulder pads used in the study. During the testing of active motor firing patterns, the foam pads relayed the distinct vibration patterns and did not exhibit the expected problems. The use of foam merits further investigation as part of any future work developing garment integrated vibrotactile displays.

A second prototype was made by mounting the motors on a thin (0.318 mm) polyester jersey knit base and creating the shoulder pad shape using polyester fiberfill, an amorphous mass of polyester fibers used in many apparel and home furnishing applications. The fiberfill performed very well at absorbing vibration and therefore isolating the sensation of each individual motor. However, the fiberfill was too soft to add structure to a garment, the primary function of a shoulder pad: it created the necessary volume for a shoulder pad, but not the structure or shape.

To compromise between these properties, the next prototype was constructed out of multiple layers of polyester and cotton batting. The polyester batting has a thickness of 1.74 mm, and was composed of a loose construction of tangled internal fibers providing the constructed pad with both structure and vibration isolation. Two layers of this batting were placed directly on top of the motors, which were affixed to the jersey knit fabric shell of the pad. Two layers of cotton batting, denser padding of similar thickness (1.75 mm), composed of cotton fibers needle-punched through a thin inner layer, were pad-stitched together and placed on top of the pad to create the curved shoulder shape and provide the additional structure. Pad stitching is a tailoring technique used to join layers of fabric together to create a shape but also maintain a flexible structure. The wires supplying power to each motor were coiled slightly within the pad, to help eliminate the transmission of vibration through the wires. This prototype proved most functional. It allowed the motors to vibrate independently, while providing the desired volume, shape, and structure for a shoulder pad.

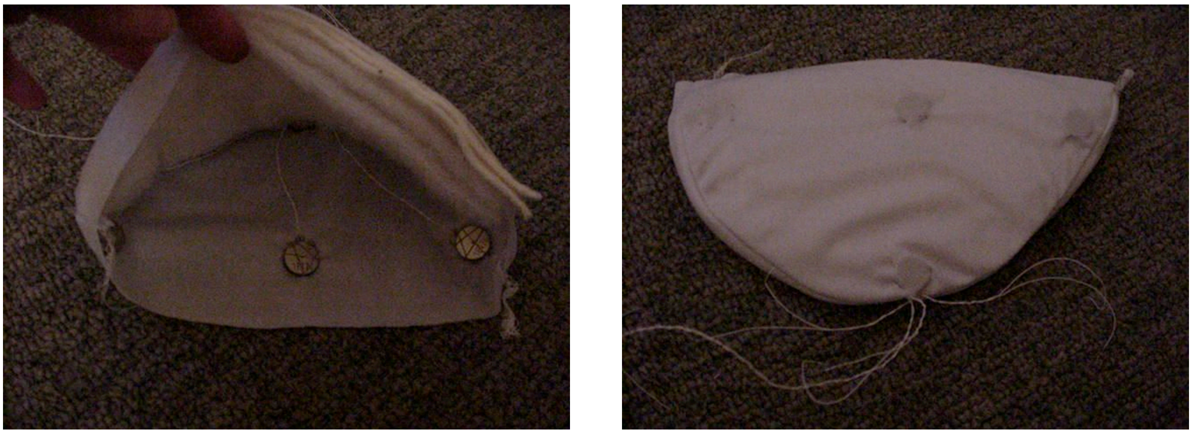

Figure 29 Final Prototype Layered Batting Construction

4.4.8 Study testing the shoulder mounted vibrotactile displays

The multi actuator shoulder pad prototypes developed for this thesis were formally tested with a user study. This section begins by presenting the development of the electronics, software, and testing apparatus used to conduct the study. This is followed by a presentation of the experimental result, qualitative subject responses, and hypothesized sources of error for the study.

4.4.8.1 Development of electronics

Upon review of the literature an initial estimate of the shoulder's two point threshold, or the minimum perceivable distance between two stimulation points, was made at 38 mm. Since a suitable measure of the two-point threshold was unavailable in the literature, this estimate was made based on two-point threshold data for the torso.

The number of motors per shoulder pad was determined by overall area presented for actuator integration by the by the smallest shoulder pad, and by using a packing topology where the motors were spread out over a maximum area and no motors were closer then the estimate of two point threshold. Using these factors seven motors per shoulder pad was determined to be the greatest feasible number of motors. After the construction of several prototypes, it was decided to use actuators in a "t-shape" pattern, as this pattern best distributed the weight of the clothing into the actuators improving their clarity. For linear arrangements flexibility issues with the chosen actuator further limited the number of usable actuators. Only three motors were useable in line from the smallest users user's neck to shoulder tip, and four motors in a line running front to back across the inside edge of the shoulder pad. Under these constrains it was decided to use only six actuators per pad.

To provide flexibility as to the number and location of motors in a shoulder pad all shoulder pads used a DIN-9 connector with a standardized motor to pin number mapping. This allowed for up to eight motors to be integrated to various test locations and patterns within a shoulder pad, while maintaining software control over the firing of a given motor. The developed system supported up to 8 motors each for two shoulder pads. Support for 8 motors was provided to allow for future testing of shoulder pads with a greater number of actuators.

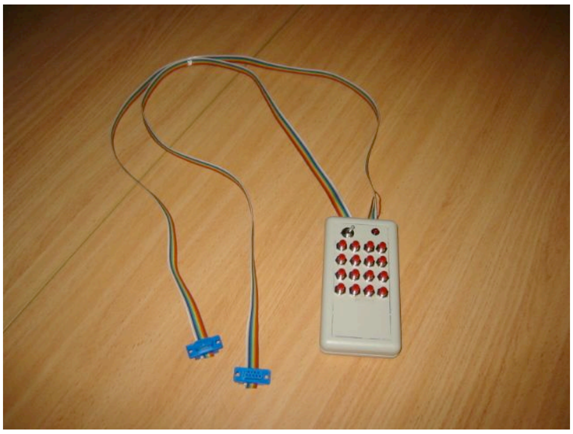

Figure 30 “Button-Box”

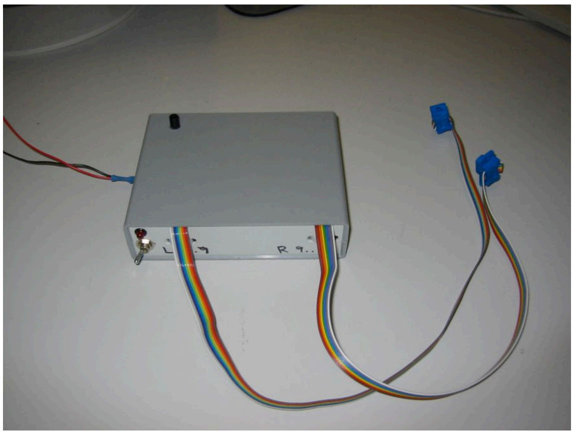

Figure 31 Controller Box

A simple battery powered “button box” was used to initially test the shoulder pads. The button box contained a battery and 16 buttons wired to the connector used by the prototype shoulder pads. The button box could be used to manually drive up to a maximum eight motors per shoulder pad. This enabled quick testing of the pads to verify all motors were firing, testing patterns of multiple motors firing, and compare the sensations of actuators firing at different positions.

A computer controlled “controller-box” was developed to enable more rigorous and formal testing or vibrotactile pattern recognition and discrimination. The controller box was built around a Texas Instrument’s[17] MSP430 microcontroller connected to a PC via a serial connection. An array of Darlington amplifiers with kickback diodes enables the microcontroller to drive up to 16 motors. The schematics of the controller box are provided in Appendix B.

A custom Microsoft Windows application written by the author used the serial connection to the microcontroller to control the duration and pattern of motor firing. A screen shot of the application is provided in Figure 32.

The software allowed the tester to create a firing pattern specifying up to seven different states for motor firings. In each firing state the tester selects which individual motors are fired, how long all the selected motors fire, and the duration to wait between states. The resolution provided for the motor firing and wait states is in units of 25 milliseconds and provides the tester a range of 0-254 units, specifying a maximum of up to 6.35 seconds. This provides the user the ability to create both fine grained and coarse testing patterns ranging in duration from 50 milliseconds to 89 seconds. Once a pattern is constructed and “fired” it is sent to the microcontroller for execution.

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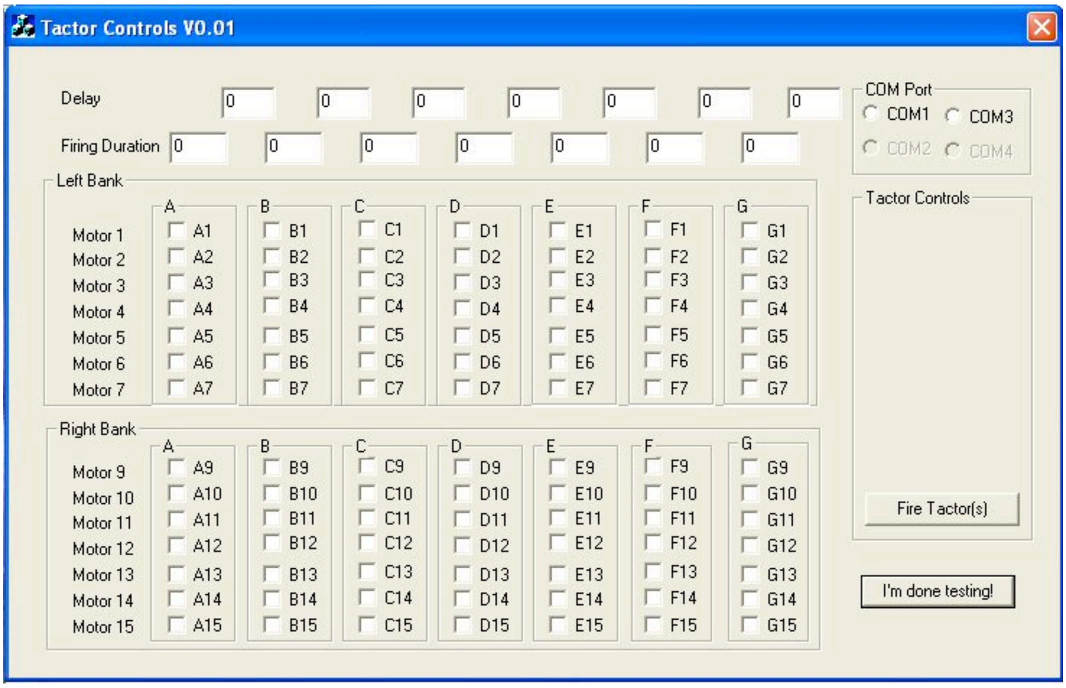
[17] Texas Instruments, P.O. Box 660199 Dallas, TX 75266-0199, Phone: 972-995-2011, www.ti.com



Delay 0 0 0 0 0 0 0

Firing Duration 0 0 0 0 0 0 0

Figure 32 Screen shot of shoulder pad testing application

4.4.8.2 Testing apparatus

Both the jacket and shoulder pad sizes were fitted to the subjects for testing. The three sizes of small, medium, and large shoulder pads discussed earlier were inserted in to one of five different sizes of jacket for testing. Both the jacket size and shoulder size were chosen for each subject based on their neck-to-shoulder measurement. For consistency, all subjects wore a standard 1-ply jersey knit cotton t-shirt with a thickness of 0.56 mm underneath the jacket.

The jackets used in the study were designed to contain conventional shoulder pads. During the study, the first task subjects were asked to do was don the jacket containing conventional shoulder pads. Later, this enabled the subjects to better judge how perceptible the vibrotactile display was when not in use, contrasting augmented and conventional shoulder pads.

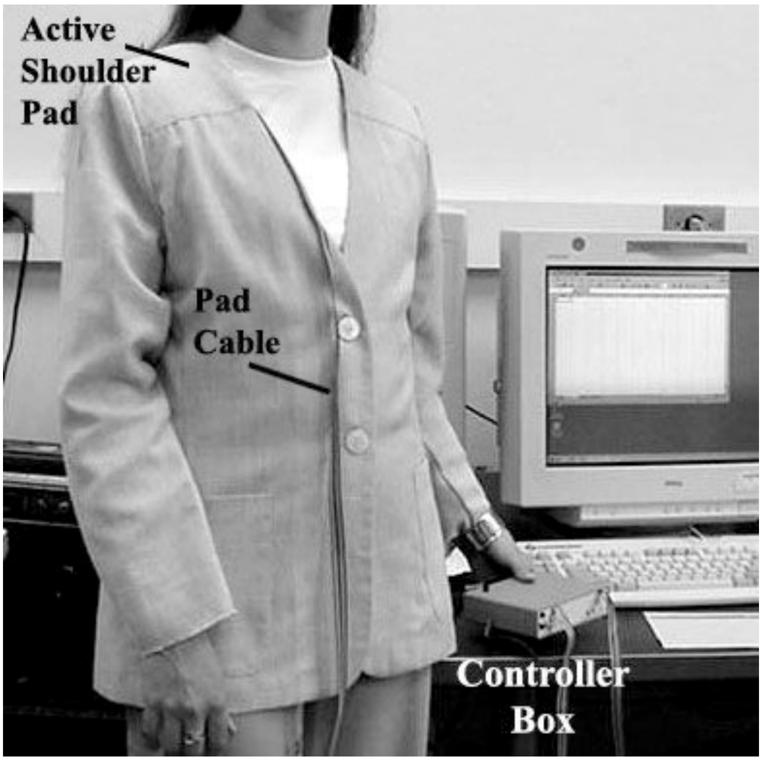


Figure 33 Testing Setup

The tested shoulder pads were constructed in two configurations, one with 4 motors and the other with 6. In both configurations, motors were arranged in a “t-shape” with the motors aligned running over the outer part of the shoulder along the shoulder ridge. The two configurations are picture in Figure 34. Testing with both a 4 and 6 motor configuration, both in the same “t-shape” layout, enabled testing of our estimate of optimal inter actuator distance.

Figure 34 Motor Locations for 6 and 4 motor configurations

After being inserted into the jacket, the pads were anchored in place using hook-and-loop (Velcro®) fasteners. Connecting wires protruded from the neckline edge of the shoulder pads, exiting the garment and falling down the front of the jacket to connect to the driving interface. This configuration is shown in Figure 33. Motor positions were numbered to ease referring to a specific motor. Right and left shoulder pads have mirrored numbering. In both the 4 and the 6 motor configurations motor number 1 is the “front-most” motor. Motor numbering then increases as the motors progress back over the shoulder. Figure 35 shows the motor numbering for both a 4 and 6 motor shoulder pads.

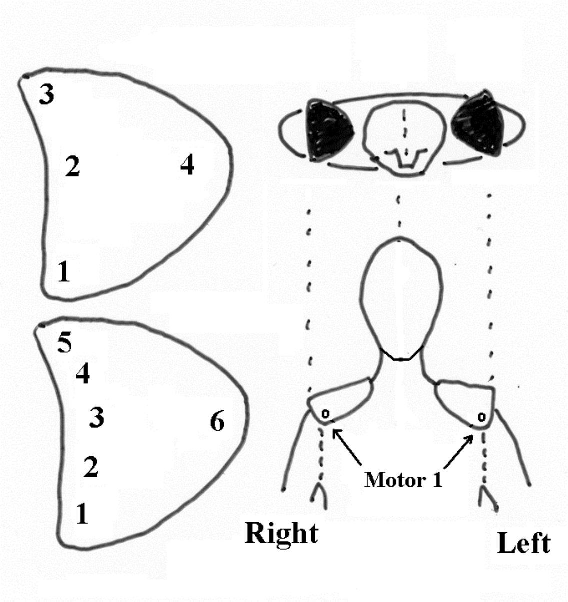


Figure 35 Motor Locations for four 4 and 6 motor configurations pictured against the Shoulder.

4.4.8.3 Subjects

Twelve subjects were run for the study. In order to eliminate sensory differences arising from gender all of the subjects tested were female. Subjects ranged from 19 to 34 years old and possessed a variety of body types within the 5th to 95th percentile of the general population in all relevant dimensions. The shoulder lengths used in sizing the subjects ranged from 9 cm to 14.5 cm.

4.4.8.4 Experimental design

In order to determine if prior knowledge of motor locations would influence vibrotactile pattern detection or discrimination subjects were separated randomly into informed and uninformed groups. These groups were then further subdivided randomly into a group testing the 6 motor configuration shoulder pad and a group testing the 4 motor configuration shoulder pad.

As mentioned earlier all subjects were asked to do was don an appropriately sized jacket containing conventional shoulder pads. Subjects then rated the comfort of the jacket in their relaxed standing position on a 5-point descriptive scale ranging from very uncomfortable to very comfortable. The jacket was then removed and the shoulder pads replaced with two electronic shoulder pads appropriately sized for the subject. The subject then rated the new configuration on the same 5-point comfort scale.

Uninformed subjects were not shown the motor configuration, but were only told that the electronic shoulder pads contained several vibrating motors, and that they would be asked to draw the area of their shoulder where they felt vibration.

Informed subjects were then shown the configuration of the motors within the electronic shoulder pad by showing them a shoulder pad with numbers showing the placement of each motor. They were told that motors would be activated in various combinations, and that they would be asked to draw the area on their shoulder where they felt vibration.

All subjects were tested by stimulating only the shoulder of their dominant hand. The vibrational stimulus was first presented by activation of all motors at once to orient them to the feeling of the motors generally. Once oriented, the testing consisted of a series of trials in which motors were activated first individually, and then with two, three, and fours motors fired simultaneously. Subjects testing the 6 motor configuration were further tested with patterns of five and six motors being simultaneously fired. All subjects for a given motor configuration were tested with the same a pre-determined set of patterns, but the order of the patters was randomized for each subject to help confound effects of testing order.

Each stimulus was activated for a period of 2.5 seconds. Subsequent patterns were activated after the subject finished drawing their response to the stimulus. Subjects recorded their responses to each trial on an illustration a gender-neutral body outline like that shown in Figure 36. They were told to indicate what they felt in a manner that they felt would best communicate their perceived sensation, by drawing points, shaded areas, arrows or x-marks, or any other depiction they felt was more suited to their experience.

Following pattern trials, the subject was asked a series of qualitative questions to determine their general reaction to the tactile stimulus. They described the quality of the vibrational stimulus, the comfort level of the stimulus, and the amount of mental effort required to localize the origin of stimulus. The uninformed group was then debriefed and shown the actual location of actuators within the pads.

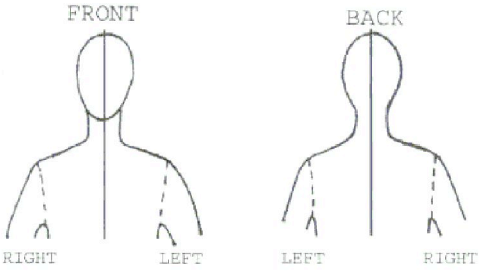


Figure 36 Subject scoring target

4.4.8.5 Results

The study generated both qualitative and quantitative results. Study subjects were asked to map perceived vibration onto the body outline shown in Figure 36. The reported patterns of perceived vibration in combination with the motors that were actually fired formed the quantitative study results. Qualitative data was also gathered from the subjects in the form of open response questions asked as part of the study.

4.4.8.5.1 Quantitative results

In order to minimize any interpretational bias inflicted on the analysis of the data by my research collaborators or myself, a blind and independent scorer mapped the user responses to motor positions. The scorer was provided a key of points across the shoulder that corresponded with motor location within the 4 and 6 motor configurations. For each subject the scorer was only informed as to which configuration (4 or 6 motors) was being tested and whether there were one or multiple motors active during each trial. Based on the subject responses, the scorer then recorded which motors appeared to be active. These results were then compared to the actual active motors for each trial. The compiled quantitative results are presented in the rest of this section.

PERCEPTION

The responses mapping sensation onto the torso outline exhibited variation. Even provided with prior knowledge concerning the size and position of the shoulder pad the subjects reported a much wider range of perceived stimulation area then would be expected. Figure 37 shows the compilation of all user responses ranges unevenly down and to the side of the torso into the armpit. Although the perceived location of active motors varied from subject to subject, most responses followed consistent patterns through a participants testing period.

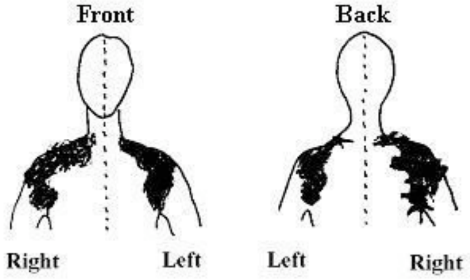


Figure 37 Composite user responses

DETECTION

Overall for trials where at least one motor was active user's reported the inability to detect any vibration 15% of the time. For the four motor configuration, this translates to a missed detection of the signal in 44% of 26 single motor firings, 13% of 47 double motor firings, and 0% of the three and four motor firings. For the six motor configuration, this translates to 27% of the 26 single motor firings, 15% of the 13 dual motor firings, 8% of the 25 triple motor firings and 0% of the four, five, and six motor firings.

Results identifying motors that subjects were consistently unable to detect were compiled and are shown in Figure 38. This compilation indicates the number of misses for tests firing of one and two motors. Tests firing three or more motors have 100% detection for the forty randomized 4 motor configuration tests and 95% detection rate for 72 randomized tests of the 6 motor configuration.

All subjects experienced at least one motor that they consistently had difficulty feeling but the problematic motor varied across the subjects. All subjects could detect motor 2 in the four motor configuration (located at the outer shoulder tip) and motors 2 and 4 in the six motor configuration (located on the upper front and back of the outer shoulder edge).

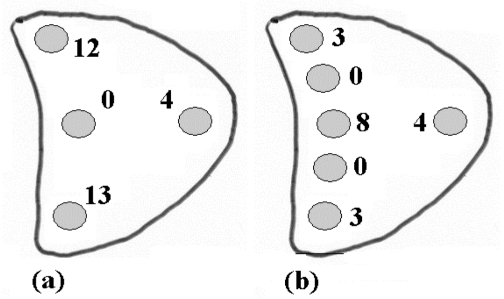


Figure 38 Miss frequency for each motor location in both the 4 and 6 motor configurations

In many cases, the motors that could not be perceived individually were also not felt at all in the multiple-motor trials—these trials were perceived as if the missed motor(s) were not active. However, in some cases the missed motor contributed to the multiple-motor patterns, by extending the perceived area of stimulus in the direction of the missed motor.

The responses of the informed and uninformed groups were similar in both number and identity of motors that were not perceived. However, the informed group drew more focused areas of stimulus in their response diagrams.

4.4.8.5.2 Qualitative responses

An external scorer read the subject's open response comments and sorted them into categories reflecting the perceived quality of vibrational sensation, degree of comfort, concentration required, and ability to distinguish between sensation locations. As part of this process the identified components of social weight are scored for a device, rated as one of five unit-less equally weighted values on one of two scales. The scales used were – (none, small, medium, large, and very large), and (very low, low, medium, large, and very large).

The scorer was provided with the questions and given the chance to ask the researchers questions prior to scoring but at no time during scoring were the researchers involved in deriving a score from a response. A large variation was observed in all of the reported subject observations concerned with the quality of the sensations they experienced.

Subjects responded with comments ranging from saying they found the display comforting or soothing to annoying or ticklish, and one subject reported that some trials were painful. Grouping the subject comments on perceived degree of comfort with the vibration the external scorer rated five of the responses as showing a medium degree of comfort, seven as high, and one as very-low. The subjects' reports of the quality of the vibration are similarly distributed with five medium responses and eight high responses.

A trend was observed in cognitive load that merits further testing. Based on their verbal responses to the questions and on observation of their response time during the trials, subjects who tested the four-motor configuration in both the informed and uninformed groups appeared to indicate a lower cognitive load than subjects testing the six-motor configuration.

The user's perception of their ability to distinguish between sensation locations was generally low or very low. This subject perception is in agreement with the gathered data. For the single and dual firing tests there were only 32% and 34% perfect matches for the four and six motor configurations respectively.

All subjects tried the testing garment with conventional shoulder pads. In general, no difference in comfort between the garment with normal shoulder pads and the garment with electronic shoulder pads was reported. Three subjects reported an increased comfort level with the presence of the electronic shoulder pads.

4.4.8.5.3 Sources of error

Shoulder pad integrated vibrotactile displays implement an uncommonly used technology, within the new context of garment integration. Further research is needed to determine to what extent artifacts of the display such as display type, display construction, or the relative novelty of these factors causes sources of error. Four sources of error were hypothesized. They were an error determining the two-point threshold of the shoulder, problems defining the shoulder area, scoring the perceived stimulus, and mechanical coupling.

ESTIMATE OF THE TWO-POINT THRESHOLD

As the literature did not contain a suitable measure for the two-point threshold in the area of the shoulder of interest, the two-point threshold value for the torso was used as an estimate of the two-point threshold of the shoulder. The torso was chosen as an area my coauthors and I believed would have similar sensitivity based on our review of the literature. This is admittedly a major potential source of error. If the two-point threshold for the shoulder is under estimated it will result in the actuators being perceived at locations other then where they were physically located. This misperception undoubtedly results in errors observed in the reported data. A formal study of the two-point threshold is needed as part of any future research refining shoulder mounted vibrotactile displays.

DEFINING THE SHOULDER

As Figure 37 shows, there was a very wide range of area that the subjects felt constituted the shoulder. A variation in subject mapping of physical perception onto the body outline shown in Figure 36 would be reflected in a range of reported responses beyond the stimulated areas, and was one hypothesized source of error.

SCORING

Once the subjects had been familiarized with the operation of the shoulder pads, and recorded some initial perceptions, their recorded responses generally increased in precision without any apparent corresponding increase in accuracy. The increase in subject precision was reflected in both an increased number of marking locations and specificity of location. A corresponding increase in accuracy would have resulted in fewer missed or mischaracterized responses during testing. No such trend was found. The smaller sized markings meant a greater number of locations were chosen confounding evaluation of the data.

MECHANICAL COUPLING

Misperceived motors on the pad edges often seemed to have an effect on the perception of multiple-motor patterns. One possibility is that the vibration of the motor is transmitted to some extent through the batting layers within the pad, and thus the mechanical coupling of the batting is felt by the subject at an intermediate point between motors where the body is in closer contact with the pad. The result is an expanded area of perceived stimulus.

4.4.9 Discussion and observations

The most-missed motors were those on the lowest and medial edges of the pads, those at the front and back axilla, and at the intersection of the neck and shoulder. These locations correspond to motors positions 1, 5, and 6 shown in Figure 35. The cause of this pattern of error was hypothesized to be attributable to four factors. First, the fit of the jacket across the shoulder influencing the amount of overall pressure applied to a pad and the amount of its skin contact. Second, changes in the posture of the subject wearing the jacket resulting in variation of the pressure in an area of the shoulder. Third, the weight of the cables attached to the pad pulling the pad away from the body at the base of the neck. Fourth, and finally, the fit of the shoulder pad affecting the location of the axilla motors on the body.

The shoulder itself has a complex curved shape with much variation in the population. The ball of the humerus creates a convex curve in the front and back of the shoulder, the outer-most edge of the shoulder curve. Underneath the ball joint, there is a concave hollow in the front of the body and a shallower convex curve in the back of the body. When the lower motors on the pad fall beneath the ball of the humerus, they are more likely to not be perceived, particularly in the front where the body curves away from the contour of the shoulder pad. The jacket construction does not provide a lateral force in to push the motor against the body. Chapter 7 provides a detailed description of the kinematics of the arm, the anatomy of the shoulder complex, depicted in Figure 59, and the bones of the arm illustrated in Figure 61.

Motor number 3 in the 6-motor configuration, which was not consistently perceived by subjects, corresponds in location to motor number 2 in the 4-motor configuration, which was always perceived by subjects. The six motor shoulder pad configuration is stiffer than the 4 motor shoulder pad configuration because of the proximity of the motors. My research collaborators and I speculate that this increased stiffness may be responsible for the difficulty many subjects experienced in perceiving motor 3 in the six motor configuration, in contrast to motor 2 in the four motor configuration.

4.4.10 Proposed design guidelines

In order to help facilitate further development in the area of shoulder-mounted tactile displays and garment-insert integrated electronics, the following five design guidelines are proposed:

The perceptibility of garment integrated vibrotactile interfaces is sensitive to both the fit and form of the garment in which the display is integrated. Garments containing an integrated vibrotactile display should be properly fitted to their users, so that the display makes firm and uniform contact with the user’s skin throughout the expected range of user motion.

Garment integrated vibro-tactile actuators should be constructed such that an even and adequate force is applied by the actuators, when worn under another garment. Where environmental or design factors precludes providing the requisite even and adequate force mechanically, the electronics of the garment integrated display should be constructed to detect the contact force, and normalize the force for each actuator in the display. While normalization can create the perception of a uniform maximum vibrotactile “volume” for the display, it does so by reducing the maximum volume of the display to the minimum contact force exerted on a display element.

It is critical that garment embedded vibro-tactile actuators remain free to vibrate along the axis normal to the curvature of the body. Garment construction that places excessive hang weight upon the actuator, or encases the actuator within a solid area, will dampen or mute their vibrational capabilities.

Care must be taken that mechanical coupling of motors within display enclosure materials does not blur the boundaries of specific vibration regions.

Shoulder-mounted garment integrated displays and their applications should strongly limit the number of discrete stimulating regions the user is expected to distinguish. Based on the study performed for this thesis, users seem able to accurately distinguish at least four discrete stimulation regions on one shoulder. However, the number of discernable regions is directly affected by the proximity of the motors to the skin and the magnitude of motor vibration. The relative importance of these contributing factors seems to increase proportionally to the number of discernable stimulation regions.

4.5 Social weight

This section uses the material on social weight presented in Chapter 3 to evaluate the social weight of the prototype user interfaces developed by the work of this chapter.

4.5.1 Auditory interfaces

While the e-SUIT used audio alerts generated by the iPAQ, audio interfaces were generally not part of the research contribution of this thesis. Auditory interfaces were not used in studying social weight since many of the factors forming social weight are in flux for mobile auditory devices. The recent and widespread adoption of Bluetooth headsets on mobile phones is driving the development of physically smaller and less visually conspicuous headsets that have a correspondingly lower physical presence. The same trend is rapidly eliminating the novelty of earpieces and headsets and changing what constitutes acceptable public behavior (Ling 1997) in terms of talking in public with no visible social partners. As a result, the associated technology apprehension is decreasing and the relevant social conventions are changing.

4.5.2 Visible display locations

The features of a user’s body that are naturally visible to themselves when they are either seated or standing are their forearms, wrists, and hands. The areas of their body visible to a seated user are illustrated in Figure 39. The pictured user is wearing the e-SUIT prototype, whose watch and cuff LED displays were covertly contained within the illustrated visible area.

Figure 39 View of user's body while sitting at a table

Locating visual displays on the naturally visible areas of the user’s body minimizes their social weight by minimizing the movement required for the user to view the display.

4.5.3 Peripheral and focal awareness of information

The four displays in the e-SUIT, the vibrotactile display in the shoulder, the cuff integrated LEDs, the watch, and the PDA’s screen, provide both tactile and visual displays requiring a broad range in the level of peripheral and focal awareness required from the user (Filho; Steinfield, Jang et al. 1999).

Peripheral awareness conveys information without requiring the user to take his attention away from other people in a group setting. Typically, applications use peripheral awareness information to draw user attention to potentially more immediate information demands, with peripheral awareness information signaling the presence of a richer stream of focal awareness information. Flashing LEDs, vibrating motors in pagers and cellular phones, and simple notification chimes or alarms are all commonly encountered examples of displays using peripheral awareness information. By contrast, applications that use focal awareness of information require the user to at least periodically give their full and undivided attention to the interface. High bandwidth displays such as reading an appointment from a PDA or notebook computer are examples of applications that utilize focal awareness information.

When a device or application progresses from peripheral to focal awareness there is an increase in social weight. A move from peripheral to focal awareness has a corresponding increase in the cognitive load required from the user that contributes to increased social weight. From the perspective of others, increased focal awareness also results in the user being less socially accessible, giving the device a greater physical presence. Moving from focal to peripheral awareness has a corresponding decrease in social weight. Peripheral awareness of requires less user attention resulting in a generally lower cognitive load and resulting social weight.

4.5.4 Social weight of the e-SUIT's interfaces

Section 3.2 of Chapter 3 presented techniques for quantitatively evaluating the social weight of a device. Being able to quantitatively evaluate social weight required being able to quantify its components. As part of this process the identified components of social weight are scored for a device, rated as one of five equally weighted unit-less values. The values are none, small, medium, large, and very large.

Table 5 and Table 6 rank the derived values for the user inputs and displays of the e-SUIT. As cellular phones and laptop computers are widely used by mobile business professionals, the social weight for these devices is also presented in these tables. The ranked components used to approximate social weight for the devices are the human processor time, loss of eye contact, and physical presence. Together human processor time and loss of eye contact provide a measure of the cognitive load induced by the interface, resulting in values for the cognitive load and physical presence for the gauged interface.

The remaining two factors of social weight, technology apprehension and social convention, are both highly subjective. To generate generic measures of device social weight these subjective factors were not directly considered. Instead, the techniques presented in Chapter 3 were used to minimize volatility and magnitude of the subjective terms forming social weight. The impact of social convention was minimized by evaluating all prototypes within a homogenous conservative cultural foundation. Technology apprehension was minimized by designing the technology prototypes to be minimally visible, and where visibility was unavoidable by making the technology possess a usage similar to an established technology.

	Model Human Processor	Loss Of Eye Contact	Physical Presence
e-SUIT Keypad	Small/medium	None	Non-visible
Wrist PC	Medium	Medium	Small
Cell phone	Very large	Very large	Small
PDA	Large	Large	Medium
Laptop	Very large	Very large	Very large

Table 5 Social weight factors for the devices used as inputs

4.5.4.1 Input devices

The social weight factors for the e-SUIT's input devices are qualified in Table 5. The evaluated devices are ordered in the table according to their derived levels of social weight, ranging from the keypad possessing the smallest levels of social weight to the laptop pc possessing the highest. The contents of the table illustrates how user interface components that are closer to the PAI side of the awareness continuum will have lower social weight corresponding to the lower human processor time and loss of eye contact their use requires.

4.5.4.2 Display devices

For displays the model human processor time equates to the time required to decode the display information, the loss of eye contact refers to the amount of eye contact lost because the user is reading the display, and the physical presence of the display is shown considered from the perspective of others. A relative comparison of each of these metrics is provided for an array of mobile devices in Table 6.

	Model Human Processor	Loss Of Eye Contact	Physical Presence
Pager motor	Small/medium	None	None
Sound	Small	None	Very large
LEDs	Small	Small	Non-visible
Wrist PC	Medium	Medium	Small
Cell phone	Very large	Very large	Small
PDA	Large	Large	Medium
Laptop	Very large	Very large	Very large

Table 6 Social weight factors for the devices used as displays

4.6 Conclusion and Contributions

Using the e-SUIT, this chapter has demonstrated the techniques for a mobile user to control social weight theorized in Chapter 3. Developed as a platform to explore use of a collection of garment integrated user interfaces, the e-SUIT demonstrated the strategies of both device and interface escalation for controlling social weight.

To present the development process for garment integrated user interface elements both the development of the keypad used in the e-SUIT and a multi actuator vibrotactile display were presented. The multi actuator vibrotactile display constituted a major research contribution for this thesis. Following up on the observed promise of the single actuator vibrotactile display integrated into the e-SUIT, the chapter presented the formal development and testing of a multi actuator vibrotactile display. The resulting research contributions included suitable shoulder pad sizes, pad construction, number and location of integrated actuators, and identified trends and concerns warranting further research.

The chapter concluded with an evaluation of the social weight of the e-SUIT's various elements. This evaluation contextualizes material presented in Chapter 3, classifying the relative social weights for both the e-SUIT's inputs and displays separately.

5

"Square peg, round hole; am I missing something or does this hammer solve the problem?"
Lost and confused Ph.D. Student (1974 -...)

Chapter 5 Integration of Technology into Garments

Commercial garment integration of technology presents the problems of integration into mass-produced garments that have a low retail cost, are simple in structure, and are worn frequently. These garments present the challenges of: automating technology integration as part of garment construction, integrating the desired functionality with a low total cost for the integrated components, and maintaining the structure and durability of the garment after integration.

This chapter provides an overview of the design concerns of garment interaction and provides an overview of both prototyping and integration techniques for the integration of technology into clothing. Work in the literature, and prototypes constructed for this thesis's research, are presented to contextualize the techniques with examples. The review of integration problems and current techniques underscores that commercial garment integration requires a modular approach, separating the production of the garment from the production of its integrated electronics.

Of the reviewed techniques, this chapter advocates use of the modular "Smart Tagging" approach for commercially viable smart garment design and production. To demonstrate this architecture a collaborative project was conducted with Leah Buechley, a graduate student at the University of Colorado at Boulder. The collaboration created a general purpose "smart-tag" for managing power in smart garments, and then used the power module in the construction of a proof of concept smart garment. A number of techniques for smart garment construction developed during the construction of the e-SUIT are also presented in this chapter. The chapter concludes with a discussion of the emerging technologies for garment construction and their possible role in integrating technology into garments.

5.1 Garment Cost

A garment's retail price directly shapes it potential for housing technology. A higher target retail cost for a garment can support a relatively greater cost for their integrated electronics before the integration cost prohibitively increases the retail garment cost. A $20 garment can support a significantly smaller cost for the integrated components compared to a $200-300 garment. If you add $80 in cost to a $20 tee shirt, regardless of functionality you are still left with a $100 tee shirt. As garment integrated technology evolves, and becomes the mainstream, this disparity will likely lead to the more expensive garments integrating components of a higher quality and that provide greater functionality to their users. Technology integrated into many types of more expensive garments also have an advantage, in that the garments receive a final tailoring as part of being purchased. When the tailor or seamstress adjusts the garment's fit and hang for the wearer, they help obscure many of the negative artifacts that can arise due to the integration process.

All researchers working on the problem of garment integration of technology are currently faced with the problem of how to affordably integrate electronics into garments that are simple in structure, worn frequently, and affordable. Considering garment affordability complicates the research problem by implicitly requiring that any developed techniques be compatible with the garment industry's existing garment production infrastructure, as a required upgrade in infrastructure would be born out in increased end garment costs.

5.2 Considering Wearability

Garment integration has the potential to impact the fit, comfort, and wearability of the garment (Gemperle, Kasabach et al. 1998; Dunne, Toney et al. 2004). If integration's impact on any of these factors is sufficiently negative, it will outweigh the other perceived benefits of using the technology integrated into technology, resulting in the garment not being worn or purchased.

In "Designing for Wearability", Gemperle et al. (Gemperle, Kasabach et al. 1998) identified 13 guidelines intended to "communicate the considerations and principles necessary for the design of wearable products." This paper was seminal in its presentation of the design concerns of a wearable device context. Gemperle et al. identified 13 considerations for wearability; Placement, Form Language, Human Movement, Proxemics, Sizing, Attachment, Containment, Weight, Accessibility, Sensory Interaction, Thermal, Aesthetic, and Long term use.

Many of the design concerns identified in "Designing for Wearability" are shared with, and inspired by, the design of clothing. Specifically garment design shares the concerns for aesthetics, impact of human movement, proxemics or the human perception of space, sizing and fit, and weight. It is the author's firm belief that commercial success for garment integrated technology will require that the user only be aware of the technology through its use, and not its presence in the garment. It is critical that garment integrated technology does not in actuality or appearance, negatively influence the aesthetics of a garment, restrict the user's motion, change the garments fit for the worse, or make the garment heavier.

In collaboration with Lucy Dunne, Dr. Susan Ashdown, and Dr. Bruce Thomas, I identified seven concerns of particular significance to garment integrated design (Dunne, Toney et al. 2004); Impermeability, Mobility, Flexibility, Durability, Sizing and Fit, Peripheral Variables, and Thermal management. Three of these concerns, flexibility, thermal management, and permeability, are of particular importance and will be addressed in greater detail in the following subsections. An additional concern, the accessories used with the garment are also identified and presented in this section.

5.2.1 Flexibility

The flexibility of integrated modules dictates where on a garment they may be successfully integrated. As part of the garment, integrated modules need to conform to the contours of the body. When they fail to do so, increasing the local rigidity of the garment, the integrated devices impact the hang and fit of the garment, and run the risk of the user feeling the "hard bits" of the integrated device pressing into their body. For a garment design, having the components press into the users body is disastrous. Integrated modules should be small, soft and flexible. In general, integration should be avoided over flexing zones on the body, such as elbows, knees, or armpits where modules will experience the most aggressive flexion and torsion. Since a smart tagging approach to garment integration uses standardize modules, the modules can be rated with flexibility ratings allowing the designer to appropriately locate them in a garment with respect to the flexing zones of the body.

5.2.2 Thermal Management

The human body tightly regulates its temperature within a few degrees of 98.6°F, while operating through environmental extremes of 68°F to 138°F (Guyton 1977). The designers of smart garments, and modules for smart garment integration, need to consider the additional thermal loading that the integrated electronics place on the garments thermal management needs. Currently commercially available garments use passive methods for heat dissipation, making use of a combination of venting, wicking, and thermostating (e.g. the user zipping / unzipping garments or adding and removing layers) in order to dissipate body heat. Garment integrated electronics dissipate power in a small region near their user's body. Care needs to be taken to ensure that unless it is specifically being channelled as a way to heat the garment, that additional heat generated by the garment integrated device is radiated into the environment and not absorbed by the user.

5.2.3 Impermeability

Garments are structured to carry moisture away from the body, and to regulate temperature. When adding an additional source of heat inside the clothing and near the body, care needs to be taken to make sure that it does not disrupt temperature or moisture regulation expected of a comfortable garment. Out of necessity, garment integrated electronics need to be sealed to protect them from moisture - such as perspiration, rain, washing, or just spilt liquids.

Unfortunately making the integrated modules impermeable to moisture for protection also makes them tend to hold moisture and heat close to the body. Backing the modules on a breathable fabric will minimize the area of impermeability. Properly designed, the module's fabric backing will also conduct moisture and heat from the impermeable electronics module, spreading it over the larger surface area of the backing material for dissipation.

5.2.4 Accessories

Just as with conventional garments, the design of smart garment must consider the context in which the garment will be used, and its role within the wardrobe as a whole. For example, the e-SUIT demonstrated using a shoulder mounted vibrotactile display (Toney, Mulley et al. 2002; Toney, Dunne et al. 2003). It is likely that the wearer of a suit will at times need to carry a bag or briefcase, for example a laptop bag. If they carry the bag using a shoulder strap then the strap will press down into the actuator. Similarly, for integration into a line of outdoor clothes a module integrated above the small of the back will encounter similar problems when the user is wearing a hiking pack.

5.3 Circuits on Fabric

While a detailed presentation of the different techniques for constructing circuits on fabric is beyond the scope of this thesis, a basic knowledge of these techniques is required for discussion of garment integration. Post et al. as part of their paper "E-broidery: Design and fabrication of textile-based computing" (Post, Orth et al. 2000) provides a detailed overview techniques used for constructing circuits onto fabric. The work of Lehn, et al (Lehn, Neely et al. 2004) continued this work, developing techniques for mounting connectors to textile integrated circuits, enabling them to be connected with non textile integrated components.

5.3.1 Mounting and electrical connections

There are four main methods for electrically connecting fabric circuit elements; soldering, welding, conductive adhesives, sewing with conductive thread or wires. Post et al. (Post, Orth et al. 2000) also identified electrospinning and stapling as potential techniques for the assembly and connection of on fabric circuits but to the author's knowledge at the time of this writing, these techniques have not yet been used to implement non-trivial circuits on fabric. Electrospinning uses electrostatic forces to guide the spray of a fine thread of conductive polymer onto a textile. Electrospinning is a powerful technique that has successfully been demonstrated for use in producing textiles. Stapling pressure forms the pins of an electronics module to grip a portion of the circuit. Post et al described stapling where "a components lead grips a sewn conductive trace by being pressed into shape around it." Since I am unaware of any smart garments that have used either stapling or electrospinning in their construction, these techniques will not be discussed further.

Soldering uses low melting temperature metals to bind components of circuit elements together. In general soldering is a slow process requiring tight thermal controls and compatible materials. The metal offered by soldered components must be compatible with the low temperature metal used to build the framework. For example, a lead based solder will bonds much better with wires made of copper then those made from steel, and many of the lead free solders can not be used with steel. When soldering components integrated or attached to a textile, the heated areas must be tightly controlled to prevent damaging the fabric during the melting and re-solidifying of the framework metal. The tight controls and heating and cooling times add time and complexity to the soldering process. Mechanically soldered components are held in a soft metal frame, soldered connections are susceptible to mechanical stresses and torsion, both of which are common in the context of garment integration.

Welding of components through thermocompression bonding applies pressure to two compatible metals to bond them together. This technique can be used with a wider array of metal than soldering and does not require the heating and cooling times of soldering. Unfortunately, the pressures required for thermocompression bonding of some materials such as steel, would crack silicon dies. In order to directly bond microchip dies to a fabric bus composed of steel a two-stage bonding would be required. The first stage would bond wires from pads on an integrated circuit to an off die pad, and the second stage would bond the bus wires to those pads. Since an exposed integrated circuit is sensitive to electrostatic discharge, and the wires used in this "bond-out" strategy are delicate, a layer of nonconductive material needs to be applied post bonding to both the chip and the intermediate wires. Conventional chips use half of this process bonding the integrated circuit out to metal pins that protrude from protective plastic epoxy. Post et al. also demonstrated a hybrid approach utilizing both welding and sewing; steel wires to the pins of conventional microchip packages and then sewing those wires to fabric to form a circuit.

Conductive adhesives are glues and resins that conduct electricity. A selection of conductive adhesives is already commercially available. While conductive adhesives are already useful, both as a fastener and as the source of an electrical connection, future generations of conductive adhesives could act as an electrical and mechanical "impedance match", bridging flowing conductive textiles and rigid modules encapsulating electronics. In a similar manner Linz et al. demonstrated covering an embroidered pattern of conductive thread with a solid conductive gel in order to improve electrical contact between the thread and skin (Linz, Kallmayer et al. 2006).

5.3.2 Fabric Circuit Boards

In late 2004 conductive threads and fabrics started becoming readily available to the wearable computing research community. Since that time their availability, low cost, and compatibility with existing garment production techniques has caused embroidering and sewing to become the most popular method of assembling circuits on fabric. With the exception of metal wrapped organzas, that literally wrap their component threads in metal foil, commercially available conductive threads and fabrics are conductive as a result of being treated with a chemical wash. As a result, the resistance of these materials increases as its coating is lost due to wear or washing.

By gluing or sewing the newly available conductive fabric to a nonconductive fabric backing researchers have recently been able to demonstrate the construction of fabric circuit boards, or FCBs. Like their fiberglass counterparts, printed circuit boards or PCBs, components are mounted to the conductive portions of the FCB in order to form circuits. The primary advantage of FCBs has been their flexibility, and the ability for researchers to construct them using only modest tools.

5.4 Prototyping Smart Garments

Smart garment development inherits all of the problems of conventional garment development and the development of mobile devices. By adopting and modifying prototyping techniques developed by couturiers and tailors over hundreds of years, a rich set of prototyping techniques become available for the production of smart garments. Due to their origin, these techniques are immediately applicable to many problems in the process of garment construction. Their modification expands their utility to help with the user interface and industrial design demands of smart clothing. This section presents three hybrid techniques for prototyping smart garments inspired by counterparts in conventional design - the use of a toile or muslin, pinning, and the construction of a reconfigurable testing garment.

5.4.1 Creation of a toile

A toile, often called “muslin” in the United States, is a mockup of a garment constructed of inexpensive cloth. Once a garment is designed, a pattern needs to be generated so that the garment can be manufactured. Toiles are “used to ‘prove’ a pattern. A toile version is made to ensure the pattern fits. Any alterations can be transferred back from the toile to the pattern before cutting out the real version” (Dicey and Dicey 2007). Once a pattern has been refined through the construction and testing of toils a patternmaker produces the card pattern for the garment from which the garment can be constructed.

The creation of smart garments can benefit from the construction of toiles. Most smart garments demonstrated for academic research purposes have retrofitted an existing garment, adding desired functionality; this was the path taken by both the e-SUIT and the smart-tag’s testing shirts constructed for this thesis. When constructing a garment from scratch researchers have demonstrated that just as the toile can be used to test the fit and hang of a garment pattern, it can also be used to roughly test the suitability of differing electronics integration positions and methods (Farringdon, Moore et al. 1999; Schwartz and Pentland 1999; Mazé and Margot 2003). In the construction of the Smart Vest (Schwartz and Pentland 1999) Schwartz et al. created a special wire mesh toil for use in prototyping the electrical components of a smart garment. After a prototype arrangement was constructed, the wire mesh backing could be attached to a conventional vest for user testing.

5.4.2 Pinning

Pinning, a common technique for adjusting the hang and fit of a garment during alteration, is a useful prototyping technique that can be used on both toiles and retrofitted garments. Pinning allows tested modules to quickly be relocated and interchanged. For example, researching where to place the keyboard module within the e-SUIT, a test keyboard module was pinned in various locations inside the suit before settling on the inside hem of the jacket below the user’s right hand.

Pinning can also be used as a way to test the impact of integrating electronics on the fit and hang of the garment. For example, to choose a location for the integrated bus master board used for the e-SUIT a wooden board was cut to the same size of the busmaster’s PCB and weighted. The mockup board was then test pinned in different potential locations within the suit to study the impact on fit, hang, and comfort. This allowed us to quickly find an optimal location for the bus master.

5.4.3 Reconfigurable Garments

When there are fundamental open questions about a garment design, it is often prudent to create a special reconfigurable garment. Using fastening technology such as snaps, straps, or hook and loop fasteners, reconfigurable garments can alter their shape, hang and fit. Similarly, by offering a number of ways, in addition to pinning, to temporarily attach devices such as sensors, interfaces can be tested at a number of different locations on the garment. Since reconfigurable garments are tested while being worn, they can be used to research garment context and usage through role-playing and user testing. The Sonic City prototype constructed by Mazé and Jacobs (Mazé and Margot 2003) is a reconfigurable garment. Strips and patches of Velcro® provided the means or attaching sensors and interfaces at varying locations. An internal structure of fixed wiring and placements within the jacket ensured that only the tested components, and not their supporting hardware, needed to be attached to the garment using Velcro®. This allowed for "each sensor to be systematically tested nearly anywhere on the upper body".

5.5 Strategies for Smart Garment Integration

Modularization allows for standardization and mass production of the electronics used to construct smart garments. There are many different strategies for how modular electronics can be integrated within a smart garment. These strategies fall into three distinct groups, carrying the integrated technology in pockets within the garment, temporarily attaching the technology to the garment, and permanently mounting the technology to or within the garment.

5.5.1 Pocketing Technology

Carried and pocketed technologies are not themselves garment integrated, these classes of devices impact device integration by providing offloading processing, storage, and sensing that would otherwise be integrated within the garment. Personal servers are emerging as the symbiotic interaction between carried, pocketed, and garment integrated devices. The symbiotic interaction increases the functionality for all of the devices, while enabling the creation of entirely new types of application and devices.

Consider the iPOD™ Sport kit, a partnership between NIKE[18] and Apple computer (Apple Computer 2007). The partnership provides "Rock 'n' Run" functionality to both devices, where sensors in the shoes wirelessly relay information to a runner's iPOD™ (a personal music player). The users iPOD™ essentially acts as a personal server, providing the storage and processing power required to overlay the music the runner is listening to with real time information about the duration, pace, and distance of the run. The system demonstrates using the information obtained from the shoes to derive rudimentary user context, allowing the user to select songs to be played at particular points in their run.

Carried and pocketed devices, being physically larger, can support a more powerful processor and higher capacity batteries than garment integrated devices. By carrying a single mobile device daily, a practice that is becoming increasingly common, the device can act as a personal server presenting smart garments with a single, persistent, source of resources. For the resource and commercial costs of integrating a means of communication with the personal server, garments are able to access and share much greater storage and computing resources the would otherwise be possible.

This type of persistence supports the interchangeability of garments and provides a rudimentary form of smart wardrobe management. Applications can check if a resource is present as opposed to checking to see if a particular garment containing the desired resource is

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[18] Nike USA, Inc. - P.O. Box 4027, Beaverton, OR – Phone: 97 076-4027 – URL: http://www.nike.com

present. Having all of the smart garments in a wardrobe store data in a common location makes the data both more accessible and provides a single point to archive.

The e-SUIT had pocketed components, using an iPAQ^{TM} PDA to provide its user with a high social weight user interface to access their schedule. The iPAQ^{TM} PDA acted as a rudimentary personal server, demonstrating a pocket based strategy for device integration. The iPAQ^{TM} PDA in the e-SUIT was housed in suit pocket. The e-SUIT demonstrated an application running on a personal server, the iPAQ^{TM} PDA, using both its own user interface and those integrated into the user's garments to interact with the user. Using an umbilical the PDA interacted with the microcontroller running the e-SUIT to control both the signaling of the user and the escalation. As an alternate example the University of Bristol's CyberJacket (Randell and Muller 2002), pictured in Figure 40, demonstrated a pocketed approach for some components, using a PDA to provide both sound and a display.

5.5.2 Attachable and reattachable technology

Temporarily attached integrated electronics to a garment enables them to be removed from the garment for washing, exchanged for repair, and interchanged to allow the user to upgrade or alter the embedded technology. This section explores three types of removable technology, inserts, padding, and patches and tags.

5.5.2.1 Removable inserts

Removable inserts are modules housed within special cavities within the garment. Inserts have been a popular way for researchers to prototype smart garments since the ability to remove the inserts provides and easy access to the electronics for upgrading, maintenance, or washing of the garment. Inserts need be little more than project boxes held in custom pockets within a garment. Considering wearability for a smart garment design means that inserts should be made smaller, softer, more flexible, and better shaped to fit the wearer's body.

Figure 40 University of Bristol's CyberJacket
Image Credit: Dr. C. Randell, Computer Science Department, University of Bristol

The CyberJacket (Randell and Muller 2002), pictured in Figure 40, provides an excellent example of using garment inserts to construct a smart garment. The CyberJacket was constructed and used at the University of Bristol between 2000 and 2005. The CyberJacket is based on the ADS[19] Bitsy ™, a 200 MHz StrongArm ™ single board computer. In addition to the Bitsy ™, the jacket housed multiple accelerometers, as well as a compass and GPS all talking over a common bus. The majority of the components were located in two hidden pockets on the inside hem of the jacket. These pockets are pictured in Figure 41.

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[19] Applied Data Systems – Phone: 301 490 4007 x 151 - URL: http://www.applieddata.net/

Figure 41 CyberJacket – Right and left internal pockets
Image Credit: Dr. C. Randell, Computer Science Department, University of Bristol

The development of the University of Bristol's CyberJackets illustrates the impact that advances in miniaturization have had on the development of smart garments. By the third version of the CyberJacket, developed in 2005, advances in commercially available technology were such that the electronics and batteries used in its construction were so small and light that they were later used to instrument hats. While removable inserts are a powerful technique for garment integration, the trend of massive reductions in size and weight for the module elements is eliminating the necessity for large hidden pockets with the garment, opening up new possibilities for integration into simple garments composed of a few light layers of fabric such as most daily wear shirts or dresses.

5.5.2.2 Padding

Padding is a common component in many garments. Inserts that provide padding are commonly found in garments ranging from suit jackets to sports wear and safety equipment. In conventional clothing, padding provides bulk and structure to a garment. Shoulder pads are a common element in suit jackets, where they are used for squaring the shoulders to increase masculinity. A technique used for both men's and women's suit jackets. Padding is typically integrated in such a way that it can be removed for washing of the garment. Removable padding provides another removable means of integrating technology within a garment.

The prototype vibrotactile displays, presented in Chapter 4, and pictured in Figure 28 and Figure 29, demonstrate using a padding insert to instrument a garment. The demonstrated pads are a single unit and have the same form factor as conventional women's shoulder pad inserts.

5.5.2.3 Removable Patches and Tags

Patches and tags are fabric-constructed objects that have integrated electronics. By temporarily attaching a smart patch or smart tag to a garment, the item can immediately benefit from the functionality and aesthetics of the attached smart objects. Researchers have demonstrated using clustering of smart tags or patches to construct both aggregate behavior and objects (Nanda, Cable et al. 2004; Buechley, Elumeze et al. 2005). This chapter addresses three methods for attaching patches and tags; as Snaps, Conductive hook-and-loop fasteners, and Insulation displacement connectors.

Construction Module

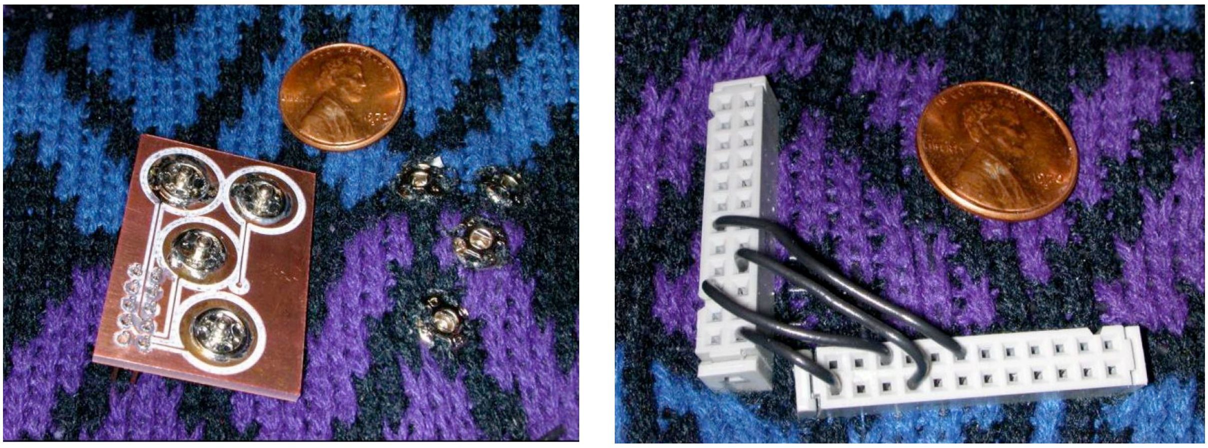
Multi-Module Quilt

Figure 42 Attachable / Reattach able Construction Modules
Image Credit: Leah Buechley, University of Colorado at Boulder's Craft Technology

5.5.2.3.1 Physical snaps

Metal snaps, as a common type of fastener, have been used for electrical connection by multiple researchers investigating garment integration (Gorlick 1999; Lehn, Neely et al. 2004; Buechley, Elumeze et al. 2006). All of these projects have used snaps to provide connection between two electrical circuits by connecting each circuit to one half of the snap. One of the most aggressive uses of snaps to date has been Buechley et al.'s fabric based electronics construction kit, the QuiltSnaps system (Buechley, Elumeze et al. 2005; Buechley 2006; Buechley, Elumeze et al. 2006).

The QuiltSnaps construction kits are designed to allow children to act as the "engineers, designers, and decorators" over artifacts, using their play to "learn about concepts relevant to programming, graph theory and dynamical systems" (Buechley, Elumeze et al. 2005). The QuiltSnap cells have three snaps on each side. The corner snaps connect power and ground between the cells, and the middle snap connection is either an input or an output pin. Output sides are with an arrow. Each tile contained "a microcontroller, an LED or buzzer and snaps on each of its sides". Touch and light sensor strips attached the cell's input sides. Once decorated children can either keep their tiles as personal displays, or connect them with other children's cells to form aggregate quilt of cells displaying idiosyncratic behavior. A sample decorated QuiltSnap construction module and a quilt constructed from four connected modules is pictured in Figure 42. Used individually the QuiltSnap construction modules demonstrate distributing power through metal snaps. Used in conjunction with other cells the QuiltSnap modules demonstrated using metal snaps for the distribution of both power and data through a multi module object.



Snap connectors Bayonet connector

Figure 43 e-Textile Group at Virginia Tech's eTAG Connectors
Image Credit: Image credit info needed

VirginiaTech's e-Textiles group has been researching weaving power and data buses into cloth. As part of this work, they also examined the use of snap connectors, and the redundant use of multiple connectors connected to the same substrate wire in order to improve the reliability of the connection between the bus and the attached circuit (Lehn, Neely et al. 2004). A PCB module that redundantly snaps to fabric-integrated connectors is shown in Figure 43.

5.5.2.3.2 Insulation Displacement Connectors

Insulation Displacement Connectors (or IDC connectors) work by displacing the insulation around a wire. The ribbon cable connectors pictured Figure 43 contains barbed v-shaped grooves at the base of their pins. Pushing the wire against the v-shaped base of the pins displaces the insulation around the wire, and the barbs hold the wire in place one a connection has been made. Virginia Tech's e-Textile group demonstrated using IDC connectors to a high density connection to a bus woven into fabric (Lehn, Neely et al. 2004). As can be seen from Figure 43, a commercially available 26 pin IDC connector requires approximately the same amount of physical space on the garment as four snaps. The primary drawbacks of IDC connectors are the connector height and the forces required by the connector. The height of IDC connectors is due to the v-shaped connectors used by the pins requiring the connector to be aligned normal to the fabric containing the bus, and the large force required for connecting and disconnecting the connector is an aggregate resulting from the small forces required for each pin compounded by the high pin density of the connector.

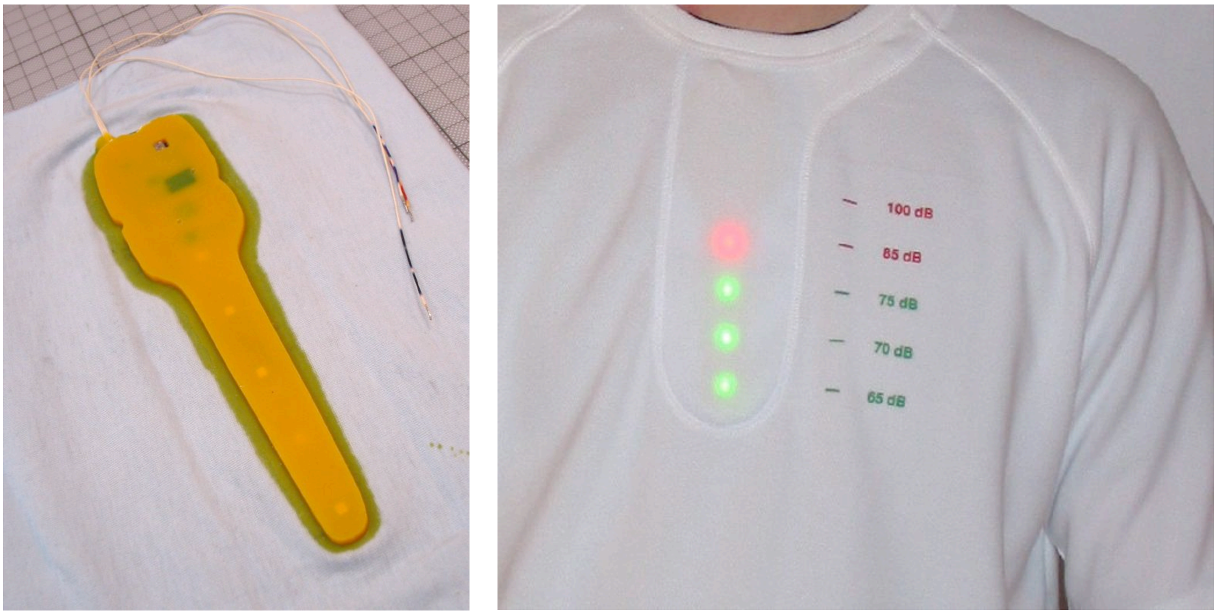
5.5.2.3.3 Conductive hook-and-loop fasteners

Hook and loop fasteners (the same technology used by Velcro$^{®}$) is another common fastening technology that has been adapted to provide electrical connection between two circuits. The bYOB system ("build your own bag") developed by Gauri Nanda et al. (Nanda, Cable et al. 2004; Nanda 2005) demonstrates the use of conductive hook and loop fasteners, as part of a system for construction of objects using LEGO™ inspired construction.

Nanda et al.'s system used simple modules connected by conductive hook-and-loop connectors to form complex aggregate objects. In their bYOB project Nanda et al. used small square modules to connect together and form a bag. Four pads of conductive hook-and-loop fasteners were located on each edge of the square construction modules. The pads allowed multiple modules to be connected together to form complex aggregate shapes, while sharing four common electrical connections provided by the pads. These electrical connections provided a common power and two wire digital bus to all of the modules.

5.5.3 Permanent Mounting Technology

Researchers have demonstrated two methods of permanent mounting, “cast on” integration where a resin is cast over circuit elements bonding them directly to a substrate fabric, and “sewn on” integration where the circuit components are sewn to the underlying substrate fabric. This section explores both of these methods of integration further. Researchers have also demonstrated several other methods of mounting components to fabric such as direct textile integration and using conductive adhesives. As the author is unaware of any garments demonstrating these techniques, they will not be discussed further.



Polymer-cast circuit board

Noise Shirt LED display

Figure 44 The Kankaanpää Unit at the Tampere University of Technology’s Noise Shirt
Image Credit: Pekka Iso-Ketola, Tampere University of Technology

5.5.3.1 Cast On Integration

Polymer casting of electronics can be used to mount the electronics to a fabric backing and provide protection from moisture, chemical exposure, and mechanical abrasion. These properties make the casting process suitable for the creation of machine washable smart garments. The Kankaanpää Unit at the Tampere University of Technology demonstrated this machine washability with their Noise Shirt (Iso-Ketola, Karinsalo et al. 2005), pictured in Figure 44, and Figure 48 of Chapter 6.

The Noise Shirt used two cast in place circuit boards. A board on the front of the shirt provided drove the red and green LEDs used to indicate the sound level display pictured in Figure 44. The second Noise Shirt board was cast with the batteries of the shirt demonstrating integrating batteries directly, and in a nonreplicable manner, within the garment. More recently several research groups have demonstrated casting integrated circuits onto fabric, in a technique similar to die bonding currently used in integrated circuit production (Kallmayer, Pisarek et al. 2003; Linz, Kallmayer et al. 2006).

5.5.3.2 Sewn Mounting

This section presents three types of permanent mounting techniques, each using conductive and conventional thread to mount electronics within a smart garment. These techniques are the use of Notions, Smart Tags and Smart Tagging, Embroidery.

5.5.3.2.1 Notions

While garments are primarily constructed of cloth a number of other attached objects, or notions, are common in garment construction. Notions are objects such as buttons, zippers, or ribbons attached to the garment. These objects have a potential for limited garment integration of technology. For example, Hitinnikainen et al. demonstrated integrating technology into buttons (Hitinnikainen, Mikkonen et al. 2005). Data and power attached by sewing the button onto the garment with conductive threads. Two different types of buttons were demonstrated, one using two conductive connections to attach the buttons to a one wire bus, and the other using four electrical connections to attach another set of buttons to an I^2C bus.

To add an enhanced notion such as a smart button to a garment, a manufacturer only needs to sew them onto prepared places on the smart garment, using conductive thread and at a prescribed position and orientation on the garment. In this way, the buttons of Hitinnikainen et al. provide an example of adding prefabricated electronic components to a garment, using techniques compatible with conventional garment production.

5.5.3.2.2 Embroidered

Lintz et al. have demonstrated using computer controlled embroidery to automate mounting flexible circuit boards to fabric (Linz, Kallmayer et al. 2005; Linz, Kallmayer et al. 2006). Using their technique the circuit board is mounted both electrically and mechanically by using conductive thread sewn through special landing pads on the circuit board and into the underlying fabric. Once sewn to the mounting fabric the circuit board and a small quantity of surrounding fabric is protected by a cast epoxy shell.

Since the embroidered tags are protected after integration and need to be sewn into place with very tight tolerances, the technique is not currently compatible with commercial garment construction techniques. The tolerances also prevent an embroidered approach from being practical for small shops prototyping smart garments with toils. It should be possible to use conductive thread to embroider traces and footprints onto fabric using conductive thread, and then sew the components directly onto the embroidered footprints.

5.5.3.2.3 Smart Tags

SmartTags refer to fabric-backed modules that are integrated into a garment. Electrical connections are formed between the SmartTag and other garment integrated devices through special patches of conductive fabric exposed along the edges of the tags backing material.

These pads are the equivalent of the pins that stick out from the epoxy body in current IC technology. A SmartTag constructed for this thesis is shown integrated into a garment in Figure 47. The SmartTag's electronics have not been cast in epoxy so they will be visible to the observers. Each of the exposed patches is an electrical pad, similar to the pin of an integrated circuit. Connections embroidered between the pads using conductive thread provide inter-pad electrical connections. This technique can be used to configure a SmartTag by jumpering its exposed pads together, or to connect the tag to other garment integrated devices. The technique is significant in that it only requires conventional sewing knowledge and equipment, and the ability to follow a pattern, to integrated the Tag.

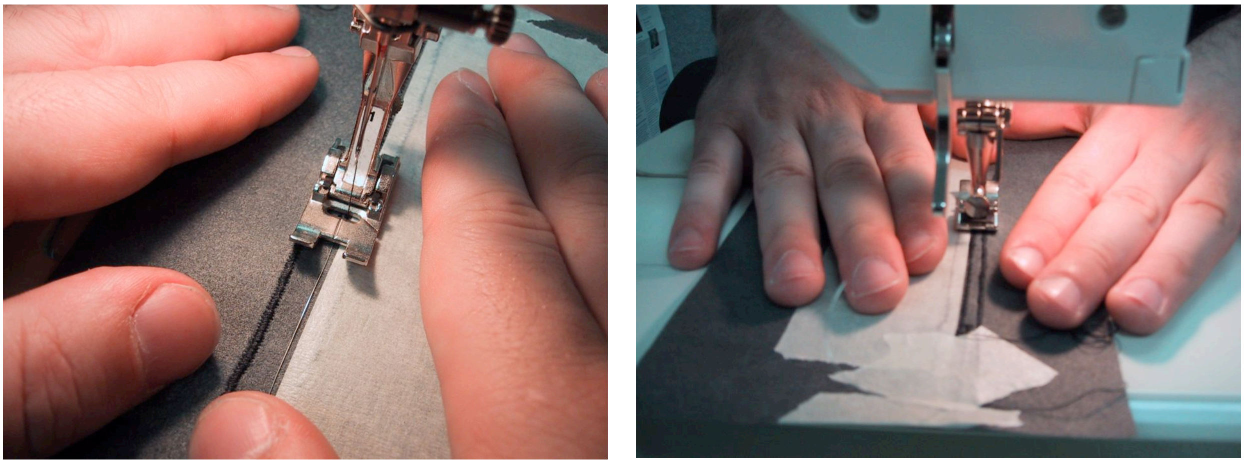
As the sophistication of FCB backings used in SmartTag construction increases, and the compatibility of Lintz et al.'s embroidery and conventional construction techniques increases, it is likely that the two techniques will become indistinguishable methods for producing elements used in a modular Smart Tagging architecture.

5.5.4 Distribution of power and data

The distribution of power and data amongst multiple garment integrated devices requires the use of a common bus. Since the initial e-SUIT construction, a great deal of progress has been made studying the means of conveying power and data within a garment. Conductive fabrics and threads have become commercially available, and researchers have demonstrated both the weaving of power and data buses into custom fabrics and silk screening of conductive material onto conventional fabrics (Lehn, Neely et al. 2004; Details and Kim 2006). Lacking these design options, constructing the e-SUIT required developing a new technique for creating a power and data bus within a garment.

5.5.4.1 "Bedding" wires to cloth

The developed technique mounted fine wires mounted onto strips of fabric that could then either be used to construct a new garment or sew into an existing garment. The wires were mounted to the fabric by being over-sewed, or "bedded", a process where a top thread is repeatedly sewn over the wire and anchored by a second thread on the back of the piece of fabric. The used bedding process is illustrated in Figure 45. Tape was used to both initially anchor the bus wires and to act as a guide while bedding the wire to the cloth. The "bedding" technique was used to construct the e-SUIT's integrated bus. An example of the e-SUIT's bus wires before they were connected is pictured in Figure 46.



Front View

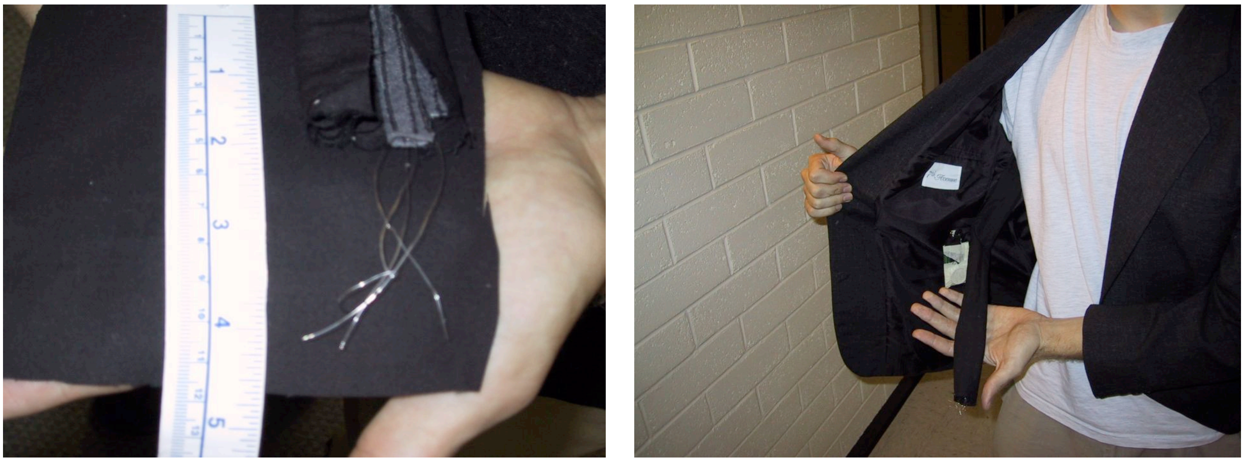
Back View

Figure 45 Couching of garment integrated power and data lines

5.5.4.2 Mechanical coupling

Power and data buses run throughout the garment electrically connecting all of the integrated components. Care must be taken when constructing or retrofitting a garment to ensure that mechanical forces are not translated by the bus, negatively impacting the fit and hang of the garment by mechanically coupling normally disjoint parts of the garment. Early experimentation in the construction of the e-SUIT quickly revealed that when the bus was directly sewn into the suit, it translated mechanical forces between parts of the garment directly attached to the bus. This was particularly problematic since reaching all of the locations where devices were integrated into the e-SUIT required the bus to run across areas of the body that were frequently in motion. For example, reaching the cuff integrated LEDs required the bus to run across the shoulder complex and down the sleeve of the jacket.

To solve the problem of mechanical coupling, the e-SUIT’s bus was not connected directly to the garment. Instead, the bus was run through a series of short cloth tubes that collectively acted as a conduit holding the bus within the garment. Since the conduit was broken up into a number of short sections it could be sewn directly to the suit without translating mechanical forces along the length of the bus. The material onto which the bus was bedded was also free to slide within the conduit, which further minimized the mechanical coupling and general impact of the bus’s integration on the hang of the jacket. The bus and conduit are pictured in Figure 46.



Bus Wires   Bus Conduit

Figure 46 e-SUIT power and data bus

5.6 Smart tagging for the production of Smart Garments

The term Smart Tagging refers to a type of modular architecture that this thesis argues will need to develop to make commercially viable production of smart garments possible. In general there will be two types of engineer involved in the construction of the component of a smart garment, the fashion and apparel designers responsible for the design, patterning, and construction of the garment, and the electrical and computer engineers responsible for the design of the integrated electronics. Smart Tagging, proposes augmenting smart garments using prefabricated electronics modules. The prefabricated modules allow a separation between the types of engineers, minimizing the need for individuals with hybrid talents straddling both domains.

As prefabricated design components these modules, or SmartTags, will be standardized in terms of more then just their functionality. Mechanically SmartTags will be standardize in parameters such as shape, thickness, size, weight, flexibility, shock sensitivity and thermal permittivity; providing both types of engineers a known form that they are working with. Modules will also be standardized within the parameters of each type of engineering domain. For the fashion and apparel designers SmartTags will be standardized in parameters such as type of backing fabrics available, moisture and thermal permittivity, suitable thread types for mechanical and electrical mounting, and the location of mechanical and electrical stitching points required for mounting. Electrical and computer engineers will have their own set of specifications, working within standardized parameters such as conductive pad location and dimensions, available power requirements, available inter-SmartTag communication protocols, acceptable thermal generation levels.

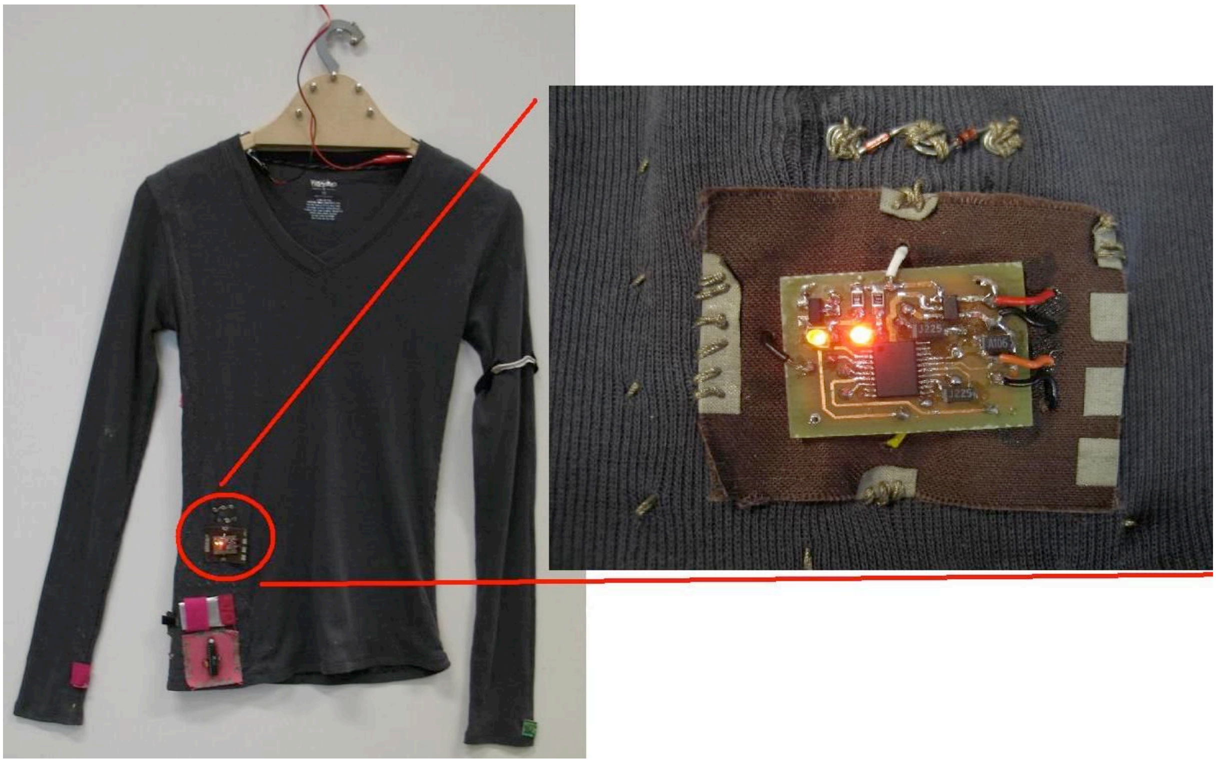


Figure 47 Smart Tag module integrated into prototype smart garment
Image Credit: Leah Buechley, University of Colorado at Boulder's Craft Technology

To demonstrate using Smart Tagging, a SmartTag was developed for the regulation of power in smart garments, and used in the construction of a prototype smart garment. The power managing SmartTags were developed at the University of South Australia's Wearable computing laboratory, and shipped to the University of Colorado at Boulder's Craft Technology Lab where one was integrated into a smart garment pictured in Figure 47. The pictured prototype is a shirt that transmits data from embedded sensors to an external device via an embedded Bluetooth™ module. The smart tag was used to enable the smart garment to be charged when hung on one of the smart hangers (Toney, Thomas et al. 2006) developed in Chapter 6. Schematics for the SmartTag, and a more detailed description of its design, can be found in Appendix B.

5.7 Emerging Construction Techniques

The process of manufacturing clothing is a complex task requiring a tremendous amount of manual labor, labor that is ultimately responsible for a large portion of the garments retail cost. Research on decreasing the manual labor required by garment production has implications for the construction of smart garments. Automation enables integration techniques that require tighter control over positioning and the construction environment. As a result increased automation is beneficial for garment integration.

Automation is used commercially to seamlessly knit entire garments (Choi and Powell 2005). Using the techniques demonstrated by previous researchers, (Jung, Lauterbach et al. 2003; Marculescu, Marculescue et al. 2003; Nakad 2003; Zeh 2006) the single knit process can enable the integration of technology during the automated construction of the garment.

Laser cutters have been demonstrated precisely cutting fabric along the lines of a pattern. Combined with printers that apply color and patterns directly to the textile (Campbell and Parsons 2005) prior to laser cutting, the rapid production of pattern pieces of an arbitrary shape, size, color, and pattern become possible. Textile and apparel researchers have already demonstrated each of these manufacturing steps.

A combination of laser cutting and weaving of a bus into the textiles being cut enables the automated production of pattern pieces that contain integrated buses for the distribution of power and data throughout the garment. Aligning cut to a pattern used to weave buses into the fabric enables the production of a stream of pattern pieces with integrated buses. Alternatively, as opposed to weaving the bus into fabric it could be printed or silk-screened on with conductive inks or electrospun (Post, Orth et al. 2000) onto fabric through the electrostaticly guided deposition of conductive polymers.

Each of these types of buses could expose conductive pads. Research is also being conduced on printing of the circuit elements themselves. Electronics can either be attached to these pads, or be directly printed onto the pad. Ultimately it is the author's belief that on demand construction techniques for clothing will be produced that will nullify the benefits of a SmartTags approach for the construction of new clothing. Until that time, which at present appears at least a decade off, the author believes a modular SmartTags approach will be the predominant method of smart garment production.

5.8 Summary

The goal of this chapter was to presents the concerns and challenges facing commercially viable production of garment integrated technology. The chapter began by presenting an overview of the design considerations idiosyncratic to the design of smart garments. A presentation of design concerns was followed by overviews of and proposed techniques for constructing circuits on fabric, prototyping garment integrated devices, and strategies for garment integration. The chapter concluded with a presentation of the techniques used in the production of smart garments.

The central contribution of this chapter was proposing and demonstrating smart tagging, a component based methodology enabling the commercially viable construction of smart garments. In support of smart tagging, a prototype smart tag was developed and used by a researcher on another continent as part of the development of a smart garment. This remote development clearly demonstrates the viability of using SmartTags in as part of the smart garment manufacturing, to separate the manufacture of the smart garment from the fabrication of its components.

In the future there are a number of emerging technologies with the potential to greatly impact garment integration. A smart garment based on technologies such as molecular computing, nanostructures and nanomaterials, or organic semiconductors would all have radically different implementations than the techniques presented in this chapter. Rather than the modular approach, these types of technologies would literally make the garment indistinguishable from the circuit. The work of this thesis used the modular approach as the other techniques were either insufficiently developed or beyond the available resources.

6

"I got a shotgun and I am not afraid to go back to jail!"
Some random guy overheard in the hospital
while I was working on my thesis

Chapter 6 Smart Garment Management

As the availability of and interest in smart garments increases, users will eventually possess, and need to maintain, a larger number of garments. In addition to possessing their own idiosyncratic requirements, smart garments inherit all of the requirements of conventional clothing. Closets and wardrobes already collect a large number of garments into a single management point, thus reducing the maintenance tasks required of the user. This chapter addresses how garment integration will change the user's management of their wardrobe, looking specifically at the changes required of existing methods of clothing management to enable them to support smart garments. While some of the techniques presented in this chapter, such as smart hangers, have definite application within supply chain management for smart garments; the focus of this chapter is Smart Garment Management within the home.

Currently the user is responsible for tracking the state of their clothing, ensuring they are clean and situationally appropriate, and in good repair. By helping the user manage the wardrobe related aspects of their appearance, the smart garment management system is able to guide the user's choice of clothing. By guiding the user in assembling a suitable outfit for the day, the smart garment management system can ensure that the final ensemble selected includes smart garments that in aggregate provide the desired minimum level of functionality. Should there be no ensemble containing smart garments with the desired minimum level of functionality, the system can warn the user that they are choosing to lower their minimum guaranteed level of support to that provided by the selected outfit.

While the chapter's focus is on domestic smart garment management, it begins by briefly discussing domestic applications for smart garment management technology being developed for industrial and commercial supply chain management. The additional concerns of implementation cost and consumer privacy are discussed for industrial applications of smart garment management in the supply chain. The chapter moves on to specific demonstrations of a smart garment management system. This discussion is followed by a review of previous research, augmenting wardrobes and hangers. Next, the three basic tasks of garment management are presented; garment storage, garment maintenance, and variation of the wardrobe. These tasks are complimented by the following sections presentation of the four additional functional requirements of smart garment management; data synchronization, recharging the garment, agency providing a single interface to all of the smart devices in the wardrobe, and regular automated diagnostic verification of the garment.

One of the primary contributions of this chapter is demonstrating constructing a Smart Garment Management System (SGMS) suitable for managing a heterogeneous wardrobe consisting of both smart and conventional garments. The next section advocates using the closet rod and hanger storage technique as the foundation for building a SGMS. Since users are already familiar with how to use a hanger and rod for storing garments, the developed SGMS will inherit a high affordence of use, as its users will only need to familiarize themselves with the systems idiosyncrasies. The chapter finishes by presenting the smart hangers and smart garment management system developed for this thesis. The mechanics of smart hanger implementation and the concerns of constructing smart wardrobes are presented. The presented smart hanger design represents the resulting design from the iterative creation of over a dozen prototype hangers, and three different prototype rods and storage systems.

6.1 Industrial and Commercial Smart Garment Management

While the garment management work presented in this chapter will have domestic rather than an industrial or commercial focus, the RFID tools developed for garment supply chain management have direct application to domestic smart garment management. Most notably garment integrated RFID solutions intended for supply chain management has the ancillary benefit of providing the smart garment management system a way to track garments that do not lend themselves to a direct electrical connection, such as garments stored in drawers or on shelves.

6.1.1 Privacy Concerns

Trials by major garment manufacturers and distributors have demonstrated that using RFID to track the garments during production (O'Connor 2006), distribution (Ilic 2004; O'Connor 2006), and sales (O'Connor 2007) provides unprecedented levels of efficiency, quality, and accountability. The potential for RFID across all areas of garment production and sale has led both manufacturers and retailers to investigate their direct integration into clothing, using a single RFID module in all stages of tracking. As garment integrated technology, clothing tracking tags help to amortize the cost of more complicated garment integrated devices intended for use after the garment's purchase. Unfortunately, garment integration has been the cause of significant consumer privacy concerns that garment integrated RFID would also lead to unprecedented levels of consumer profiling, as garment integrated tags were read after the point of sale (Landwehr 2004).

To date the industry has addressed concerns about garment integrated tags being queryable after the sale, by developing "privacy-friendly" tags. The two principle types of privacy-friendly tags are "hang-tags" and "clipped tags". Hang-tags bundle the RFID electronics on a large easily visible paper tag attached to the garment, while Clipped Tags integrate directly into the garment during construction, like a conventional label. The tags are perforated and "Clipped" by having their antenna torn free after purchase. Tearing its antenna mutes the Clipped Tag, reducing its readable range from 6-7 meters down to less than ten centimeters (Swedberg 2006). Keeping "privacy-friendly" tags readable from such short distances is desirable as it allows stores to read the Electronic Product Code (EPC), from returned garments, while protecting the privacy of the consumer after their purchase is made.

6.1.2 Application to domestic smart garment management

As garment integrated device that will remain readable at close range for the entire garment life cycle, a Clipped Tags make its garments available for management by a SGMS. By integrating RFID readers within drawers or near shelves and hooks, an SGMS will be able to read an ID code from clipped tags at close range, identifying the garment. This enables the SGMS to track total usage and availability for tagged garments. Storing information about the tagged garments such as its type, style, cut, and color, enables the tagged garments to be a part of attire suggestions made by the SGMS. Since Clipped Tags are garment integrated during construction and their cost is amortized by their role in supply chain management, there is no additional cost or manufacturing complexity added to the garment to enable it to be recognized by the SGMS.

6.2 Relevant prior research

There have been several significant pieces of prior work relevant to supporting smart garments. Two previous projects have embedded connectivity into clothing hangers, and two projects which address the potential of the wardrobe as a place for in home, ubiquitous computing applications.

6.2.1 Smart wardrobes

The Accenture "Magic Wardrobe" (Wan 2000) describes the development of a smart-wardrobe. The Accenture wardrobe is relevant in that it casually focuses on helping users manage their wardrobe. A RFID reader built into the wardrobe enabled the wardrobe to track its contexts through garment integrated RFID tags. However, the primary focus of the Accenture wardrobe is commercial, acting as a home shopping portal allowing the uses of the wardrobe to act as "a consumer" in the online market place. Accenture users were provided with one of four core new features to support them as consumers. First generic access to online stores while the consumer is in the presence of their current collection of clothing. Second, the Accenture wardrobe provided a software interface enabling the user to view their clothing, and accessorize and compare them against others on the market. Third, the system makes suggestions of garments to purchase in part based on the garments the user has on their current wish list, and a record of past interests. Fourth, the system provides a personalize store providing a single personalize interface to the contents of multiple online stores.

Physically the Accenture wardrobe fit a high-end wooden wardrobe with a touch screen interface, and tracked what the clothes were present in the wardrobe. Accenture wardrobe's garment management consists of a web interface to suggest garment pairings or items of clothing for purchase. This paradigm assumes standard garments, with no intelligence or electronic capability beyond the integration of RFID tags.

The concept of a smart wardrobe and that of a smart dressing table were also briefly mentioned by Park et al. in a paper on smart homes to engineer the user's domestic life (Park, Won et al. 2003). Their presentation was concept only and provided no implementation details, discussing both ideas for several sentences as part of a larger concept of augmenting common items in the home to improve the user's home life experience.

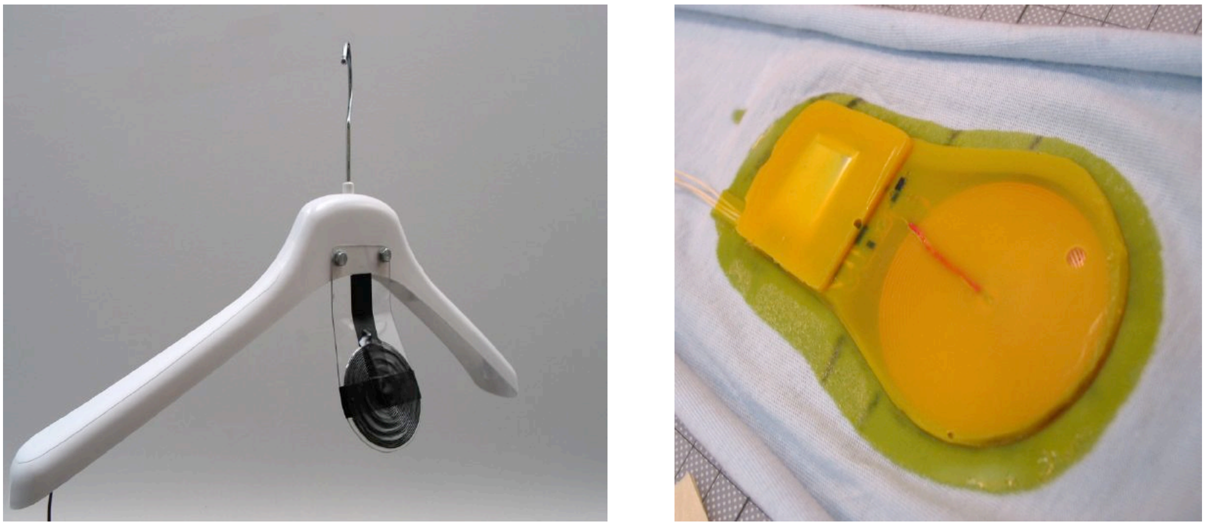

Recharging Hanger Garment Integrated Recharging Coil

Figure 48 Kankaanpää Unit at the Tampere University of Technology's Recharging Hanger
Image credit: Pekka Iso-Ketola, Tampere University of Technology - Kankaanpää unit

6.2.2 Prior research with hangers

The earliest work on augmenting hangers was performed by Matthews et al. (Matthews, Gellerson et al. 2000), and explored the use of a collection of hangers to form an ambient display. Their system used a one wire bus to both parasitically power the hangers and to detect the hangers currently present within the wardrobe. Mathews' work restricted hanger insertions and removals so that hanger order would be known. Taken as a collection with a known ordering and IDs uniquely identifying the hangers, LEDs integrated into the Matthew's hangers formed pixels within a simple ambient display. Unlike the work of this thesis, Matthews' work focused on ambient displays and their system did not support garments. Their hangers were unable to detect, communicate with, or charge garments. Since their work was not required to support garments, they were able to use an off the shelf solution for their one wire bus, basing their system on Maxim[20]'s one-wire™ technology[21]. This approach does not allow garments to announce themselves when plugged into the bus, and can only supply very small amounts of power for running and charging devices on the bus.

The Kankaanpää Unit at the Tampere University of Technology, developed the Noise Shirt (Iso-Ketola, Karinsalo et al. 2005). While not focusing on smart garment management, their work constructing the Noise Shirt demonstrated a novel concept and prototype based on the ideals: a simple, easy-to-use maintenance system that builds on pre-existing concepts of garment care and storage. Specifically, their work was primarily concerned with inductive charging and washability of smart garments, demonstrated using a hanger-based inductive

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[20] Maxim Integrated Products, Inc – 120 San Gabriel Drive, Sunnyvale, CA 94086 – Phone: 408 737 7600 – URL: http://www.maxim-ic.com

[21] http://www.maxim-ic.com/products/1-wire/

system to recharge a battery that had been cast in place into the garment. Hanging the noise shirt on a special hanger (pictured in Figure 48) aligned a pair of inductive charging coils, one in the shirt and the other in the hanger. Once aligned inductive coupling was used to charge the cast in place battery in the Noise Shirt. The battery and charging coil is also pictured in Figure 48.

While an excellent start, the Kankaanpää unit's focus was on washability and not the management of smart garments. As a result, while the external plug they used on their charging system was acceptable for their needs it restricts the techniques generic use in a generic smart garment management system.

6.3 Tasks of Smart Garment Management

In addition to inheriting all of the storage and maintenance requirements of conventional clothing, smart garments possess their own idiosyncratic requirements. I have identified four core tasks required for smart garment management; synchronization of data, recharging the garment integrated devices, agency or providing a single interface to all of the wardrobes garments, and being able to query the more complicated garments in the system to run self-diagnostics. These requirements are listed in Table 7.

In order for an SGMS to manage the recharging and diagnostics for a smart garment, it needs a mechanism for uniquely identifying the garments in the system. While it is a simple matter for a smart garment to report a unique identifier, such as an EPC, as was discussed in Section 6.1.1, the integration of globally unique identification into garments is a tremendously sensitive social issue due to concerns over consumer privacy.

Synchronization	The system must be able to synchronize data between the garment and the SGMS. While simple "read only" garments are possible, at a minimum synchronization requires all smart garments be individually identifiable and be queryable for configuration information.
Recharging	The SGMS must be able to recharge any smart garments attached to the system. This requires the SGMS be able to query smart garments for their power and charging requirements. As part of reporting their power needs any smart garments that wishes to remain active while connected to the SGMS need to first request and obtain the systems approval of its intended power consumption.
Agency	Agency is the primary requirement for smart garment management. The SGMS provides a single interface to all of the user's smart garments, enabling them to be treated as a single device with many components as apposed to a large number of devices that need to be individually maintained.
Diagnostics	In addition to querying smart garments for information, the SGMS must have a way of directing the smart garment, specifically the SGMS needs to be able to direct garments connected to the SGMS to run self-diagnostics. Whenever a garment is returned to the system after being worn or cleaned, the querying of the garment for diagnostic information enables the SGMS to ensure the smart garment is still functioning properly before it is next worn.

Table 7 Core task of smart garment management

6.3.1 Storage

The mechanics of home garment storage can be grouped into three broad categories; features on which the clothing is mounted such as racks or hooks, separate objects on which the garment is draped before the pair is collectively stored, such as hangers, and places reserved for storage where the garment is deposited such as drawers, or shelves. While some specialty garments are stored on custom structures when not in use, such as mannequins, this practice is extremely rare for domestic garment storage, and thus it is not discussed further. Racks, hooks, pegs, and in general features over which a garment can be draped are not considered here as the basis for an SGMS for two reasons. First, they are typically only suited for concurrent use by a small number of garments; and second, many common materials used in the construction of western business attire are not suited to being hung or draped in this manner (Cabera and Meyers 1983).

Differing types of garments often lend themselves to, or require, a particular type of storage (Karlen 1998). Purely passive devices, such as passive RFID smart labels, lend themselves to most types of storage. By placing transceivers near the garment storage areas, garments with integrated tags, such as the previously described Clipped Tags, can be interrogated and synchronized.

Inductive charging, or power harvested parasitically from special RFID systems, can be used to supply garments with small amounts of power over extended periods. However, short-term storage poses a problem for garment integrated devices requiring high charging currents, especially if there is more then one garment which requires charging. Inductive coils like those used by the Kankaanpää unit's hanger (Iso-Ketola, Karinsalo et al. 2005) require either large coils or high voltages to deliver high charging currents. Since only small amounts of power are available without a direct electrical connection, garments stored in drawers or on shelves only have relatively small amounts of power available to them.

The SGMS employs a common hanger, or "coat hanger", as its foundation. Hanging a smart garment on a specially modified hanger electrically connects the garment's integrated devices to a common power and data bus. The bus is shared with other smart garments hung on a special rail. The shared bus provides the same garment interrogation as RFID technology, but in a manner that addresses privacy concerns associated with RFID (discussed in Section 6.1.1) by only being queryable when the garment is hung up and electrically connected to the system. Under the proposed implementation, unless the smart garments had deliberately integrated wireless connectivity, such as Bluetooth™, ZigBee™, or 802.11, it would only be queryable while hanging within a smart wardrobe.

The closet rod and hanger storage technique forms the foundation of the smart garment management system developed for this thesis. When properly used, hangers are compatible with the majority of garment types and fabrics, and are regularly used to store a variety of garments such as shirts, pants, dresses, and shawls across a wide range of price and formality. By using a direct electrical connection between the hanger and the supporting rod, and then in turn between the hanger and the garment, significant power is available for garment integrated devices stored on hangers. The smart garment charging system in Chapter 5, demonstrates delivering sufficient power to charge garment integrated Lithium ion batteries, without requiring the prohibitively large garment integrated features like the inductive coil in the Kankaanpää unit's hanger.

6.3.2 Garment availability

Currently, the user must maintain their wardrobe in order to have both a clean and appropriate selection of clothing available. A responsibility which requires the typical user to regularly either wash the garment or get them to and from special professional cleaners. This task is complicated by the fact that not all garments are automatically washed after every wearing. Suits for example, constructed from fine cotton and silk fabrics that have a memory that requires that garments constructed from those materials be hung for several days between wearings. Depending on local weather and climate a suit should be washed every eight to twelve wearings, and given at least two days to hang between wearings (Karlen 1998).

A key task of smart garment management systems will be to track the usage and availability of garments present within the wardrobe. Knowledge of when clothing was last worn enables the SGMS to make recommendations to the user. The system can remind the user if the garment they have chosen has been worn recently, or if the selected garments have been too frequently worn together. The system can also notify the user when to schedule washing of garments those are not automatically washed after as single use. For example, the system can signal the user when enough garments are ready for dry cleaning.

6.3.3 Assembling the day's outfit

Smart garment management system can present the user with their available options factoring in scheduled events for the next several days, weather, and recently worn clothing to suggest outfits and garments to the user.

6.4 Smart Wardrobes

The term Smart Wardrobe is proposed in this thesis as a way to describe the physical components of a smart garment management system, the cabinets or closets that provide place to store, synchronize, and recharge a collection of smart garments. By incorporating the SGMS infrastructure into a standard garment storage system, such as clothes hangers and a wardrobe, smart closets and wardrobes can fulfill the maintenance and management requirements of smart garments with minimal impact on the existing physical relationships between users and their clothing. In its role of supporting a smart garment management system, there are three requirements of smart wardrobes. These requirements are outlined in Table 8.

The research into smart hangers presented in this chapter fulfills all of the requirements of smart garment management. This chapter demonstrates building a smart garment management system by modifying a hanger and closet rod in order to provide power and data to smart garments. The system developed for software testing, and to initially demonstrate the smart hanger approach to SGMS, is pictured in Figure 49, and shows how the modified hangers, clothes, and bar all interact. A smart wardrobe or smart closet instrumented with this approach allows its collection of smart garments and hangers access to a one-wire bus integrated into a closet rod. Communicating over that bus, the garments interact with a bus master, which acts as the gateway between devices on the bus and the software of the garment management system. This approach was chosen in part because it leant itself to integration within existing closets and wardrobes.

1. For the near future, users of smart wardrobes and closets must support both conventional and smart garments and hangers.

2. Smart wardrobe must detect both smart garment and hangers inserted or removed from the wardrobe.

3. A smart wardrobe must supply power, either directly or parasitically, to the smart garments contained in the wardrobe. Supplied power should be sufficient to enable recharging of garments.

4. The wardrobe must provide a communications channel between the garments contained in the system and the smart garment management system.

Table 8 Requirements of a Smart Wardrobe or Closet

To demonstrate the construction of a smart wardrobe the Narnia system, pictured in Figure 50, was created in collaboration with Wynand Marais. Mr. Marais has professional cabinet making experience, which allowed him to build a custom wardrobe to house the Narnia system as opposed to retrofitting a commercially available wardrobe as had originally been planned. While both Narnia and the Accenture system look similar, integrating a display on the outside of a formal wooden wardrobe, Narnia is intended for daily use, becoming an integrated part of its user's ritual of dress, whereas the Accenture system focuses on providing home-shopping experience.

Figure 49 Smart hangers on closet bar

Narnia used an embedded bus master built around a Texas Instruments[22] MSP430F1232 microcontroller. The bus master bridges communications between the computer running the smart garment management software and a custom one-wire bus that provided power and a communications channel to the smart garments and hangers. A 1042x768 LCD display and touch screen are connected to an integrated computer and used to provide the user with a graphical interface to Narnia's integrated SGMS. I designed all the hardware for the smart hangers, garments, and bus master. In addition to writing software for these devices, I wrote the early proof of concept SGMS software. Working with Mr. Marais the SGMS software was ported from Windows XP to Linux, expanding its functionality, and extended the software for the smart hangers.

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[22] Texas Instruments, P.O. Box 660199 Dallas, TX 75266-0199, Phone: 972-995-2011, www.ti.com

Figure 50 Narnia

6.5 Smart Hangers

Similarly, as the means of data transfer between applications increases in complexity, the user becomes less likely to facilitate this transfer on a day-to-day basis (Pentland 1998). The role of the smart garment management system is to solve these two problems by presenting the user's collection of smart garments as a single new device, and not as a number of individual devices, each of requiring individual maintenance. By instrumenting an existing clothing management system, the hanger and rod, smart hangers can enable smart wardrobes to be supported without requiring the user alter their existing behavior supporting and using their conventional clothing.

The hanger and closet rod is a well-established means of conventional garment management. As an after effect of the industrial revolution, the availability of woven textiles increased causing the retail cost of garments to plummet. The cost of clothing quickly reached a point, where for the first time the average person could afford to own and maintain multiple sets of clothing intended for daily wear. The expansion of the average wardrobe created new problems in managing the contents of wardrobes. The records of the patent U.S. patent office reflect that clothing hangers in various forms started appearing almost immediately as a way for persons immediately to provide a way for persons owning multiple garments to manage their wardrobes. Thee origins of the hanger and rod style storage system used today date back to at least the 1860's (Clemence 1867; Kelley 1868), with a round of minor refinements to arrive at the current hanger form in the early 1920s (Al 1923; Brinkman 1923; Fetters 1925).

The forms of the clothing hanger and rod have been standardized for over four generations. As a result, there are entrenched expectations about the operation of coat hangers in existing garment management systems such as wardrobes and closets, expectations that need to be met by successful smart hanger designs. In conducting research into smart garment management, six core expectations were identified. These expectations are enumerated in Table 9.

1. Individual hangers must be inexpensive.
2. Hangers must be able to slide along the closet bar to enable searching, sorting, and compacting of the wardrobe.
3. Hangers removed from the system must be able to be reinserted in any order.
4. Garments must be able to be hung on the hanger facing in either direction.
5. Hanging garments must not require extensive or precise user participation.
6. Smart hangers must be capable of operating while co-mingled with conventional, un-instrumented, hangers.

Table 9. Expectation of Conventional Hangers

Incorporating the smart garment management infrastructure within an existing garment storage system such as the clothes rods and hangers used by wardrobes and closets fulfils the maintenance and management requirements of smart garments with minimal impact on the existing physical relationships between users and their clothing.

6.5.1 Requirements for garment electrical and mechanical connection

There are five requirements for electrical connections formed between smart garments and their hangers. The requirements, outlined in Table 10, must be meeting if the smart garment is to achieve the minimal impact on the user's life, and use of their clothing, required for successful adoption of an SGMS.

1. Electrical connection must be made by simply placing the garment on the hanger, without connectors requiring gendered mechanical mating.
2. The connection must not require extensive adjustment of the garment on the hanger.
3. The electrical connection must be reliable and consistent, even when hangers are jostled, moved, or compressed.
4. The garment connector must have minimal impact on the garment's comfort and appearance.
5. The garment connector must provide consistent contact with the hanger regardless of garment shape, type, construction, or materials.

Table 10 Requirements for garment connections

6.5.2 The closet rod integrated one-wire bus

A one-wire bus was selected as the way to deliver both power and data to the smart hanger and its connected garment, while keeping the required connections as mechanically and electrically simple as possible. The smart hangers use a spring-loaded hook to connect to a special closet rod that contains a one-wire buss. The approach of using a gendered plug to connect the hanger, taken by the Kankaanpää unit's hangers, fail several of the requirements of smart garment management and hangers outlined in Section 6.3, Table 7, Table 9, and

Table 10, since each hanger will need to be plugged in or unplugged as part of hanging or removing a garment.

The closet rod containing the one-wire bus is pictured in relation to the hanger head in Figure 51. Two metal rails run the length of the closet rod providing the bus lines shared by all the hangers in the system. The ground rail rises above the top of the bar ensuring contact with the hangers. The data and power connection is recessed in order to minimize the potential for conventional metal hangers from shorting the bus. Recessing the power and data line enables a heterogeneous assortment of conventional and smart hangers to be mixed in the system. Figure 52 shows one of the early hanger prototypes sharing the one wire buss with two other conventional hangers. A number of hangers and garments are pictured concurrently connected to the rod and bus in Figure 49.

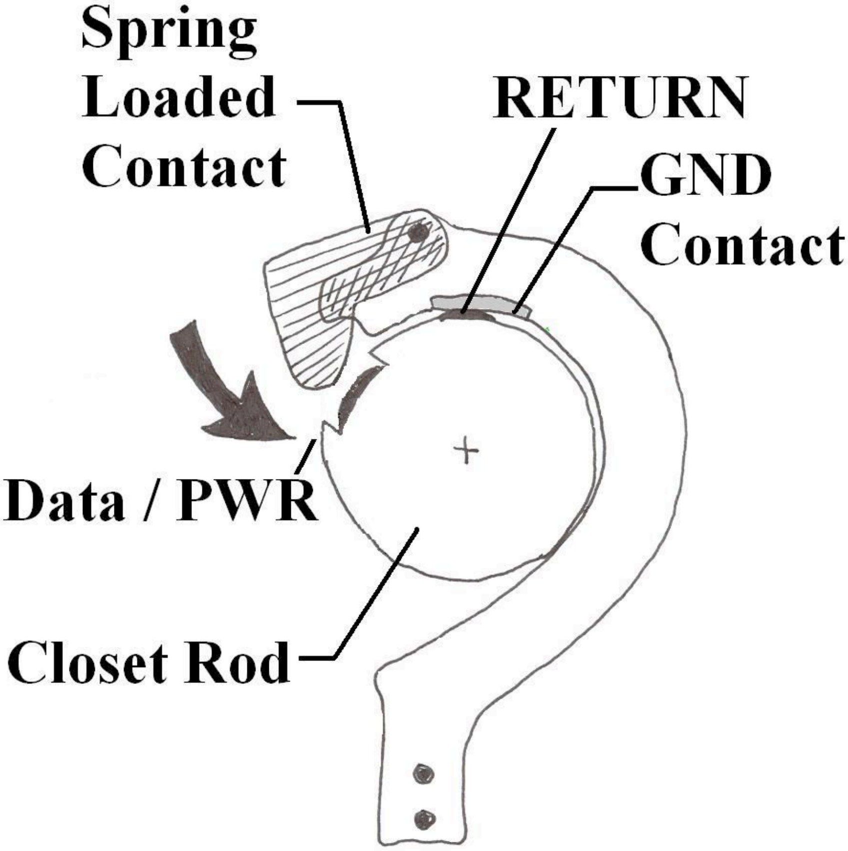

Figure 51 Smart Hanger head design

6.5.3 The smart hanger head

Once hung up, with or without a garment, the hanger settles into the desired operating position on the bar, gravitationally aligning its contacts with the special closet bar. Contact is made with the closet bar in two places; through a ground return connection and through a spring-loaded contact to a recessed data/power connection. A commercial system could use a symmetrical arrangement with three bars so that hangers would still be connected to the data and power bus regardless of the direction in which they were hung up. The ground connection rises above the top of the bar ensuring contact with the hangers. The data/power connection is recessed and connected via the spring-loaded contact in order to minimize the potential for conventional metal hangers from shorting the bus. The recessed connection maximizes the isolation of the bus, and minimizes the potential for shorts. Figure 52 illustrates how the recessed connection allows a heterogeneous collection of smart and conventional hangers to safely be mixing on the bus.

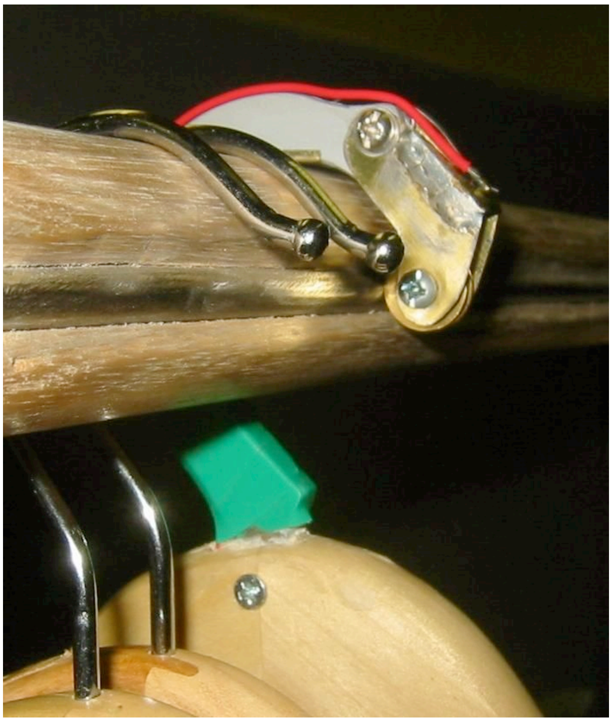

Figure 52 Prototype Smart hanger and conventional hangers

6.5.4 The smart garments' electrical and mechanical connection

Once connected to the one wire bus, the hanger uses special conductive pads on its shoulders to supply its smart garment with a direct electrical connection to this bus. Figure 53 illustrates the smart garment's electrical contact with a smart hanger. The early versions of the smart hanger, like those pictured in Figure 49, used two 12 cm by 1.5 cm steel contacts on either shoulder of the hanger. While effective, steel pads made the hangers noticeably heavier and had a tendency to snare the fabric unless they were carefully filed and mounted during hanger construction. Later hanger designs used conductive Velcro®, as shown in Figure 54 and Figure 55, to form the pads. The Velcro® pads significantly reduced hanger construction time by eliminating the need to cut, shape, and recess two metal pads in the hangers. As the Velcro® pads were flexible, they molded to the curved shape of the wooden pads.

The latest smart hanger design, construction Mr. Marais, is shown in Figure 55. The center panel of the hanger contained a chamber containing Li+ batteries and electronics used by the hanger. Schematics for the electronics contained in the smart hanger, and a brief description of their design, is presented in Appendix B. A picture of an early prototype hanger with its front panel removed, and the electronics exposed is provided in Figure 96 of Appendix B.

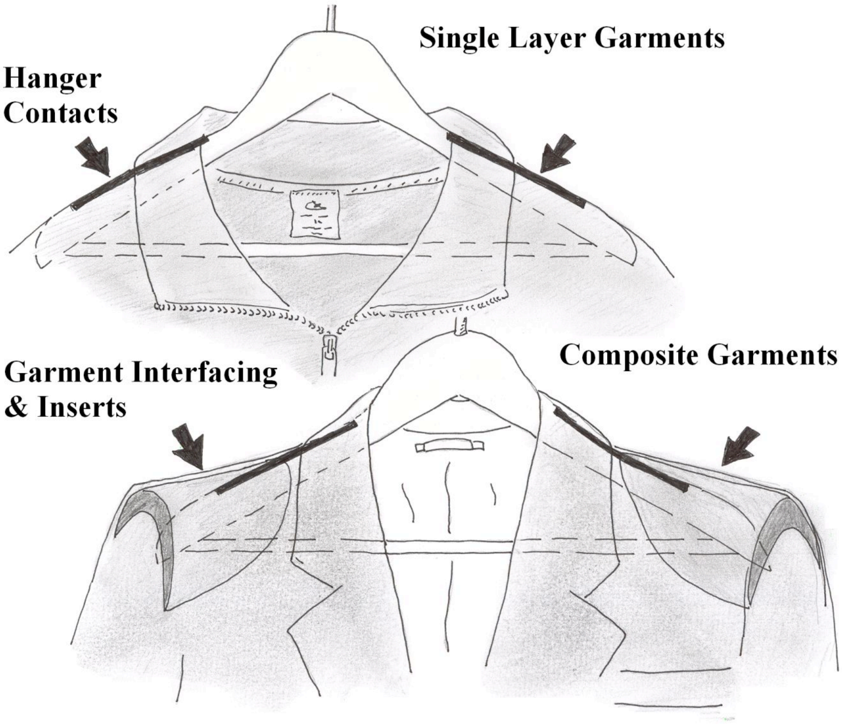

Figure 53 Smart Garment electrical contact with Smart Hanger

Figure 54 Velcro® smart hanger to garment connector

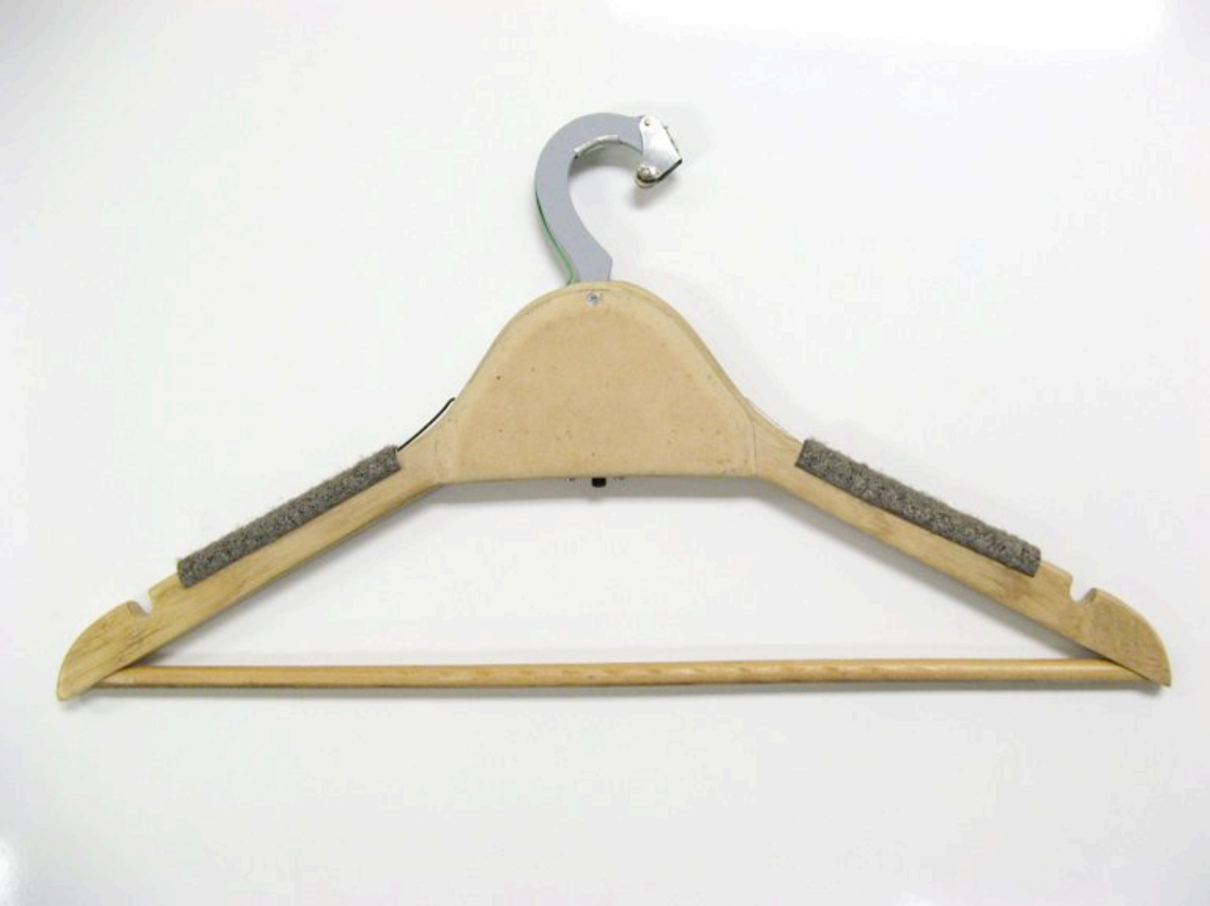

Figure 55 Most recent Smart Hanger prototype

Direct electrical contact is made between the garment and the one wire bus through patches of conductive fabric sewn into both shoulders of the garment. Figure 56 and Figure 58 shows the two different pad orientations used in prototype smart garments constructed for this thesis. The conductive patches were made from silver coated fabric. The coated fabric was composed of 92% Nylon and 8% Dorlastan[23] and connected to the garment electronics by conductive thread.

Fabric patches add minimal bulk, even in single-layer garments. The "normal" action of storage of the garment needs to be able to make and maintain the connection. It is crucial that contacts be sized and located such that a reliable electrical connection is formed without relying on the hang weight of the garment. Increasing contact depth will increase the probability of garment bus connectivity. Unfortunately increasing the depth of the contact is not always appropriate as it may impact the garments comfort or appearance. Examples of the different shoulder patches used in smart garments are pictured in Figure 56 and Figure 57. These patches were only tested mechanically and were not tested as part of a smart garment.

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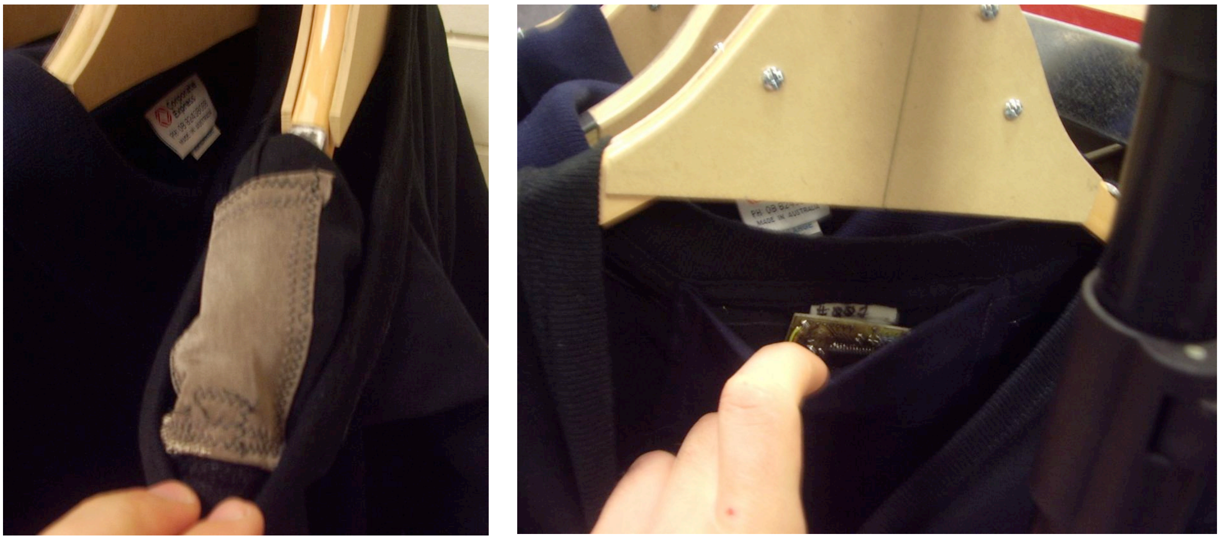
[23] EMF Shielding & Conductive Fabrics 809 Madison Ave, Albany, NY 12208 PHONE: 518-432-1550

URL: http://www.lessemf.com/fabric.html

Section 6.5.7 further discusses ways smart garments can be modified to better support interaction with smart hangers.



Garment Conductive Pads

Pocketed Garment integrated Electronics

Figure 56 Smart Garment used to test Smart Hangers

6.5.5 Bus arbitration and protocol

Devices on the SGMS bus used an open collector connection for active low bus assertion. Schematics for the Smart Hanger and bus master are available in Appendix B. Unlike most one-wire buses, the one wire bus developed to connect the smart hangers was designed specifically for smart garment management and does not use a bus master to arbitrate the buss. The systems bus master acts only to power the bus and provide a bridge between the systems bus and the controlling PC. A bus master was used in the specific SGMS implementation used to drive the Narnia smart wardrobe. Bus arbitration for the system used carrier sense multiple access with collision avoidance (CSMA/CA). During transmission, the bus state is monitored and in the event that the device detects the bus being asserted during an expected de-assertion time, in such an event a collision is assumed. After a collision is detected, the device enters a low power state and waits, for a period derived from its unique ID, before attempting retransmission. While the recessed power connection minimizes the potential for shorts, a CSMA/CA was chosen as it minimizes the impact of shorts on the bus.

The developed one wire protocol uses three byte packet headers that can contain from 0-7 additional bytes. As implemented, each packet contains a one byte source and destination address. These address bytes are followed by five configuration and status bits and three successive bits indicating the number of accompanying data bytes in the current packet.

6.5.6 Evaluation of the smart hanger design

In order to evaluate reliability of alignment and electrical contact in both the hangers and the smart garments, a small user study was performed. Seven subjects were each given a smart hanger, and asked to repeatedly hang a smart garment, the t-shirt shown in Figure 56. One hundred and eleven garment insertions were tested. The hangers repeatedly broadcast a packet announcing its presence on the bus once every 420mS. Successful reception of these packets signaled an insertion. The ID of the device being inserted was read from the received packet by the testing software interacting with the bus master. The system successfully recognized 110 of 111 insertions. The missed insertion resulted from a mechanical failure within the spring loading of the hanger head, causing the spring mechanism to fail open.

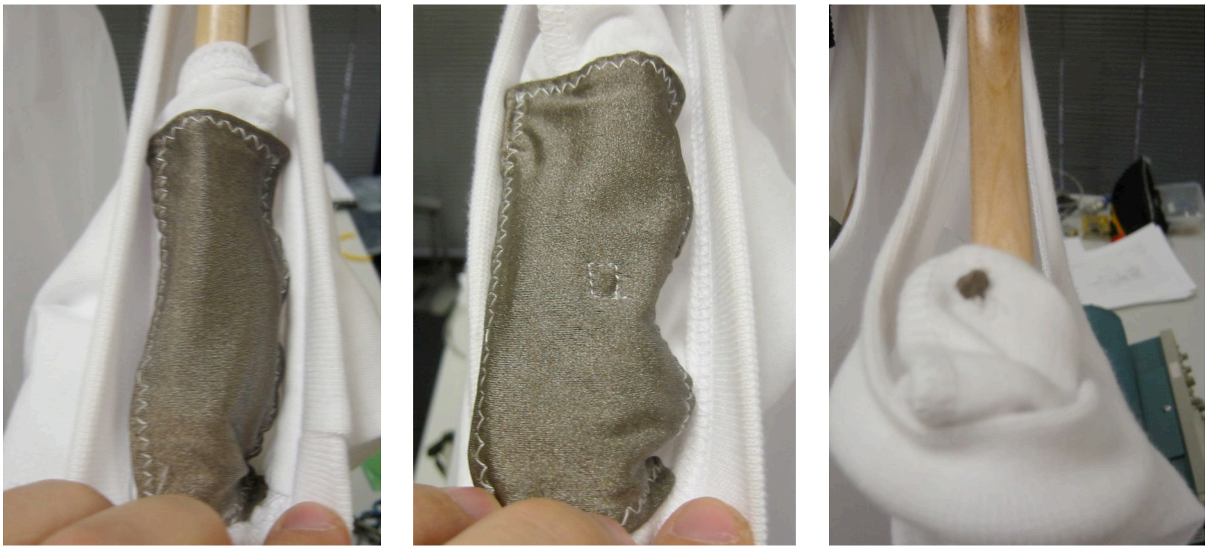
The current hangers used thin metal for the spring-loaded portions of their head. During insertion searching, sorting, and compacting of the wardrobe, hangers are slid from side to side and rotated. This motion caused the metal to slightly bend over time, increasing the system failure rate. Reinforcing the spring-loaded portion of the Smart Hanger design should eliminate this problem in the future, and heavily improve on reliability and mechanical robustness of the current hanger model. There is also a settling time after any hanger motion where bus reliability is variable. As a result, insertions in our study required a varying length of time to be recognized. The longest time required to reliably recognize an insertion, which should give an initial estimate of desired settling time for the tested hanger design, was 9 seconds. Most insertions were recognized within 1 to 2 seconds. Increasing the contact pad size and the spring force in revisions of the current hanger design should help reduce the settling times.

6.5.7 Modifying smart clothing to work with smart hangers

Testing the smart hangers and building a demonstration SGMS necessitated the design and constructs several smart garments. As a result of this process, and from observing and interviewing the subjects in the hanger evaluation trial, several observations were made that will influence future designs and run counter to initial expectations.

6.5.7.1 Magnetic contacts

The patches of conductive fabric in the shoulders of the garments rely on garment weight to provide contact force between the conductive material and the hanger contact. Garment integrated magnets may provide this contact force, ensuring a minimum level of contact force, and improving the hanger-garment electrical contact. Both Lucy Dunne and Ross Smith independently suggested this technique to me. Having a magnet in the insert and a small piece of ferrous metal integrated into the garment, or the reverse, aligns and presses together the two fabric electrical contacts, and ensures a minimum contact force.



Shoulder Contact Magnetic Contact With Magnet 'Button' Magnetic Contact

Figure 57 Magnetic Garment Contacts

After inquiring about the reason for purchasing the magnets, Mr. Smith was first to suggest the use of magnets to align and enforce the garment to hanger electrical contact. Later Miss Dunne, who visited the WCL as part of a collaboration researching garment integration, independently suggested a similar use for magnets in hanger mounting. Miss Dunne created the prototypes pictured in Figure 57 that demonstrate a conductive cloth contact, a cloth contact reinforced with a magnet, and a 'button' contact.

The prototypes pictured in Figure 57, were only used for mechanically testing the use of magnets. The use of magnets was independently tested in a smart garment constructed by the author, pictured in Figure 56. The small square of stitches visible in the figure originally held a magnet in place. After informal testing where the magnet negatively influenced how the garment would hang on the garment, and the realization about garment weight discussed in 6.5.7.2, the magnets were removed prior to conducting the small trial of the smart hangers discussed in Section 6.5.5.

6.5.7.2 Garment Weight

Iinitially it was believed that the hang weight of lighter garments would be insufficient to cause reliable electrical contact between the garment and the hanger, and that as a result smart hangers would not be suited for storing single layer smart garments like t-shirts or the western business shirts. As prototype development progressed it became clear that compared with the resistance of the data bus, variations in the resistance in the hanger to garment connection was a negligible. The hanging weights of the light prototype t-shirts proved sufficient to provide reliable contact between the garment's and the hanger's pads.

Figure 58 Strip shoulder contact
Image Credit: Leah Buechley, University of Colorado at Boulder’s Craft Technology

6.5.7.3 Pads orientation

The initial smart garment prototypes all used shoulder-to-hanger contacts. In the garments, the contacts were formed from conductive fabric strips running laterally along the user's shoulder. This arrangement aligned the contact pad parallel to the hanger’s contact, providing the maximum inter-pad connection area. The pads shown in Figure 56 and Figure 57 are examples of a parallel pad configuration. This configuration has the drawback that it requires relatively wide and long tags to ensure alignment with the hanger.

After experimenting with a number of prototype garments a perpendicular pad orientation, running over the wearer's shoulder front to back, proved much easier to align with the hanger. Overall, contact area between the connection pads is reduced, but the resulting connection is much less sensitive to how the garment is hanging on the hanger. Further, perpendicular connections can be used with strapped garments such as women’s dresses and gowns. The smart garment shown in Figure 47 was charged by hanging it on a special smart hanger. The garment used a perpendicular contact orientation; it is shown turned inside out in Figure 58. The configuration shown in Figure 58 was able to carry 100mA of charging current, sourced at 3.7V, to recharge the Li+ batteries integrated into the prototype.

6.5.8 Future improvements to smart hanger design

My collaboration with Mr. Marais explored a number of different smart hanger designs and resulted in the construction of a dozen different prototype hangers. As a result of this process, and observing and interviewing the subjects in the hanger evaluation trial, several important improvements were identified for future development of hangers.

6.5.8.1 Finding a garment

The current version of Smart Hanger hardware demonstrated in the work of this thesis has no way of directly establishing a mapping between hangers and garments. Instead, the system gathers this functionality by watching what garments and hangers announce themselves on the systems bus, and taking advantage of the one to one mapping between hangers and garments to infer pairing. Implicit detection of the garment hanger pairing also is applicable to the "Clipped Tag" garment integrated RFID tags discussed in Section 6.1. Once a garment-hanger pairing has been established the SGMS can provide the additional functionality of helping the user find the garment from within the wardrobe.

A feature that was demonstrated by the hangers developed by Matthews et al. (Matthews, Gellerson et al. 2000) but which was lacking in the hangers developed for this thesis was the ability for an individual hanger to signal its location to the user. Intended for use as an element in an ambient display the hangers developed by Matthews et al. had an integrated LED which could be turn off or on as one of their system's display elements. Given a visible signal on the hanger, such as a blinking LED, and a known hanger to garment, mapping the SGMS can signal the user the location in the wardrobe of a particular garment. For the sighted, such a feature will help them quickly find suggested garments in a cluttered or large wardrobe. Most importantly, it removes the need for the user to keep any known ordering of garments within the system, meeting the requirement that hangers be reinserted into the wardrobe in any order (see Table 9). The relatively simple addition of an audio cue to the hangers enables audio cuing of garment location and extends the SGMS to be able to support blind and vision impaired users. An SGMS that provides hanger level audio cuing is a particularly beneficial to visually impaired users, who currently must maintain a tightly ordered wardrobe in order to be able to find desired garments quickly.

6.5.8.2 Standardized Production

The hangers constructed for this thesis were all hand built prototypes. As a result of every hanger being similar but unique, each hanger brought its own idiosyncrasies to the system and to testing. Over time, each hanger wore differently impacting mechanical reliability, requiring the system be recalibrated if another hanger was added for testing. This became problematic as the research progressed from using a single hanger to using multiple hangers simultaneously. For example moving from, say, testing three hangers, to four hangers, would require a one time careful calibration of the hanger and rods orientation. Producing hangers from mass produced identical interchangeable mechanical parts will remove the need for mechanical recalibration of the system, and should support a large number of smart hangers.

6.6 Conclusion and Contributions

This work is the first to recognize that garment integration of technology will lead to entire wardrobes of smart garments, necessitating some form of management system. The concept of smart garment management and the use of smart hangers were presented in this chapter, as a way to provide the user with a single interface for managing all of their smart garments

(Toney, Thomas et al. 2006). Instead of having many different devices to track and manage, a smart garment management system essentially turns the user's collection of clothing into a single distributed device.

A smart garment management system was developed which integrates a one-wire bus into special hangers and a closet bar, and was accompanied by a software management system. This work is the first to use intelligent hangers as a tool for managing both the power and data requirements of smart garments. By augmented hangers, a single management system can care for a wardrobe consisting of a heterogeneous mixture of conventional and smart garments. A small user study was conducted to prove the usability of the developed hangers, validating their use for building a smart garment management system. Finally, the modifications required of the smart garments, to be able to use the smart hangers, were minimal and suitable for use by both single and multiple layer garments.

7

"Benjamin Avery said he would buy me a case of beer if I used the phrase 'Anthropologically speaking' in my thesis..."
Ph.D. Student

Chapter 7 The space available to the user interface

User interfaces are emerging which extended their elements off of the screen and directly into their user's environment. Direct touch user interfaces have demonstrated using large touch sensitive display surfaces to present their interface to the user (Shen, Ryall et al. 2006) (Forlines, Wigdor et al. 2007). Alternately, graspable and tangible user interfaces have demonstrated using physical props (Fitzmaurice, Ishii et al. 1995; Fitzmaurice 1996; Small and Ishii 1997; Pierce and Stearns 1999) as part of metaphors for interacting with the computer, and abstractly mapping user interface actions and elements to physical objects or 'phicons' (Moore, Want et al. 1999). Early in my thesis work, I began to construct prototypes in order to investigate these emerging user interfaces. It quickly became apparent that there were several open questions fundamental to implementing tangible and direct touch user interfaces. Most notably the question of "What is the region of space available for use by elements of the user interface directly manipulated by the user?" remained unanswered.

As part of the overall work of this thesis, I present the idea of the deployable device context. Deployment will be formally presented in chapter Chapter 8, however briefly described deployment is the act of meaningfully placing a device or its components into the user's environment. As an example of a deployable device that we can reasonably expect to be commercially available in the near future, picture a cellular phone whose screen is detachable, magnetically backed, and contains a camera. By temporarily clipping the camera onto any ferrous surface, such as the wall of the train they are riding in, the user gains freedom over where they are looking when using the display. For video calls with this type of device it is easy to imagine situations where the more natural placement of the display near the user's eye level would lead to an increased sense of presence for the remote person in the call. Additionally by deploying the display onto a surface within sight, the user can set up a mobile ambient display (Wisneski 1999; Schmidt, Hakkila et al. 2006), where subtle changes in the display can privately signal the user with minimal accompanying social weight. As an alternative example of deployment, consider a device placed on a desk at the beginning of a meeting. As deployable devices become familiar the visible act of deployment, and the devices presence on the table, makes others aware that the device is in use. As part of deployable devices becoming more familiar, it is reasonable to expect that a common signal will develop, similar to the red recording light present on many cameras, to indicate when the device is active.

The previous deployment examples demonstrate that objects can be deployed onto convenient horizontal surfaces such as desks or tables, onto walls, or even just attached to convenient objects in the user's environment. Devices designed for use by astronauts or divers operating in zero gravity or buoyancy-neutral environments can take advantage of arbitrary deployment anywhere within reach. The common bound placed on all of these deployable contexts, however, is the volume of space that the user can easily reach. The space available for deployment, then, is contained with the user's reachable space.

Each deployment context brings with it a unique set of restrictions. For example, a person using a mobile device on a crowded train or elevator will not enjoy the same range of motion and deployment options as they would seated at a desk in an office or in an unpopulated open space. Adherence to social conventions and cultural expectations will further limit the available space. The research of this thesis only considers deployment by seated users from a western cultural context, deploying onto discovered horizontal surfaces. Under these constraints, the earlier open question about available space becomes "What areas on the horizontal working surface are available for use by elements of the user interface that are directly manipulated by the user?" Knowledge of the size and shape of available space allows the user interface designer to tailor the user interface to the target population of users. If the information required in calculating the size and shape of available space can be detected in real time then applications can be developed that make run time modifications to their presented user interface to better fit their deployed context and current users.

In order for a user interface element to be directly manipulated by the user, it must at some point lie within the user's reach. This means that a formal description of reach also provides a formal description of the maximum space available to the user interface: reachable space contains the available working area. The space that a user is comfortable consuming on a working surface on the other hand is subjective and heavily dependent on the physical and social contexts of where they are working. One of the goals of the user study presented in this chapter was to determine how suitable existing physical models of reach were to representation of the user's comfortable reach.

Models of reach, combined with observations about the physical context of the user, empower user interfaces with the ability to afford usage for their elements. For example, by guiding placement and size of user interface elements, models of reach can empower applications running in a collocated collaborative context to afford a public or private nature for its elements. Using a model of reach, the user interface can afford a shared user interface element by placing the elements in spaces reachable by multiple users. These techniques can also be used to discourage or afford perceived ownership of user interface elements by displaying the elements either within an area that is reachable by many users or only by a single user. Equations and observations about how reach can be applied to shape table segmentation and user perception presented in this chapter and in Chapter 8. These equations and observations are summarized in Appendix C.

In non-collocated collaborative applications, models of reach can help establish scaling constants for actions and data shared across displays. Non-homogenous scaling can help ensure equal representation in the collaboration, or afford dominance for one of the users, or ownership over regions on the shared working surface.

7.1 The maximum space usable by the user interface

For stationary users, or for moving users considered at some fixed time *t*, the set S_R contains all points currently reachable by the user. Models that describes S_R also describes a superset S_U (where $S_U \in S_R$), describing the set of all points currently usable by the directly manipulated elements of the user interface. Fortunately, human reach has been well studied and is commonly used in ergonomics and industrial design. Whenever you effortlessly find a handrail or a button on a dashboard in a "natural" position, you are experiencing the product of applied anthropometric models. Designers of everyday objects like buildings, cars, and appliances regularly use anthropometric models to tailor their designs to their intended user population. Standardized construction dimensions such as ceiling height or width and slope of the stairs are all driven by anthropometric models of the intended users. Similarly the width of the seat in a car, the interior height of the car, and placement of screens and gauges in a car are also all driven by anthropometric models of the intended user.

Mathematical and statistical models of human reach are ripe for use in user interface design. Detailed anthropometric descriptions of various human populations are available and provide context for applying the models. Mathematical and compiled quantitative models describing human reach under a number of common conditions are available. The work of this thesis and the earlier published works of the author (Toney and Thomas 2006; Toney and Thomas 2006; Toney and Thomas 2007) represent the first attempt to formally apply these existing resources for use in user interface design.

In restricting the usable space to a working surface the answer is further contained within the set S_{WS} of all points on the working surface. So the usable space, $S_{U,}$ is contained within the intersection of available working space with the reachable space ($S_U \in S_R \cap S_{WS}$). Given quantitative descriptions of both the working surface and a user's reach, this relationship allows programs to dynamically generate a quantitative description of their maximum potential usable space.

7.1.1 User Motion

As the user moves, they increase the range of space over which they have influence. Common actions, such as walking around a working surface or leaning over it, will increase the area reachable by the user. The reach of a moving user over a window of time can be considered to be the sum total of their reach at every moment within the designated time interval. In light of our earlier observations, the set of all points usable by the directly manipulated elements of the user interface over some window of time $(S_U \big|_{t=t_{start}}^{t=t_{stop}})$ is contained within the union of the sets of points reachable by the user during that time; $(\bigcup_{t=t_{start}}^{t=t_{stop}} S_R)$. ; $(S_U \big|_{t=t_{start}}^{t=t_{stop}} \in \bigcup_{t=t_{start}}^{t=t_{stop}} S_R)$.

7.1.2 Collocated users

For collocated collaborating users, the total space usable by the user interface elements is the union of all the individual user's uniquely usable spaces $(\bigcup S_U)$, which, as before, is contained within the union of all of the users' reachable space $(\bigcup S_R)$; that is, $\bigcup S_U \subseteq \bigcup S_R$. When collocated users collaborate, however, collaborative sub regions will form. In this context, the question addressed by this chapter can be rephrased as "What areas on the horizontal working surface are available for use by UI elements directly manipulated by more then one user?" The maximum potential communal group space for all users is given by the intersection of all users' reachable spaces, $S_G = \bigcap S_R$. Similarly, if k represents a subgroup of N collaborating users, the available collaborative space is contained within intersection of each of the reachable space for each members of the group $(S_k = \bigcap_{i \in k} S_{Ri})$. These definitions allow the application to calculate the total collaborative area for servicing N collaborating users, or to derive the collaborative areas for any of the $(N-1)!$ possible collaborating subgroups.

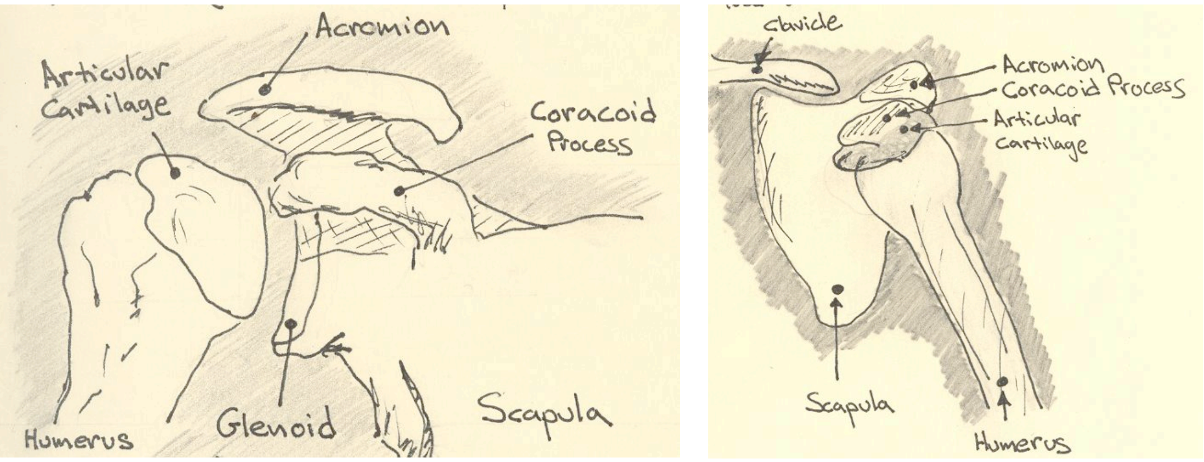
7.2 Reach

Thus far, the maximum usable space has been formally, but abstractly, defined in terms of the set S_R of all points reachable by the user. Implementation in software will require a numerical description for reachable space, in the form of data generated in real time by mathematical models of reach operating on the observed anthropometric characteristics of the user, or possibly from precompiled statistical data.

The human body is mechanically very complex. Understanding either statistical or mathematical models of reach requires an understanding of the anatomy, anthropometry, and the kinematic operations of the arm and shoulder complex.

7.2.1 Anatomy relevant to reach

The spine allows for bending and torsion in the position of the upper body. For the purposes of modeling reach it can be viewed as a long series of possible elements, the vertebrae, on which the shoulders and arms sit. Changes in the pose of the spine alter the shoulders' range of motion and hence the reachable space. The models of reach presented in this thesis all operate relative to the position of the shoulder complexes of the given users. This position can be observed directly, through video scene analysis, or estimated.



Right Shoulder shown Left shoulder shown

Figure 59 Anatomy of the Shoulder Complex

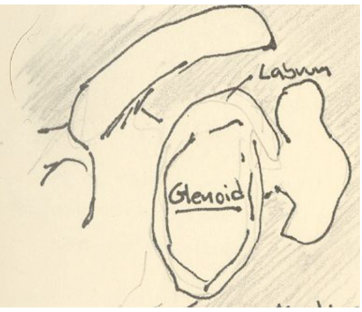


Figure 60 Anatomy of the Shoulder Complex – Looking “into” the shoulder socket

The models presented in this thesis use the acromion as the landmark for shoulder rotation. The acromion, shown in Figure 59, is a bony feature of the scapula that caps the shoulder. The Acromion and Coracoid process can be seen in Figure 59 and Figure 60 wrapping around the head of the Humerus, forming a ball and socket like joint lined by the Glenoid, the Glenoid-Humeral joint. The acromion sits at the midpoint of three joints; the joints in question are the Glenoid-Humeral, Acromion-Coracoid, and Scapula-Clavicle joints, which together determine shoulder motion. Since the acromion is a bony feature, and is near the center of rotation for the shoulder, it is both visible for video analysis (Henriques and Crawford 2001) and can be physically appreciated when measuring subjects anthropometric parameters.

To estimate the height of the shoulder complex for a seated user, the models presented in this thesis use the height of the seat pan plus the distance from shoulder to hip. This height is then offset by the thickness of the ‘glutes’, or the distance from the hip to the chair pan. The curved segments of the spine are treated as a straight-line segment with a fixed distance from the L5 vertebra to the midpoint of the line between the two acromia, just below the T1 vertebra. The seated shoulder height of users was measured for the user study presented in this chapter in order to remove errors arising from poor estimation of shoulder height. The seated shoulder height measures the distance from the acromion landmark to the ground while the user is seated.

Moving or twisting the torso is a relatively expensive way to extend reach in comparison with moving the arms. Absent a reason to explicitly move the torso, such as reduced range of motion due to injury or age, humans strongly prefer to extend their arms to extend their reach. For the purposes of ergonomic and industrial design, the typical definition for the maximum workspace reflects this and is typically defined as “the distance that can be reached by the fully extended arm as it pivots about the shoulder.“ (Sengupta and Das 2000). The models of reach presented in this thesis use the torso to describe the position of the shoulder complex and focus on the motion of the shoulder complex in describing reach.

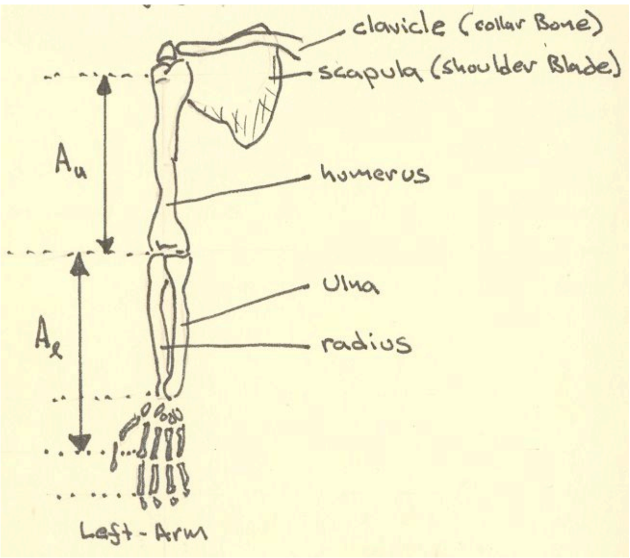


Figure 61 Anatomy of the Arm

The arm is composed of three bones; the humerus bone forms the upper arm and the ulna and radius bones form the lower arm. Figure 61 shows a rear view of the bones in the left arm. The models developed in this thesis use the shoulder-to-elbow distance in determining the length of the upper arm. The acromion-radiale length, the distance between the acromion landmark in the shoulder and the radiale landmark on the right elbow, was used to measure the shoulder-to-elbow distance. The radiale landmark is used due to its being close to the center of the elbow, and the models need to predict the center of joint motion within the elbow. The olecranon landmark sits on the bottom of the elbow and is thus less desirable for modeling a center point of rotation. When applying anthropometric data to build models of reach, care needs to be taken in order to ensure that the correct measures are used: the acromion-olecranon distance is the source for many figures of shoulder-elbow length.

The forearm length is measured from the elbow to the wrist. The terms “elbow” and “wrist” also lack the specificity required for a software implementation; this work uses the radiale-stylion distance, the distance between the radiale landmark on the elbow and the stylion landmark on the wrist. Since the hand is composed of many independent bones, there is no convenient bone-relative landmark for use in determining the midpoint of the palm. Donelson and Gordon, in compiling the U.S. Marine Corps anthropometric database and its supplements (Donelson and Gordon 1996; Paquette, Gordon et al. 1997), used the perpendicular distance from the base of the middle finger (digit three) to the first wrist crease. Using this definition for palm length allows using the Marine Corps anthropometric database as a source of data on palm length.

7.2.2 Anthropometry and obtaining anthropometric data

Anatomy describes the structures of the body while anthropometry is the study of the size and proportions of those structures. Readers wishing to continue the work of this thesis will require anthropometric data for the users to which their applications can tailor their user interfaces. This anthropometric data is either directly observable characteristics of the current set of users, or statistically derived characteristics for the intended target user population. There are many sources of anthropometric data targeting different populations. NASA’s Man-Systems Integration Standards (NASA 1995), and the U.S. Marine Corps Anthropometric database and its supplements (Donelson and Gordon 1996; Paquette, Gordon et al. 1997) were used to provide anthropometric dimensions for this work. Both sources are freely available and provide extensive anthropometric data. It should be noted that this data was compiled to describe soldiers and astronauts, and is only statistically representative of measurements for the 5th through the 95th percentile of the population of the United States.

The physical artifacts of our everyday lives, like tables and counters, are all sized to fit the majority of the population. Users that are at the extremes of anthropometric ranges, or users with medical conditions that limit their mobility, are typically poorly matched to their available working surfaces. As mobile users, they bring with them additional design concerns. While the techniques discussed in this thesis are a useful starting point for building more inclusive applications, the implementation of special needs user interfaces is beyond the scope of the work of this thesis.

7.3 Modeling of Reach

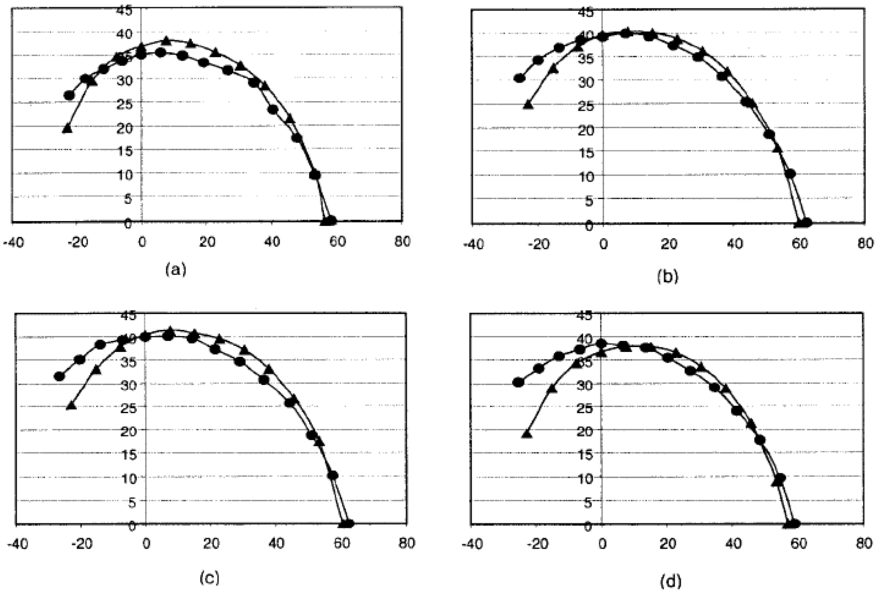
Broadly speaking, there are two methods for modeling reach: statistical modeling, and derived mathematical models. The models presented in this chapter provide only a binary measure of the “reachability” of space, describing a space as either reachable or not. Models of reach that predict the “reachability” of space with a higher degree of granularity are discussed in Chapter 8.

Statistical models work by assembling a large number of controlled experimental observations of subjects, and using that assembly of observations to represent the reach of a target population. They only describe the reach under conditions similar to the study, and only for members of a population representative of the deriving study’s users. By comparing the anthropometric characteristics of the user with the compiled observations from earlier studies, the reach of the user can be approximated. Mathematical models attempt to provide an equation that uses the anthropometric characteristics and physical context of the user to estimate reach. Where statistical models use a lookup table approach to estimate the user’s reach, algorithmic application of parameterized closed-form mathematical models can compute a predicted reach at runtime. Although very different, both approaches are fortunately well suited for software implementation.

None of the models of reach discussed within this thesis are kinematics or inverse kinematics models describing reach or reachability. Inverse kinematics treats the body as a system of mechanical linkages under motion constraints in order to derive range-of-motion constraints. Kinematic models of reach have the potential to be very accurate. Unfortunately, however, even the simplest kinematic reach models (Klopčar, Tomšič et al. 2007) require large numbers of interdependent variables to account for the motion of each major joint and bone. As a result of their complexity, they are neither simple nor intuitive for the applications developer to apply. Their complexity also makes solving them in real-time computationally expensive and hence they are ill suited for driving the user interface in lightweight mobile devices.

7.3.1 Statistical Models

In “Maximum reach envelope for the seated and standing male and female for industrial workspace design” (Wang, Das et al. 1999; Sengupta and Das 2000), Sengupta presents the results of their user study measuring reach for seated and standing industrial workstation users. The presented material is an excellent presentation for anyone wishing to implement the techniques presented within this thesis. In addition to detailed survey of previous work on describing the reach envelope, Sengupta and Das provide tables of their data for the 5th, 50th, and 95th percentile maximum reach envelopes. They also provide data describing the reachable space for both seated and standing individuals of both genders measured at 0, 15, 30, 45, and 60 cm above the working surface. This paper also recaps the work of Faulkner (Faulkner and Day 1970), who performed another significant measurement of the reach envelope. Figure 62 shows a comparison of Sengupta et. al. (Wang, Das et al. 1999; Sengupta and Das 2000) made between their and Faulkner's (Faulkner and Day 1970) results.



(a) (b) (c) (d)

●Sengupta & Das(2000) (Wang, Das et al. 1999; Sengupta and Das 2000) and ▲Faulkner & Day(1970) (Faulkner and Day 1970)

Figure 62 Reach envelope measured at (a)0, (b)15, (c)45, and (d)60 centimeters above the working surface

7.3.2 Mathematical Models

The simplest model for the envelope of maximum reach is a mathematical model, the Zone of Convenient Reach (ZCR), sometimes also referred to as the Zone of Comfortable Reach. The model is hemispherical, assuming the maximum reach is a hemisphere formed at an extended arm's length from the fixed rotation point of the shoulder. Reachable space for the ZCR is considered to be a hemisphere $(|P_{\{x,y,z\}} - S_{\{x,y,z\}}| < R)$ centered on the shoulder at point $(S_{\{x,y,z\}})$ with a radius less then the extended arm length (R).

7.4 Trial studies

This thesis and the other works of the author (Toney and Thomas 2006; Toney and Thomas 2006; Toney and Thomas 2007) are the first to suggest applying reach in dynamic user interface design. None of the existing resources describing reach was intended to address the same task context. While statistical and mathematical models of reach are available, the models were developed for use within other disciplines. As a result, the models were often developed or compiled under a different set of operational assumptions. For example, a standard experimental procedure in the statistically compiled models immobilized the subjects with respect to the table. In Kennedy (Kennedy 1978) the subject's backs were pinned to the chair, and Sengupta et. al. (Sengupta and Das 2000) had a bar holding their subjects in place.

Existing models of reach were assembled by researchers of industrial design and ergonomics, and intended for use describing the reach of industrial workers at a workstation at which they would perform some industrial task. The physical activity of user's of a workstation varies depending on the task they are performing. Industrial tasks promote repetitive reaching, sorting, and lifting motions. The workspaces themselves have been designed in order to promote an economy of motion, presenting their entire working surface to the user while requiring they make a minimum of motion. While knowledge workers may one day use boutique applications in this type of industrial setting, currently this is a very different context from the direct touch or tangible user interfaces that are being developed.

Currently the intended users of tangible and direct touch user interfaces are working in a collaborative and social context, outside of an industrial setting. As a result, they are free to move comfortably. This expectation of free movement is particularly significant for the mobile systems discussed within this thesis. One of the goals of the user study presented in this chapter was to determine how suitable the available models of physical reach were in representing the user's comfortable reach. This required gathering previously unavailable data describing the subjective measure of the user's comfortable reach, preferred working distance from the table and preferred table height. As a result, one of the central goals of the user study presented in this chapter was to determine the impact of user motion on the maximum reach envelope.

(A) Minimum (B) Preferred (C) Maximum

Figure 63 Measured comfortable reach

It was clear from a review of the literature that a user study would be required to evaluate the impact of user motion on the reach envelope. Due to their intended industrial background previous work had left aspects of subjective user preference completely unaddressed. A series of informal trials were conducted, the results of which are presented in this chapter. These trials only tested a small number of participants, typically from 3 to five individuals, and were used solely to inform the design of the larger more formal user studies. As a result of the trials, a number of observations were made about regions of overlapping reach for collocated users and how these regions impact collaboration on the table. The collaborative aspects of reach are dealt with in Chapter 8, which is focused on 'Table Usage, Segmentation'.

Figure 64 Overlapping reach when adjacently seated

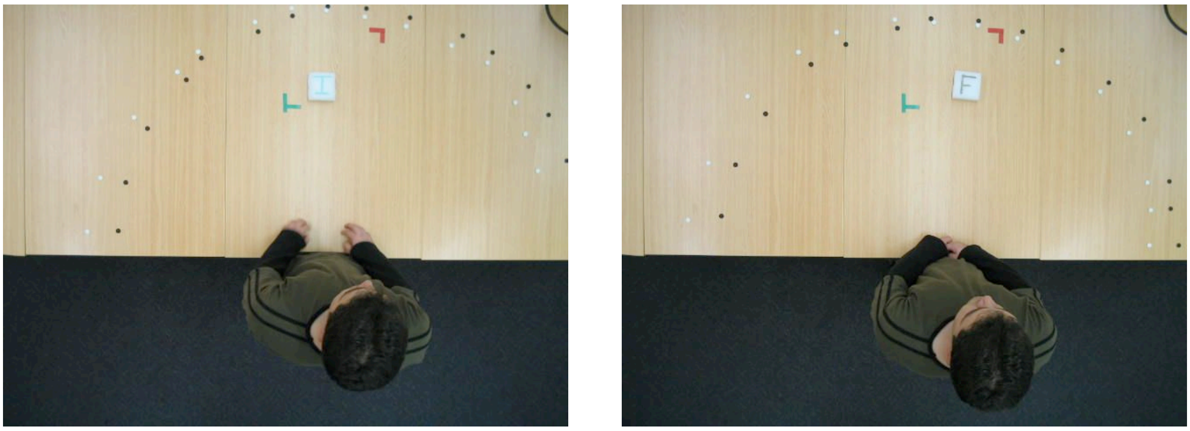
7.4.1 Minimum, preferred, and maximum comfortable reach

The first trials, pictured in Figure 63 and Figure 64, were used to establish the differences between minimum, preferred, and maximum comfortable reach. The trial also shows how reach would overlap for co-located users seated both on opposite sides of the working surface, Figure 63, and seated adjacently, Figure 64. Subjects were asked to push tiles to the extent of their minimum, preferred, and maximum comfortable reach. These tiles collectively formed arcs indicating reported maximum reach for a given comfort level. Figure 63 and Figure 64 show the reach envelopes for two individuals. In Figure 63 the black tiles were placed by the user shown in the picture, while the white tiles were placed by another user seated at the table but not shown.

As expected from our review of the literature, on-table reach formed an elliptical curve in front of the subjects. What was unexpected was that comfortable on-table reach was observed to be a shallower than expected. From the existing studies, reach was already expected to penetrate into the table a distance of 40-60 cm, depending on the size of the subject being measured. The small size of this area already limited the expected implementation of tangible and direct touch user interfaces. The existing measures of on-table reach had all either fixed the user with their torso directly in contact with the table edge, or immobilized them very near the table edge. In all of the studies of reach conducted as part of this thesis, users were observed to position their chairs such that there was a significant distance between the torso and the table edge. Distances ranging from 10 to 20 cm were common, potentially reducing the depth of on-table reach by as much as 50%. There was surprisingly little usable area available on the table in comparison with the reachable space expected from the existing literature. The scarcity of available on-table real estate makes it important to attain an accurate description of available space, and to tailor the user interfaces to take maximal advantage of the space available.

(A) Seated Informal Reach

(B) Seated Formal Reach



(C) Standing Informal Reach

(D) Standing Formal Reach

Figure 65 The impact of formality and of seating or standing

7.4.2 Formality’s impact on seated and standing reach

The next aspects of on-table reach to be informally investigated were the impact on reach of the user being seated versus standing, and the impact of situation formality. Both the red and blue angles and the white squares shown in Figure 65 are artifacts used for aligning the camera taking the photographs, and can be ignored by the reader. Users were again asked to push tiles away from themselves, forming an arc representing the reach envelope. The users were first asked to push the tiles to what they felt would be their maximum comfortable reach, once in a formal and once in an informal situation. This task was repeated for the users both seated and standing. Examples of the reported reach envelope are depicted in Figure 65.

For both seated and standing individuals, and both formal and informal contexts, reach appeared as the expected elliptical curves on the table. While standing and formality of context changed the shape of the curve, the overall effect could be described as a “scaling up” of the seated or informal reach. This observation agreed with the available literature that "standing reach is significantly larger then seated reach" (Sengupta and Das 2000), and justified limiting the formal studies of this thesis to seated users.

Measuring the impact of a formal context on reach turned out to present a more difficult problem. The informal studies highlighted that acceptable "formal" behavior is dictated by social partners, current social context, and convention. Users asked to place the tiles as if they were in a "formal setting" all were confused and ended up requiring analogies, such as "as if you were in an important meeting or at a job interview," to clarify the meaning. In order to minimize variations in reported comfortable reach based on varying perceptions of formality, in the studies of reach presented in this chapter, subjects were instructed to report their subjective reaches as if they were in a specific formality level and environment: semi-formal to formal business meeting.

7.4.3 Torso orientation with respect to the table

Seated users frequently align their bodies towards objects and individuals in their environment other than those at the table. It is common for users seated at a table to be taking notes or typing while orienting themselves to a speaker or white board. The note-taking behavior depicted in Figure 66 is an example of this. The impact of torso orientation was informally tested using the method of placing black and white tiles used earlier. In this case black tiles represent the envelope of right handed reach and white tiles represented the left envelope of left handed reach.

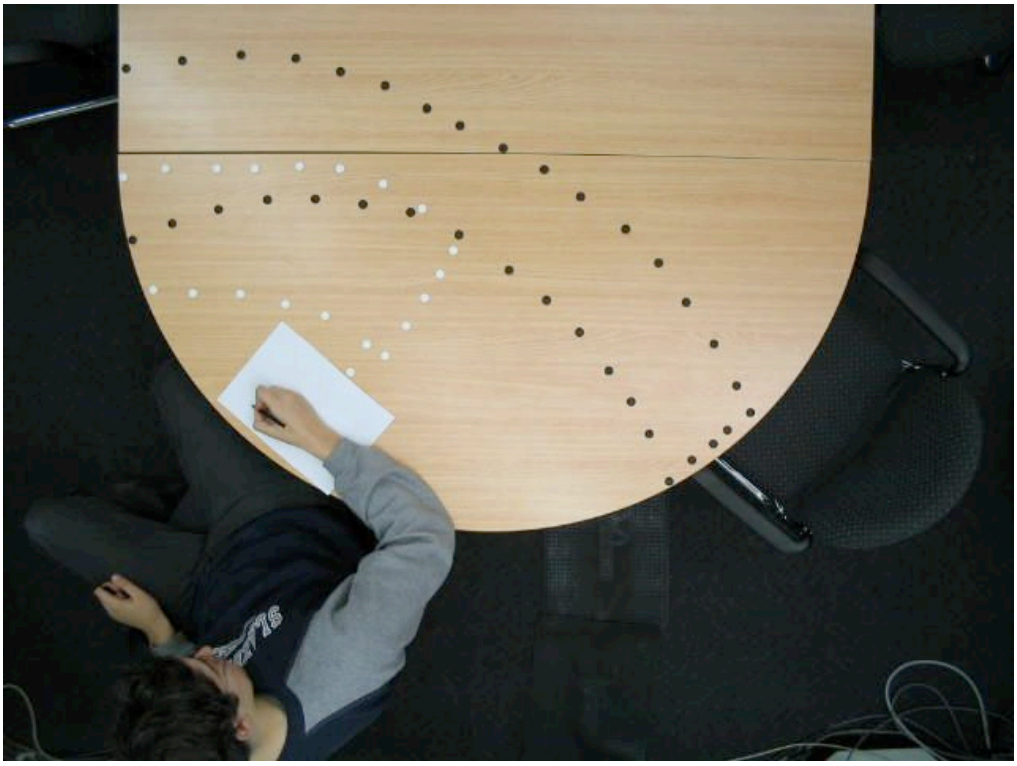


Figure 66 Torso alignment to an off table person or object.

Another unexpected attribute of on-table reach was observed in this informal trial: the torso casts "shadows" into reachable space. This effect is very visible in Figure 66 and Figure 67, where the white tiles, representing the subjects left handed reach, show a distinct maximum reach in comparison with the right handed reach, represented by the black tiles. When the torso is not aligned normal to the edge of the table in front of an individual, the hand farthest from the table has to reach across their body in order to reach the table. The farther hand has its on-table reach shadowed by the torso. Reaching into these shadowed areas requires the expensive physical operation of twisting the torso such as the adduction pictured in Figure 69. This effect of "shadowing" will likely be frequently encountered for collocated applications designed for meeting support where the group members often align themselves to focus on off table resources such as a wall display or a presenter.

In Figure 67 and Figure 68, the white tiles represent the reach of the hand farthest from the table. The white tiles clearly show an area of unreachable space on the table formed for the "far", left, hand of the pictured subject. The reachable space is constrained within a maximum and minimum adduction and abduction angles. The adduction angle represents the torso blocking rigid arm movement. Compiled resources describing these angles for various parts of the population are available (NASA 1995; Wang, Das et al. 1999).

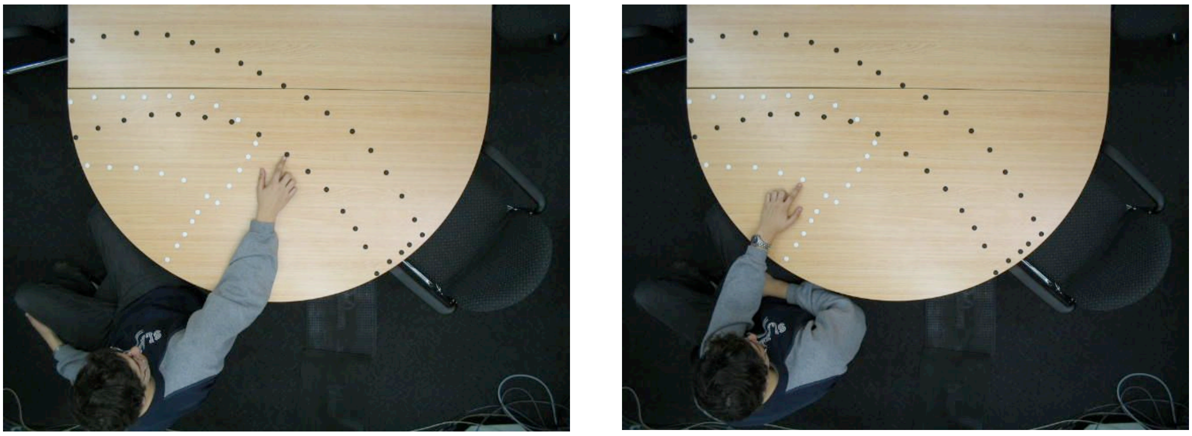
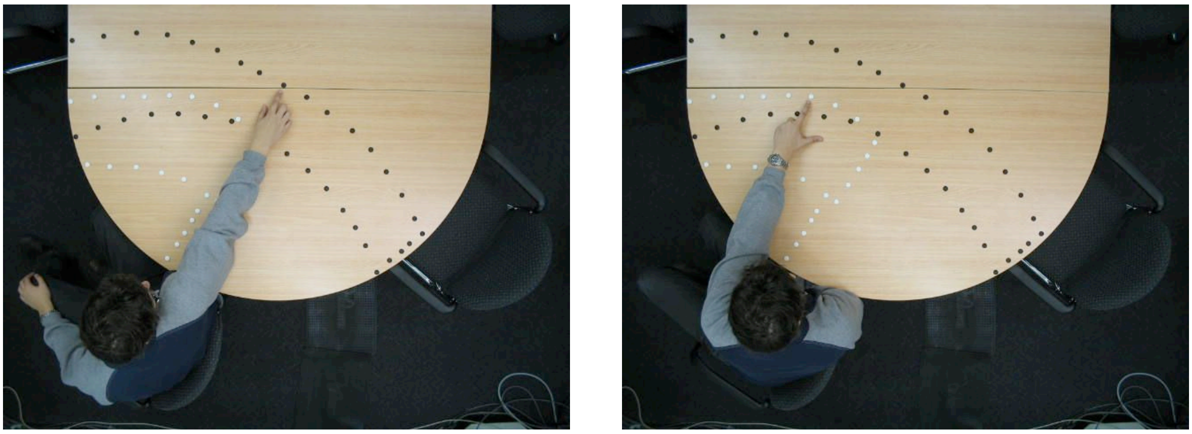


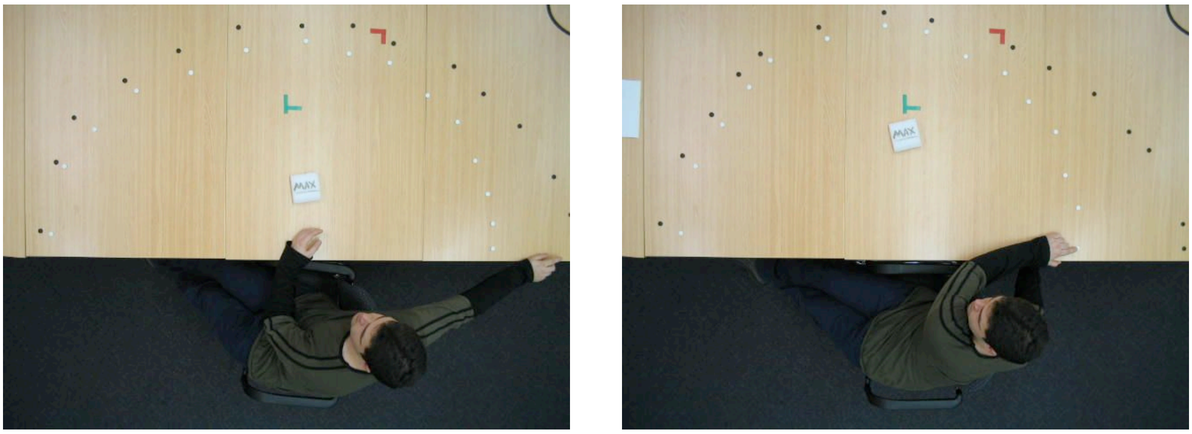
Figure 67 The impact of torso alignment on minimum comfortable reach



Abduction Adduction

Figure 68 The impact of torso alignment on maximum reach

As a result of the torso's shadowing of reach, the most reachable space on the table is significantly decreased. Areas of unreachable space can be expected for users with any of the wide variety of common mobility impairments such as age-related loss of motion, arthritis, or sports injuries. These observations indicate that the design of on-table tangible and direct touch user interfaces will need to be conscious of the specific mobility constraints impacting their users. This will be especially important for applications that are used by older members of the population, as flexibility and range of motion decrease with age.



(A) Abduction (B) Adduction

Figure 69 Off table user focus causing twisting of the torso and hips

7.5 User study: The impact of motion on reach

Existing studies of reach have all constrained the subject position with respect to the table. For example, in Faulkner and Day (Faulkner and Day 1970) the subject's chair was positioned to place their torso against the edge of the table. Sengupta and Das (Sengupta and Das 2000) used a bar to hold subjects' torsos 2.5 cm from the table edge. What was missing from the literature was a measure of the impact of user motion on maximum reach. This chapter presents a study run by the authors to gather data on the user's self-reported minimum, comfortable, and maximum working reach.

In the study, users were allowed to move during measurement as long as they stayed firmly, but comfortably, seated. While subjects were asked to keep their backs comfortably resting on their seatback, no mechanical restraints were used as in earlier studies. The study table was height adjustable and, along with distance of the user from the table, the study also recorded the users' reported minimum, comfortable, and maximum working heights.

Twenty-one subjects were run as part of the study, recruited from the student population of the University of South Australia. The subjects used were chosen to be representative of the population as a whole in terms of both gender and handedness. Subjects were told to center their body on the indicated mid-line for the table (shown in Figure 70). No physical or verbal cues were given to help the users to "square their body" with the edge of the table. Rails on the floor kept the chair squared with the table edge and prevented the subject's chair from moving laterally. The subject was free to adjust the distance of their chair from the table edge.

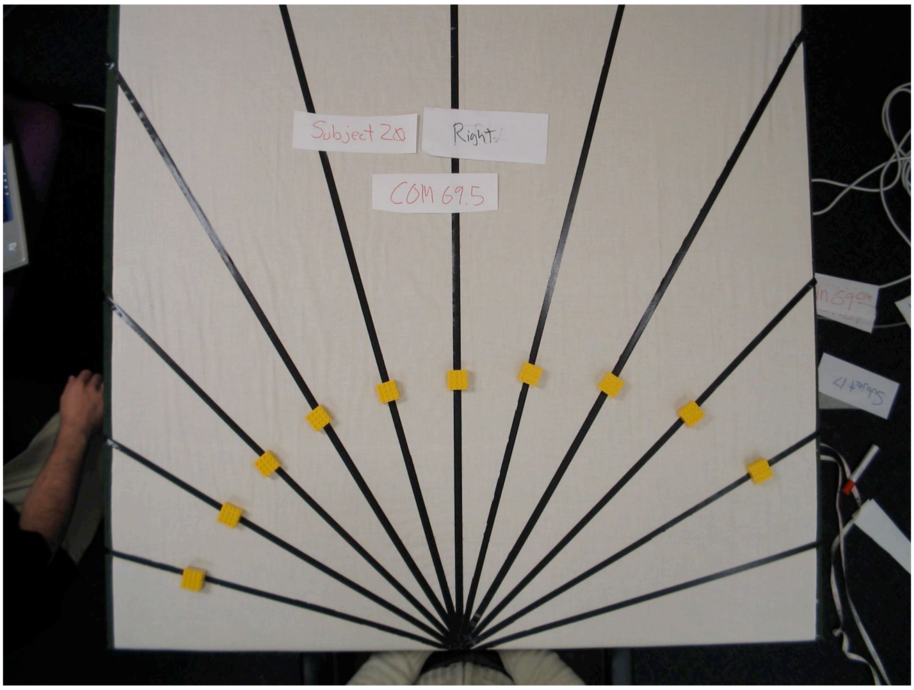


Figure 70 Measuring the on table reach

The study table was powered and height adjustable, enabling users to easily alter the table height. The table was initially set to its maximum adjustable height of 73.5 cm, which represented the maximum working height for the study. Subjects were asked to seat themselves at a comfortable working distance from the table at this height. Subjects were then asked to adjust the table height to two different subjective table heights. First, what they felt was their minimum comfortable workable height, and then to their ideal working height. Subjects were instructed to select heights assuming they would be performing a task working with a large number of physical elements, such as assembling a puzzle or model.

7.5.1 Table Height

The average reported comfortable working height was 68 cm, with a standard deviation of 1.83 cm. The height of the seat pan for the chair used in the study was 42 cm. In ergonomics and industrial design, the ideal working plane is placed at the height of the elbow measured with the arm hanging freely and the body in a relaxed posture. The ideal working plane for a subject was predicted to be the seat pan height, plus their torso height, minus their shoulder to elbow distance. Using this definition, the average ideal table height predicted across all users was 60.46 cm. Reported comfortable shoulder height deviated from this globally predicted height by a mean of 7.55 cm (8%). Reported comfortable reach for individual users deviated from that predicted by shoulder to elbow distance by an average of 4.72 cm. The reported mean minimum workable table height of 62.5 cm, with a standard deviation of 5.05 cm.

7.5.2 Distance from the table

The observed distance from the table across the 21 subjects ran ranged from 10.5 cm to 23 cm from the table. The average distance from the table was 17.07 cm with a standard deviation of 3.28 cm. To place this distance in context, when corrected to account for our observed average comfortable working distance, the results reported by Sengupta (Sengupta and Das

2000) show on-table reach to be an extremely shallow phenomenon. At a working depth of 17 cm from the table edge, seated-maximum-reach will penetrate the ideal working plane only 42 cm (male) and 38 cm (female) for the 95th percentile population, and 24 cm (male) and 20.1 cm (female) for the 5th percentile of the population.

The practical implications for user interfaces that are not scaled to fit their current user are that over 95% of users will either be unable to reach, or will have to move and stretch to reach, user interface elements that are more then 38–42 cm from the table edge. If a user interface element needs to be reachable by over 95% of the population (represented in the study) it needs to be placed within ~20 cm of the table edge. These are maximum derived distances measured on the sagittal plane of the users body. The distances decrease with distance from the sagittal plane of the user's body.

7.5.3 Maximum Observed On-Table Reach

As was expected from the trials and from the literature, reach was observed to have a symmetrical elliptical nature. Sengupta's research predicted shallow subject reach. The reach observed in the study exhibited the predicted shallowness, with mean reaches of 45–48 centimeters across conditions. Figure 71 shows the average of left and right handed reach observed in the study. The observed reach was shallow as expected, but slightly greater then the data predicted from a correction of Sengupta's results.

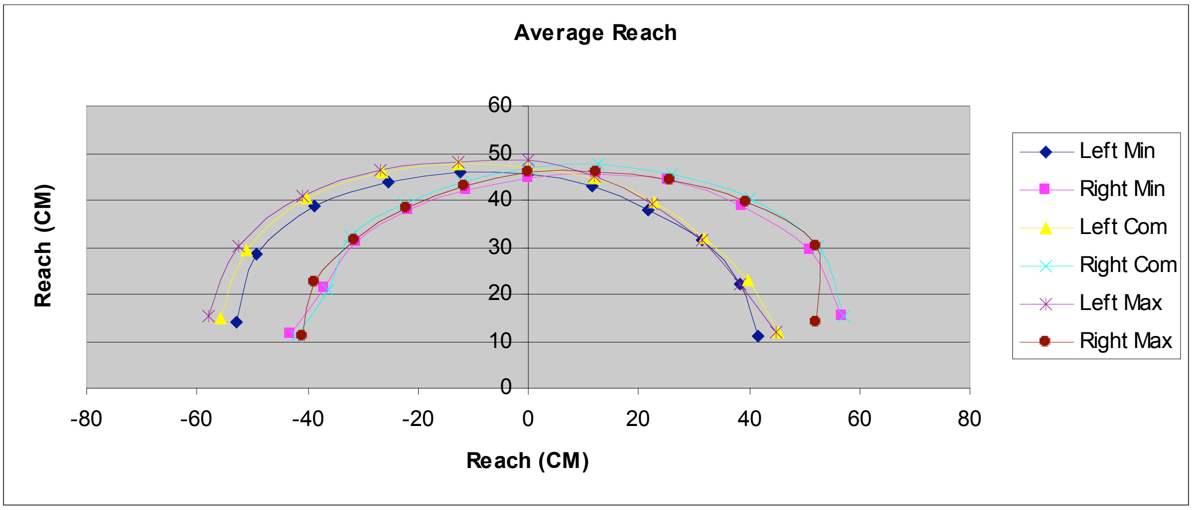


Figure 71 Average Observed Reach

The standard deviation of reach depth versus angle is illustrated in Figure 72. This figure, when compared with Figure 71, shows that within a 120 degree wedge in front of the user reach is largely independent of table height, while variation in reach depth for the left or right hand, within the 30 degree wedge closest to the hand in question, varies noticeably with table height.

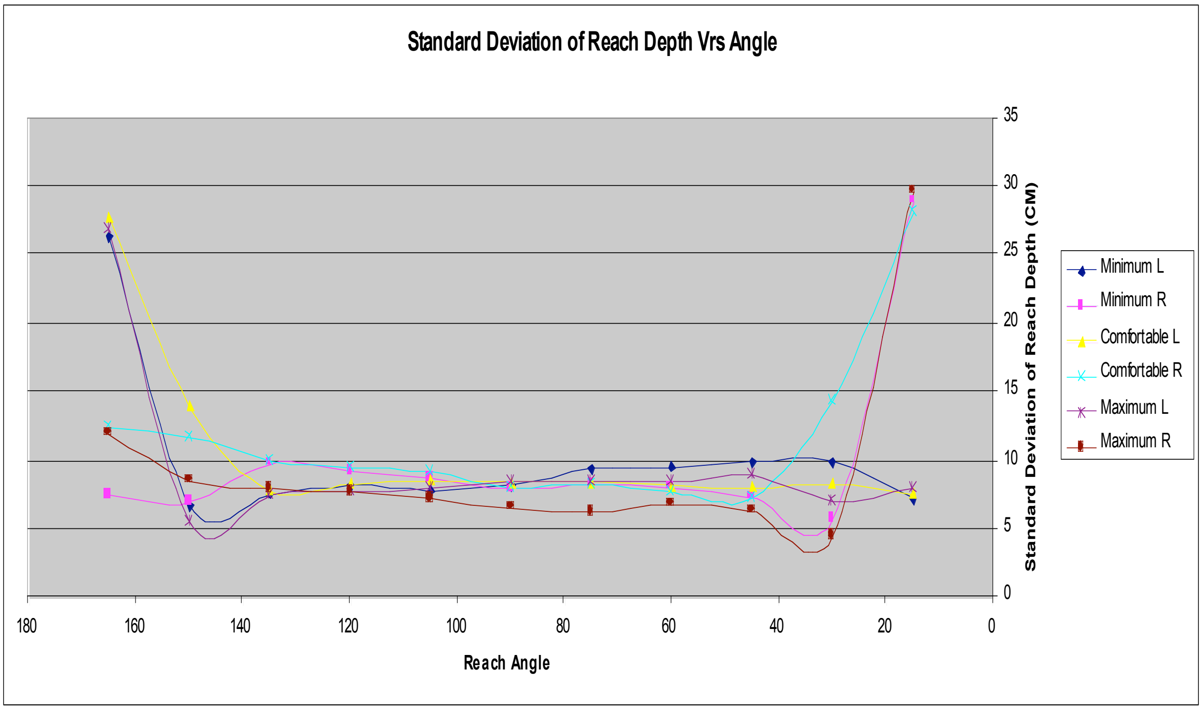


Figure 72 Angular accuracy of the ZCR model

7.6 Selecting a Model

Selecting a type of reach model for use in implementing an application responsive to its users' reachable space has ramifications. The type of model selected determines when and how the model can be accurately applied.

7.6.1 Statistical models

While statistical models have the potential to be very accurate, they require previously recorded representative data. Since models of reach are built from data gathered about specific target populations, they are only as accurate as the target populations are representative of the current user. For the model data to be gathered, the experimental conditions under which the data was gathered must also be representative of the physical context under which the models will be applied. This condition requires foreknowledge of the type of conditions under which the user will be using an application. For applications servicing mobile users, detailed knowledge of the application environment may not be possible.

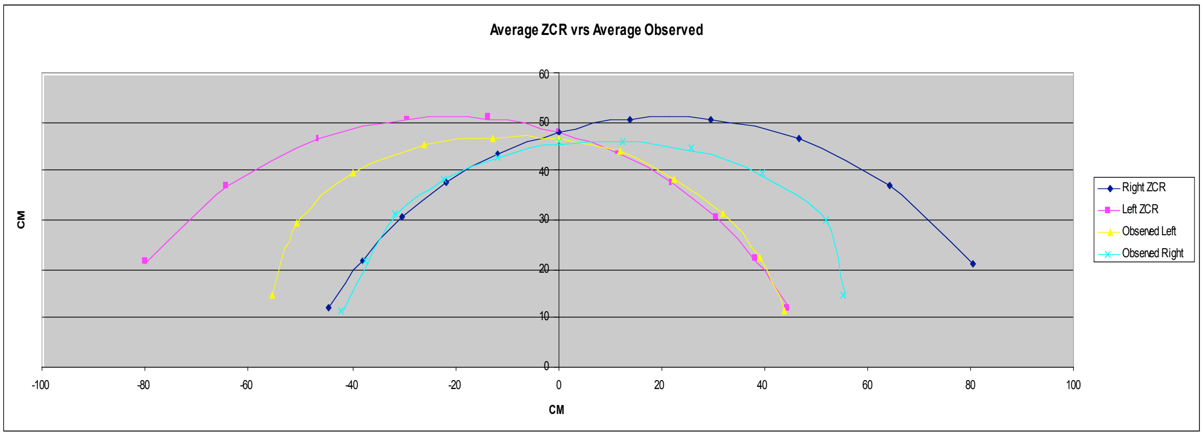


Figure 73 Average ZCR versus Average Observed Reach

7.6.2 The ZCR model

Figure 73 shows the average observed reach for all of the subjects compared with the average expected research calculated by the ZCR. The figure illustrates that, when reaching across the body, the ZCR provides a close approximation for reach between the sagittal and medial planes. In other words, the ZCR model is most accurate when predicting the reach across the body (i.e. reaching to the left with the right hand or to the right with the left hand). The figure also illustrates that the ZCR model is a poor approximation of reach depth when not reaching across the body.

For a given posture, the reachable space (S_R) is by definition the total space reachable by either hand ($A_L \cup A_R$). Similarly, the intersection of the left-handed reach (A_L) with the right-handed reach (A_R) provides the area of bimanual reach (S_{RB}), the area reachable by both hands. These regions are illustrated in Figure 73. Comparing the results expected by the ZCR model with the observed results, as in Figure 74, shows that the ZCR model provides an accurate approximation of reach across the body. These figures show the ZCR model to be accurate for use in estimating the left (A_L) and right (A_R) handed reaches for use in calculating the area of bimanual reach (S_{RB}), but not accurate for calculating the reachable space (S_R).

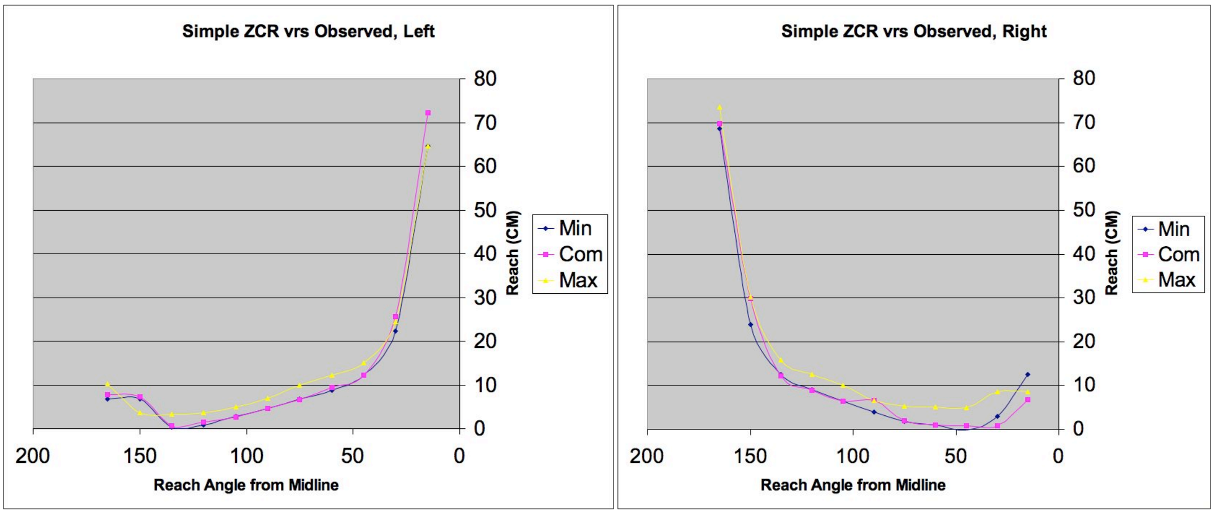


Figure 74 Depth accuracy of the ZCR model

7.7 Contributions of Applying Models of Reach in User Interface Design

Models of reach can afford usage by guiding placement and size of user interface elements. This section specifically looks at how privacy can be afforded. Models of reach can also dynamically scale a user interface to fit its current users, or predict the segmentation of available space by task for the number of users.

7.7.1 Affording Privacy and Ownership

Applications can afford privacy and ownership of user interface elements by placing the "private" or "owned" user interface elements in areas uniquely reachable by their intended user or users. Conversely a discouragement of "ownership" and "privacy" can be afforded by placing shared elements in areas reachable by the entire group of users.

For a group of collaborating users *k*, the available collaborative space is contained within the intersection of the reachable spaces for each member of the group $(\bigcap_{i\in k} S_{Ri})$. For the *n*th member of the group *k,* their uniquely reachable space, or the "private" space for the user, is their reachable space complement the rest of the group's reachable space $(S_{Rn} - (\bigcup_{i\in k, i\neq n} S_{Ri}))$.

Similar affordences can be achieved for groups of users by using the union and intersection of reachable spaces. For example, when the group of users *k* is a subset of a larger group of users, *l*, ownership of a user interface element can be afforded either to the group *k* or to one of its members. To afford ownership to a subgroup the element can be placed in the area uniquely reachable by that group: $((\bigcup_{i\in k} S_{Ri}) - (\bigcup_{j\in l, j\notin k} S_{Rj}))$. This relation also holds for the individual, as that is just a subgroup with a single member.

7.7.2 Scaling User Interfaces

For remote collaborators, models of reach provide a way to uniquely map each of the local collaborative display spaces into a common space equally accessible by all group members. In this way, when a 6'3" user moves a shared user interface element to his maximum reach, its remote counterpart, mapped onto the local display, will still be reachable by a 4'8" collaborator.

Having a description of a user's reach implicitly creates a zero-to-reach-length scale that can be applied to all interface objects. This scale can be used to gauge an object's distance from the user in order to dynamically control the user interface (Poupyrev, Billinghurst et al. 1996).

7.7.3 Predicting Table Segmentation

Reach immediately divides the table into regions, both psychological and physical. For an individual, the table is segmented into areas of reachable and unreachable space. The reachable space at the table is further subdivided into the area reachable by a single hand or by both hands. The space reachable by a single hand is further divided by the user's dexterity into dominant and non-dominant regions, reflecting regions reachable by the users dominant and non-dominant hand (e.g. a region on the left side of a left handed person would be a dominant region for that person). For users engaged in a collaborative task, the individuals regions are further subdivided to include areas of perceived mutual reach. The models of reach presented in this chapter provide a mechanism for formally describing each of the resulting regions. Chapter 8 will build on these techniques to examine how these formal models of segmentation can be used to predict higher-level user behaviors.

7.8 Summary

The goal of this chapter was to develop a way to formally describe the space available for tangible and direct touch components of the user interface. There were two questions that the work presented in this chapter sought to answer. The first question was, "What areas on the horizontal working surface are available for use by elements of the user interface which are directly manipulated by the user?" The second question was a refinement of the first within a collaborative context: "What areas on the horizontal working surface are available for use by elements of the user interface which are directly manipulated by more then one user?"

This chapter provided formal answers to both of these questions. Existing models of reach developed for use in industrial design and ergonomics were shown to provide usable descriptions of on table reach. Both statistical and mathematical models were presented.

The chapter conducted a series of informal trials and a formal user study to gauge the suitability of the existing models for application in on table user interface design. The user study examined reported comfortable reach. The study determined the impact of freedom of motion on the reported maximum comfortable reach envelope for the seated user. The results showed that the relatively simple mathematical model of reach, the ZCR model, provides a close approximation for the area of comfortable bimanual reach. The study revealed reach to be a surprisingly shallow phenomenon constrained to the edges of the table. As a result of the trial studies, reach was also observed to partially explain the territoriality and segmentation previously observed in the literature. These observations spawned the work presented in Chapter 8.

8

"I listened all day but no one said anything quotable. That does it, tomorrow I head to a humanities department."
Ph.D. Student

Chapter 8 Table Usage, Segmentation, and Deployment

Working surfaces naturally segment into regions. How and where the segments form depend on a number of variables, such as on the tasks being performed, the people present, the objects already present on the working surface, and on the size and shape of the working surface. The work of Chapter 7 provided models that formally describe the segmentation of the table into reachable and unreachable regions. This chapter applies the models presented in Chapter 7 in order to determine how the location of an interface object affords its usage.

Past work in the literature has shown trends in how people utilize available working surfaces, observing both segmentation and territoriality (Stacey D. Scott, M. Sheelagh T. Carpendale et al. 2003). This chapter presents applying models of reach to predict table segmentation, and models of overlapping reach to predict patterns of operative and social table segmentation. Being able to predict the placement and extent of these spaces enables applications to have user interfaces that predict and respond to the subjective social behavior of its users.

This chapter provides the formal introduction to deployable devices and device deployment for mobile devices. By combining the projection of a display onto the working surface with the tracking of user gestures and objects on and near the working surface, a mobile device deployed onto a flat surface can provide its users with a direct touch and tangible user interfaces. Using the techniques presented previously a deployed device is able to actively tailor the user interface it presents to the users current context and the available working surface. The ability for applications running on deployed devices to tailor their presentation in real time to their current context will be critical for deployed devices, as the available space will change with each deployment.

This chapter concludes by presenting a small study observing users of a simulated deployable device and application. A simulated deployable device was used in the study. As deployable devices are not currently commercially available, and the technology required to suitably prototype a deployable device with the desired functionality does not yet exist in a sufficiently small form factor.

8.1 Table Segmentation for Individuals

Based on a review of the literature and observations of table usage in informal trial studies, working space (S_W) was hypothesized to be primarily contained within the most easily reachable areas. Further, it was hypothesized that the most frequently used areas on the working surface will be the areas of bimanual reach (S_{RB}), while lowest usage will occur in areas reachable by only one hand (S_R - S_{RB}). Under these hypotheses, the region of bimanual reach, S_{RB} , describes the user's working space, S_W.

These hypotheses predict the previously observed table segmentation into storage and working spaces (Scott, Carpendale et al. 2003; Scott 2005), and were supported by the results of the formal user study (which is discussed in section 8.6). For a given posture, the reachable space (S_R) is, by definition, the total space reachable by the left and right hands ($A_L \cup A_R$), while an individual's bimanual reach (S_{RB}) is by definition ($A_L \cap A_R$). Under the hypothesis that the working space (S_W) is equivalent to S_{RB}, the storage space (S_S) is the relative complement of the total reachable space and the working space (S_R - S_{RB}).

8.2 Table Segmentation for Co-Located Users

For co-located users in an equal power relationship it was hypothesized that group spaces are formed in preference to personal spaces. Under this hypothesis the group space (S_G) can be described as the intersection of all users' reachable spaces ($\cap S_R$), and the co-located working space (S_W) can then be described as the reachable area that is not a group space (S_{RB} - $\cap S_R$) or (S_{RB} - S_G). These definitions also predict the observations in the literature (Scott, Carpendale et al. 2003; Scott 2005), and were confirmed by the results of the study presented in section 8.6.

8.3 Affordance of use

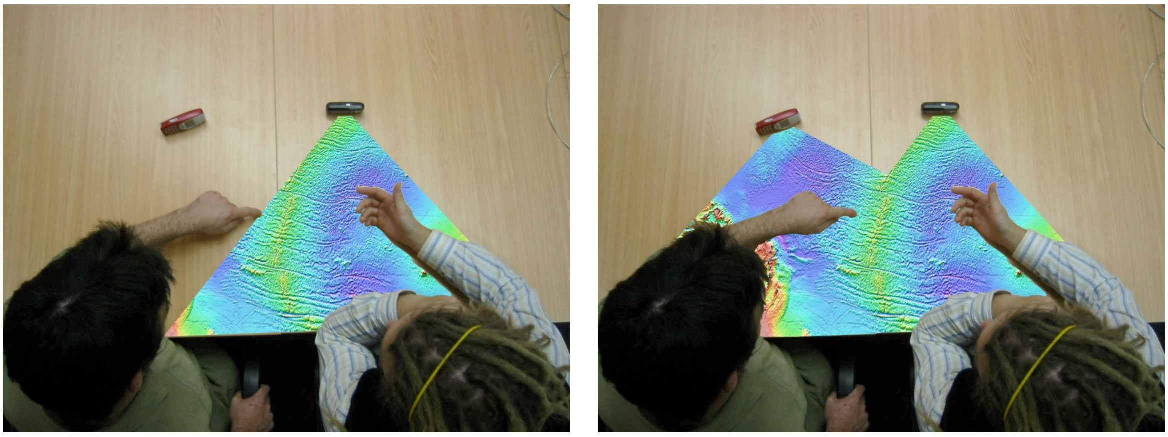
By segmenting the working surface into regions, reach automatically enforces both physical and psychological roles to elements of the user interface. One of the hypotheses presented and tested in this chapter is that the location of a user interface element affords usage and ownership. For example, user interface elements placed on the table within the group space S_G can be expected to afford collective ownership. In a like manner, the uniquely reachable areas of the display each afford ownership uniquely to one of the users. By placing a user interface element within the area S_{RB} - $\cap S_R$ uniquely reachable by a particular user, the application can afford ownership of the element. Figure 76 provides examples of how the locations of a user interface element can afford usage. The regions in Figure 76 divide the reachable space on the working surface into areas of bimanual reach, shown in red, and into areas reachable by only one hand of either user, shown in yellow and green. Under the operational hypothesis of this chapter, the areas reachable only by one hand afford use as storage areas, while areas reachable by both hands afford usage as working areas.

8.4 Deployment

Deployment is a new usage context for mobile devices, advanced in this thesis as a way to ensure a mobile user's ubiquitous computing coverage (Toney and Thomas 2006; Toney and Thomas 2007). Deployment enables a user to instrument their environment by temporarily placing, or deploying, a device into that environment. When devices are deployed overtly, the act of deployment can act as a social cue to all parties that support technology is in use. For example, a businessman using a mobile device to capture the content of a meeting might place the device on the table before him. Not only would this better position the device for the task of capturing the meeting, it also discreetly signals all other parties that recording technology is in use. In a more overt usage, the deployed device could project data or track objects immediately in front of the businessman, instrumenting his immediate environment with displays and tangible user interfaces. When the user moves on to a new environment, the deployed devices are simply collected and redeployed.

The example that introduced deployment in Chapter 7 was a next generation cellular phone that could be deployed on arbitrary surfaces. While the techniques introduced in Chapter 7 have applications to deployment onto arbitrary surfaces, in this thesis research into deployment primarily focuses on deploying onto horizontal found working surfaces. In this context, device deployment temporarily turns convenient horizontal surfaces such as counters, tables, desktops, or the hoods of cars into working surfaces.

As an example of deployment onto a horizontal surface or table, consider two businessmen meeting to plan the location of an under sea cable. Each businessman starts the meeting by deploying a device such as a next generation cellular phone. Either or both of the devices may provide a projected display, as seen in the mockup shown in Figure 75. By deploying their devices visibly onto the table, both businessmen are signaling that they are using deployable technology and potentially recording the current meeting. Recording the meeting with deployed technology provides the businessmen with an agreed version of what was said and done at their meeting. When both businessmen have deployed technology, their respective wearable devices can hand-shake during the meeting, thus ensuring that each businessman walks away from the meeting with an agreed upon, and cryptographically signed, record of what was said and done. This type of record provides both parties with a record for future reference as to what was agreed upon such as specific deliverables or quoted costs.



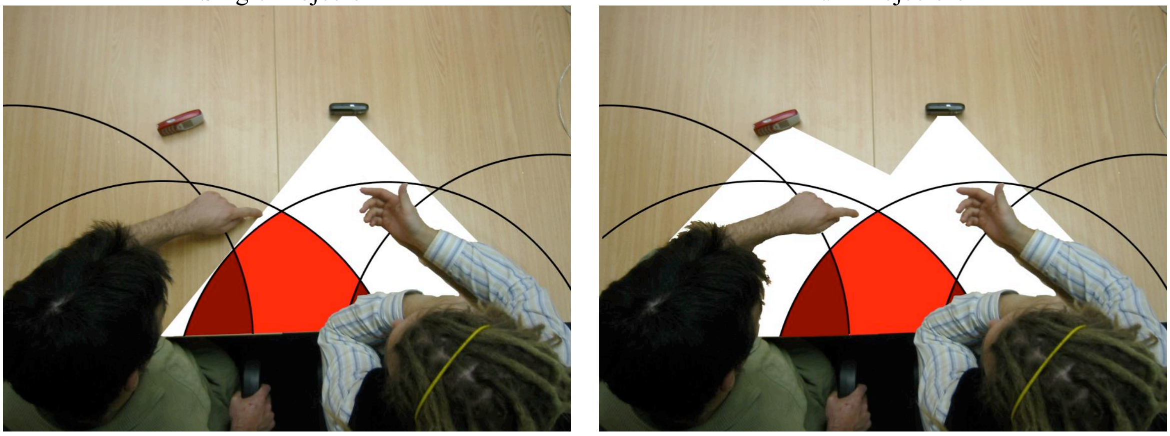
Single Projector Dual Projectors

Figure 75 Deployable devices and a projected display

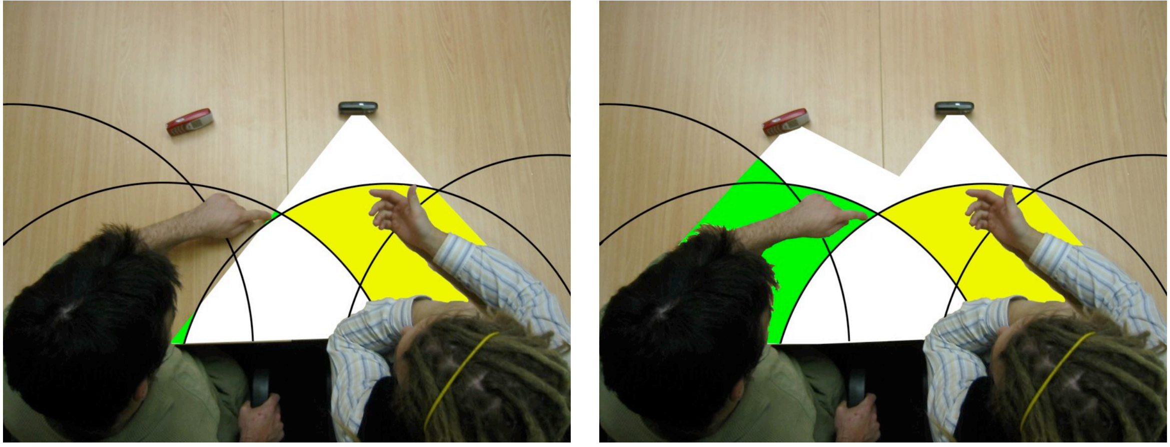
When more than a record of the events of the meeting is required, deployed devices can provide their users with tangible and direct manipulation of user interface elements. In the mocked up example depicted in the mockup shown in Figure 75, projectors integrated into the phones project a display onto the table surface; in this case, a topological map of the ocean floor. Real time processing of data from integrated cameras allows the deployed devices to gather a rich stream of data about its users and their environment. Camera data allows the deployable devices to track gestures, postures, and to gather anthropometric data about its users. During the meeting, the deployed device lets the users interact with, and annotate, their data while recording their interactions.

The gathered postural and anthropometric data allows the user interface to predict the reach of the current users. Example regions of overlapping left and right handed reach for both users of the mocked up example depicted in Figure 75 are displayed Figure 76. Four regions of predictable reach are annotated with black lines in the figures. (The annotation lines predict the reach envelope suitable for tangible user interface elements, and thus the annotations reflect grasp measured to the mid point of the palm.) An example of the comfortable left- and right-handed reach for both people in the figure is indicated with a black line. For clarity, the annotated versions of Figure 76 use a white background to replace the ocean floor.

Single Projector Dual Projectors



Bimanual Reach – Afforded Public Space



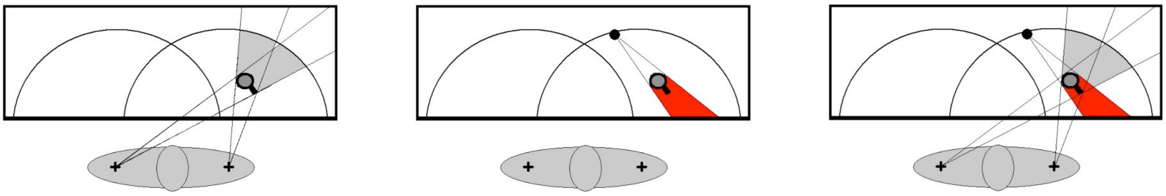
Uniquely reachable space – Afforded private or owned space

Figure 76 Collaborative Space

The red regions in Figure 76 indicate the area of overlapping reach, $S_{R_a} \cap S_{R_b}$, between two users a and b. In the figure, the left user is user a while the right user is user b. The darker red areas indicate overlapping areas of bimanual reach $(S_{RB_a} \cap S_{RB_b})$. Overlapping reach predicts the potential group space on the table (S_G). The yellow and green regions of Figure 76 represent the areas uniquely reachable by one of the collaborators. The area reachable by user a, $((S_{Ra} \bigcap S_{Rb}) \bigcap (S_{RBa}))$, is pictured in green, and for user b, $((S_{Rb} \bigcap S_{Ra}) \bigcap (S_{RBb}))$, is pictured in yellow.

8.5 Shadowing and occlusion of the working surface

Objects on the working surface consume more than just the space they physically occupy. They can cast shadows of unreachable and unobservable space. These shadows are a design concern for any type of tabletop user interface. The objects that users bring with them to the working surface, such as a coffee cup, pad of paper, or a laptop computer, will consume potentially usable space on the working surface. Shadowing of the working surface presents a particularly significant challenge for deployable systems. Devices are deployed onto found working surfaces such as counters, tables, or desks, so the working surface will be shadowed not only by the objects the user and their collaborators bring with them, but by all of the artifacts present on the discovered working surfaces. For example, when deploying onto a coffee shop or restaurant table it is common to have artifacts such as a bowl of sugar packets, a napkin dispenser, candles, and salt and pepper shakers present to obscure the working surface.



(A) Reach Occlusion

(B) Sensor and Projected display Occlusion

(C) Occluded Space

Figure 77 Shadows of unreachable space cast by objects on the working surface

Shadows cast on the working surface have four central potential consequences: (1) The user is prevented from physically accessing an area, (2) the user is prevented from viewing an area, (3) the deployed device's sensor coverage of an area is occluded, and (4) the deployed device is prevented from projecting display elements into an area. Figure 77 provides an illustrated example of how the presence of a cup located on the working surface will cast shadows impacting working space. The black disk in Figure 77 represents a deployed mobile device, the grey area is the occluded reachable space, and the red areas, sensor coverage and projected display space occluded by the cup.

8.5.1 Shadowing of collaborative regions

The shadows cast by objects present on the working surface can also impact the formation of and access to collaborative areas. The communal group spaces (S_G) were shown in Chapter 7 to be contained within the intersection of multiple users' reachable spaces $(\bigcap S_R)$. When objects cast shadows of unreachable space into these regions, they impact the potential collaborative spaces. Figure 78 depicts the shadowing example of Figure 77, extended to a collaborative context with two adjacently seated users. For two adjacently seated users, the corner of the table is the area of overlapping reach.

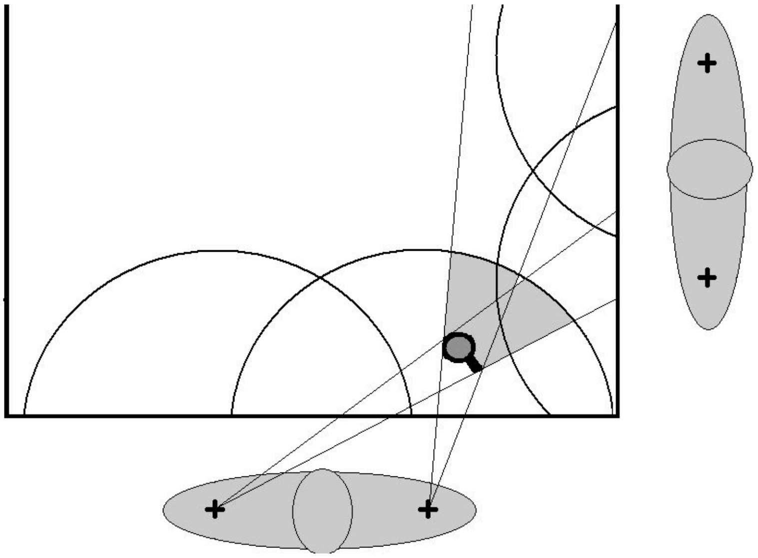
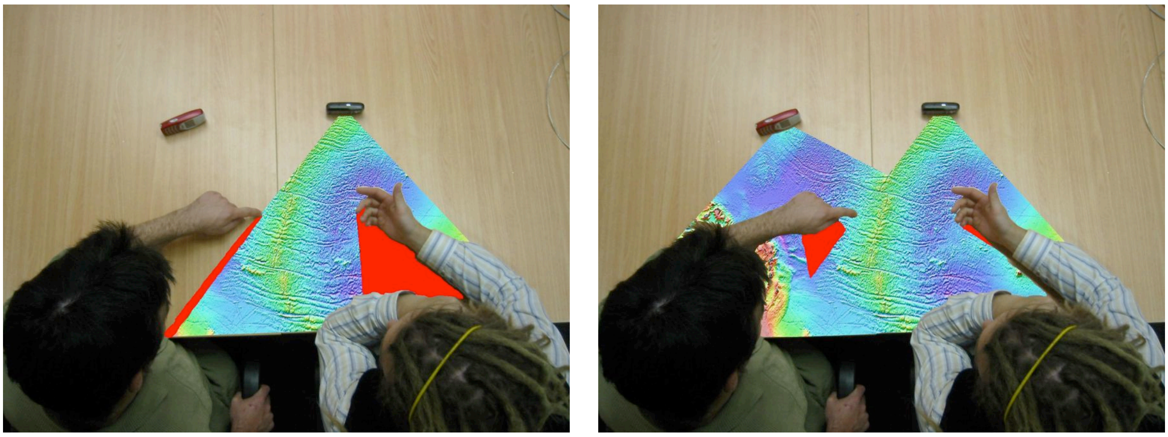


Figure 78 Shadowed reach impacting available collaborative area

By placing a cup within easy reach of his right hand, the cup's owner has significantly impacted his access to the potential collaborative space. This illustrates an important property of objects casting shadows of unreachable space; object cast different shadows of unreachable space for each user. In this example, even though the owner of the cup is no longer able to access all of the potential collaborative space, the person without the cup in Figure 78 is still free to access all of the potential group space. This strongly suggests that future development of models of table segmentation and territoriality will need to consider the presence of objects on the table.

8.5.2 Shadowing of sensors and projected displays

Occlusion caused by objects present on and near the working surface presents a problem for implementing direct touch and tangible user interfaces with deployed mobile devices. The physical nature of these types of user interfaces means that some occlusion of the working surface is unavoidable. The elements of a tangible user interface, much like the cup in Figure 77 and Figure 78, will directly occlude regions of the working surface. While direct touch user interfaces do not have physical user interface elements to occlude space on the table, they do require that their user touchable interface elements be projected on the table. When the user touches the table, interacting with a projected direct interface element, such as pressing a projected button or making an annotation gesture, the user also potentially occludes space on the table. Unintentional actions such as resting an arm on a table also occlude regions of the working surface.



Single Projector Dual Projectors

Figure 79 Shadowing and deployment

Occlusion of the table for the example of the two businessmen meeting to plan the location of an undersea cable is depicted in Figure 79. The red areas indicate regions on the table occluded by the arms and hands or the users resting on the working surface. In the example the businessman are using a direct touch user interface. The businessman on the left is gesturing onto the working surface and as a result shadowing part of the projected display. The businessman on the right is unintentionally shadowing part of the display by resting his harm on the table. The single projector panel of Figure 79 shows the occluded area where only a single device is projecting the display, and the dual projector panel of the Figure 79 shows the occluded area where two deployed devices are provide the display. The different panels in the figure illustrate how having multiple deployed devices providing the display will limit the occlusion occurring within the overlapping display areas.

8.6 A study of working plane usage and segmentation

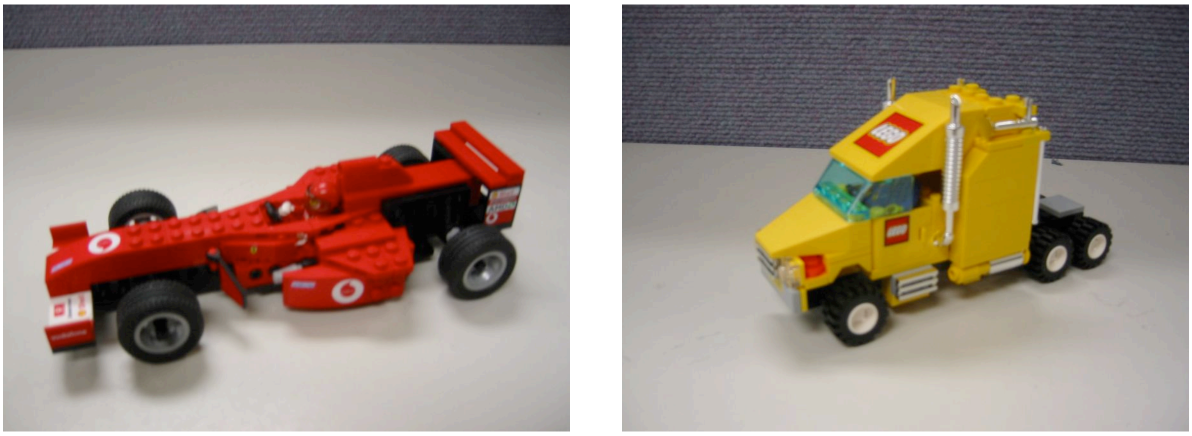
The work of this chapter builds aggregate models describing complex segmentation of the working surface from the models of left and right handed reach from Chapter 7. These aggregate models are contextualized within a deployed usage context by annotating an example of two users interacting with a deployed device. Simulating conditions similar to those in the literature, then comparing the observed results to those of the simulation established the accuracy of the models. After the predicted models were found to explain the gross table usage observed in the literature, a user study was conducted in order to perform a more accurate assessment. The user study investigated how working space is used for complex assembly and manipulation tasks.

In order to construct the study, a study task was required that was representative of the table usage expected of a deployed mobile user interface. After a review of the literature, the assembly of LEGO™ models was chosen as a task representative of complex tangible and direct touch user interfaces. The assembly of LEGO™ components was chosen in preference to mocking up a deployed user interface, as described in section 8.8. As an assembly task, LEGO™ models require significant acquisition and manipulation of tangible elements to accomplish a task. The models are also rated with a part count and recommended minimum developmental age. This allowed for the selection of several different models with a comparable number of pieces and cognitive complexity.

The primary advantage of LEGO™ as a study task, and the reason it was chosen in preference to a mocked up deployable user interface, was its affordence of real-time information about the segmentation of the table. Having the trial participants assemble a model whose pieces were worked in with a large number of distracter LEGO™ pieces forced the users to demonstrate searching and sorting behavior. Searching through the LEGO™ pieces and sorting the model pieces from the distracter pieces spreads all of the pieces out over the table. The spread out pieces quickly converge on a filled region of space on the table corresponding closely to the participant's comfortable reach. If the chosen model consists predominantly of one single color, when the user sorts out possible candidate pieces into storage regions, the storage areas will become apparent on the table as areas that are predominantly the color of the models being assembled. By including distracter pieces that are the same color as the model being assembled, the distracter pieces that are moved into the storage regions as candidates will still be visible after the model is assembled. This ensures that the search piles will still be visible for analysis after the task is completed. These visible regions, present during the LEGO™ assembly task, allowed an informed observer conducting the study to observe artifacts of table segmentation as it occurred. Since the observed artifacts are naturally present in the intended use of LEGO™, they caused minimal alteration of the subjects' behavior.

8.6.1 The trial and study task

The participants in the informal trial of LEGO™ and the users in the eventual user study were given the same assembly task. Participants were provided with a bucket of LEGO™ containing an assortment of 997 pieces of standard LEGO™ designed "for ages 4+". These were the distracter pieces for the study. Mixed in with these pieces were one of two different LEGO™ kits designed "for ages 7+". In the informal trial, testing the suitability of LEGO™ as an assembly task, all of the participants were asked to assemble the LEGO™ 1:24th scale Ferrari F1 Racer (LEGO™ Model 8362) composed of 167 pieces. For both the informal trial testing multiple subjects and the formal study, users were given either the Ferrari model or the Truck Show Semi (LEGO™ Model 10156) composed of 104 pieces. Both models are pictured in Figure 80. Each model was primarily of a single color. Duplicates of pieces used in either model were removed from the part bucket.



Model 8362 – Ferrari F1 Racer

Model 10156 – Truck

Figure 80 LEGO™ Models used in the studies.

After some negative early trial experiences, all participants and subjects were instructed that all work should be done on the table surface. They were specifically instructed not to sort pieces into jacket or shirt pockets or to rest partially assembled LEGO™ structures in their laps. After instruction, subjects were provided the official LEGO™ pictographic directions for assembling a particular LEGO™ kits. The trial participants were then given 45 minutes to assemble their model. All of the informal trial participants completed their assembly task within the allotted time.

8.6.2 The trial and study participants

All of the participants but one reported having previous experience with LEGO™. On a scale from 1 to 5, the participants self rating of their LEGO™ ability averaged 3.61 with a standard deviation of 0.59. As color was used as part of the analysis, no colorblind individuals participated in either the trial or the study. All subjects were also selected to be free of any condition limiting their reach, and to be capable of sitting comfortably for extended periods.

8.6.3 LEGO™ trial studies

A trial was run to test the hypothesized suitability of LEGO™ as an assembly task in our study of table usage. Several undergraduate subjects were observed assembling one of two different LEGO™ models. Personal, storage, and group spaces were observed during the trials, occurring in the table territories previously observed (Scott, Carpendale et al. 2003; Ryall, Florlines et al. 2004; Scott 2005).

8.6.3.1 Informal trial of LEGO™ as the study task

Two of the trial runs are depicted in Figure 81. In both cases, the sorting pile spread out, as predicted, to fill the comfortably reachable area. The region of comfortable reachable space for the user was apparent by the end of the trial in the shape and position of the search piles. All users maintained a working area immediately in front of themselves that was kept free of pieces. The trials indicated that the edge of the search pile nearest to the user would also provide an approximate edge to the users working surface. What did vary amongst the users, as can be seen in Figure 81, was the searching strategy employed by the users.

In general, two classes of searching were observed during the trials. In both cases, candidate pieces that could potentially be used in assembling the model were removed from the larger sort pile fanned out in front of the users. These pieces were placed in storage locations closer to the user. When a piece was required for assembly, users would first search the candidate storage locations for the desired piece. Failing to find the piece in a candidate storage region the users would then start searching the sorting pile looking for the desired part while extracting candidate pieces that looked like they could be used in assembling their model. Up until this point, observed participant behavior matched expected behavior.

(A) Starting:
0:00

(B) Mid way:
13:10

(C) Finished:
32:08

(C) Starting:
0:00

(D) Mid way:
16:08

(E) Finished:
32:54

Figure 81 First Informal LEGO™ Trial

Two examples from the trial studies, illustrating the different search strategies, are shown in Figure 81. While in both observed strategies the users formed a candidate searching piles, two different locations for the candidate piles were observed. In one case, users were observed forming candidate storage locations to either side of their working space. The formation of these regions, visible as the red areas in Figure 81 (F), agreed with those observed in the literature (Scott, Carpendale et al. 2003; Ryall, Florlines et al. 2004; Scott 2005). The other observed behavior had users forming a searching pile directly in front of them, between their working area and the fanned out sorting pile.

8.6.3.2 Informal LEGO™ trial with two subjects

The goal of the user studies in this chapter was to generate data about the usage of the working plane for a task representative of the type of tasks that commonly will be performed when interacting with deployable devices. The first informal trial established that segmentation was observable with LEGO™ as a study task, and that the LEGO™ storage and working regions were readily visible where predicted. Before a formal study could be conducted, the suitability of LEGO™ as a task showing table segmentation where subject's reach would overlap needed to be determined.

For the informal trial, each user's reach was calibrated using the same technique as in Chapter 7, using tiles pushed radially outward from the torso. The calibration angles for the tiles, pictured in Figure 82, were 20, 40, 60, 90, 120, 140, and 160 degrees respectively. The lines were left on the table during the trial to act as a reference in understanding where observed regions on the table formed with respect to the observed reach envelopes of the user. The table used in the trial was rectangular in order to assess the impact of non-square shapes. A rectangular table significantly impacted the right hand reach envelope for one of the participants. Measuring reach with the tiles in this manner provided the reach envelopes, as discussed earlier in Chapter 7. The measured reach envelopes for the trial are pictured in Figure 82. Nine pictures, taken at approximately 5-minute intervals during the trial, are presented in Figure 83.

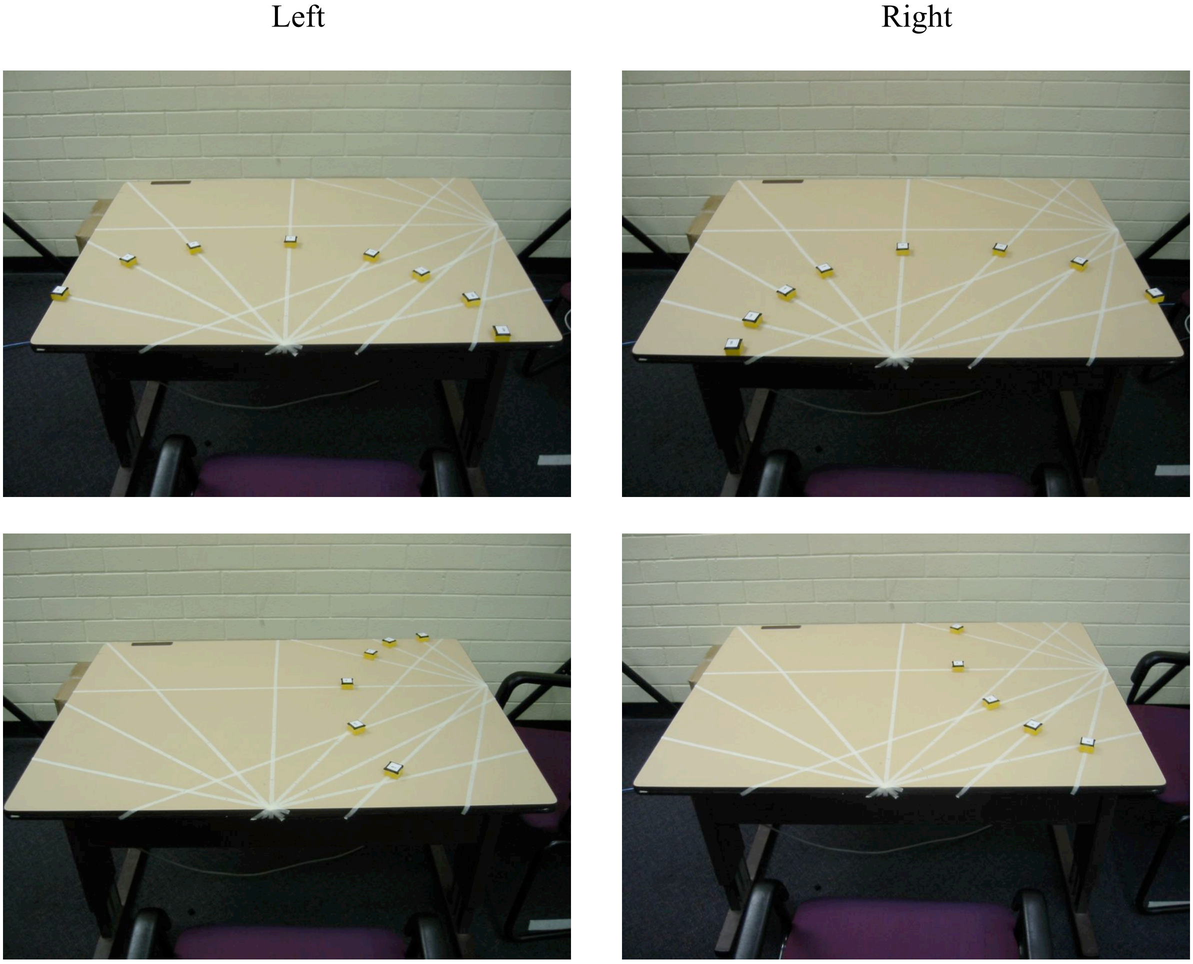
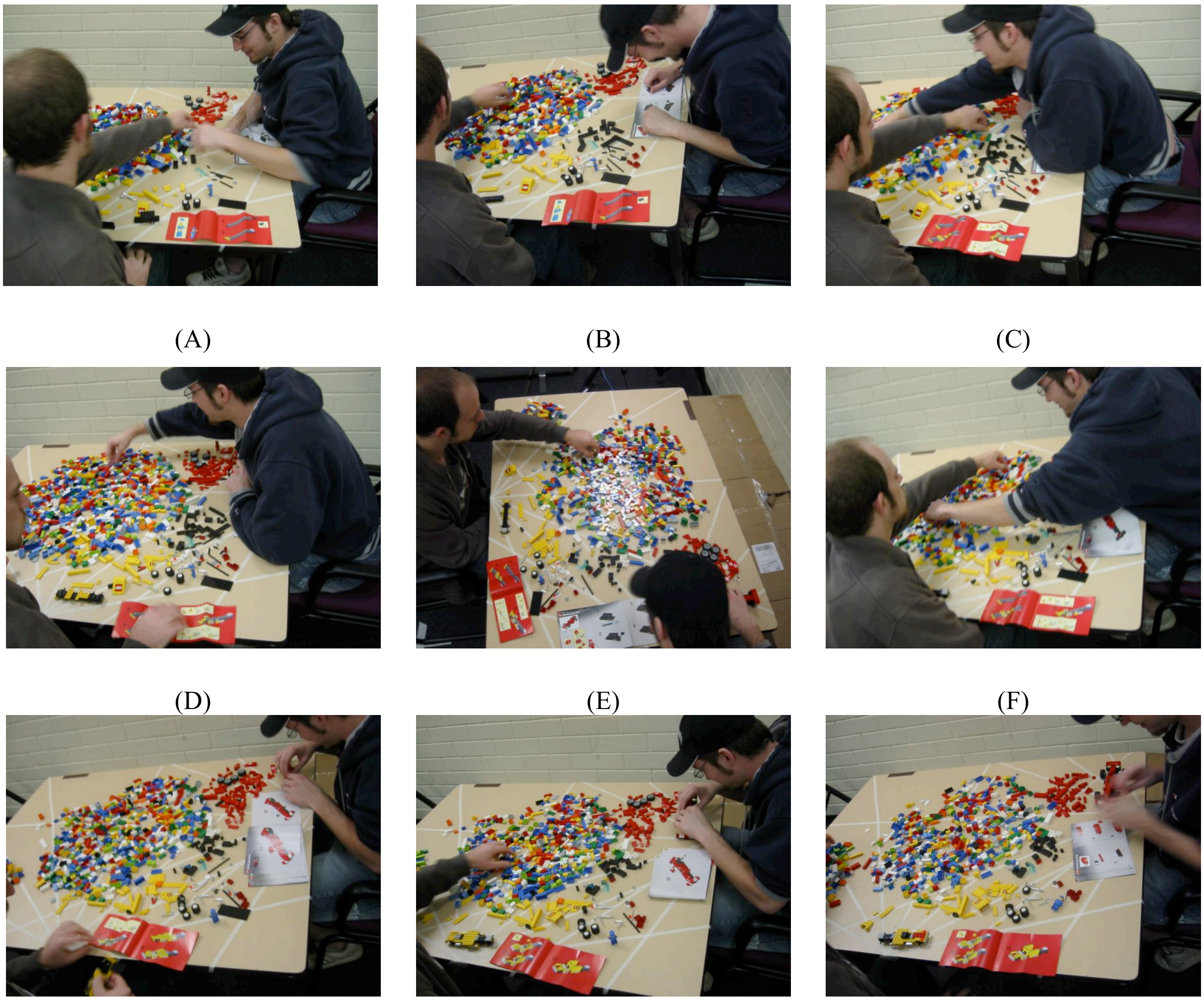


Figure 82 Calibration for Informal Dyad LEGO™ Study

Users were observed to be comfortable working right up to the edges of the table. The most significant observation of the trial was that the corner of the table between the participants remained completely unused throughout the study. Corners between adjacently seated users present the most jointly reachable real estate on the table. For the trial, this corner was anticipated to be an area where users would exchange pieces when they possessed pieces of the other user's model. Instead, users were observed either handing the pieces directly to the other user or, with an accompanying gesture, reaching into their space and depositing the piece in one of their search piles.



(A) (B) (C)

(D) (E) (F)

(G) (H) (I)

Figure 83 Informal LEGO™ Dyad Study

8.6.4 LEGO™ Study

After the initial trials confirmed the initial hypothesis that LEGO™ model assembly was a suitable as the basis for a study, a formal study was conducted. The formal study recruited sixteen participants from staff and students in the School of Computer and Information Science at the University of South Australia. Participants were selected with the same three physical restrictions outlined in Section 8.6.2. The subjects were chosen to be representative of handedness in the population as a whole, and include both genders. Two participants were female and two were left-handed. All of the participants but one reported having previous experience with LEGO™. On a scale from 1 to 5, participants self-rating of their LEGO™ ability averaged 3.61 with a standard deviation of 0.59.

The study tested two collocated subjects seated adjacently at a 73 cm tall, 120 cm x 120 cm table. Each of the subjects was given a different model to assemble. Since the models were selected with a comparable number of pieces and developmental age range, their assembly was expected to incur a comparable cognitive load for both subjects.

Subjects were asked to seat themselves at the table. The rails used in the study of reach conducted in Chapter 7 were again used to center the subject's chair on the mid line of the table. The rails left the subjects' chairs free to move towards and away from the table edge while keeping them oriented normal to the table edge and preventing them from moving laterally. The restricted chair movement helped align and hold the resting position of the sagittal plane of the subject's torso (the plane bisecting the left and right halves of the subject's torso). Restricting chair movement aligned the sagittal plane of the users torso normal to the table edge without requiring verbal cues be given to the subject to help them "square their body" with the edges of the table.

A sensor from a Polhemus[24] FASTRAK was strapped to the back of each wrist of each participant. Wires led from the sensors to special scaffolding erected above the table. The scaffolding was used to position the wires so that they did not occlude the users' view of the table or each other. The scaffolding also provided a mounting point for a camera that recorded the participants' interactions. These sensors allowed participant hand position to be tracked with sub-centimeter accuracy at a rate of 15 samples per second. Samples were recorded for all sensors throughout the 45 minute study.

A thresholded spatial histogram of the gathered data is presented in Figure 84. The thresholding removed locations with fewer than five samples. The figure indicates the number of times a participant's hand was recorded as being within each cubic centimeter above the working plane. The formation of regions on the table was observed centered on the sagittal plane of the body. The spatial histogram shows reach to be an elliptical phenomenon, confirming the hypothesis that highest usage will be in areas of bimanual action (S_{RB}), and lowest usage in areas reachable only by one hand (S_R - S_{RB}).

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[24] Polhemus Corporation - 40 Hercules Drive, Colchester, VT 05446 Phone: 802-655-3158 URL: www.polhemus.com

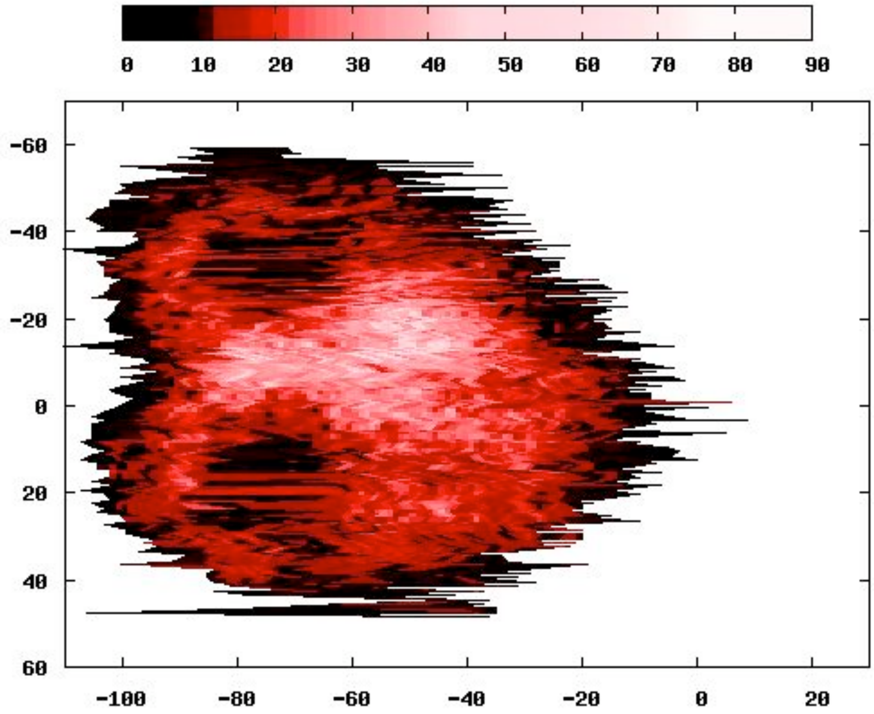

Figure 84 Observed Hand Positions – User seated facing right

8.6.4.1 Problems

Post-hoc analysis of the data included an inter-subject comparison of the study data. This comparison revealed an intermittent interference with the magnetic trackers attached to one of the study participants. In order to avoid possible conflicts caused by filtering, all of the data from the subjects using the suspect tracker was removed. What is seen in Figure 84 is the table usage for all of the subjects using the validly tracking sensors. The users whose data is pictured in the figure were seated facing to the right, with the sagittal planes of the users' bodies parallel to and slightly above the horizontal axis. The dimensions of the figure's axis are in units of centimeters.

8.6.4.2 Results and discussion

The results and discussion are presented in context of the different areas of the table the participants employed during the study. The areas presented in this section are as follows: the entire table, edges, corners, storage areas, and the "sweet spot". In addition to data recorded from the trackers instrumenting the subjects, results were derived from observations made during the study and from post analysis of subject video.

8.6.4.2.1 Edges

One of the on table phenomena the authors originally set out to measure was the minimum distance from the edges of the table that participants were comfortable placing artifacts. All participants in the study were comfortable working right up to the very edge of the table. Each subject had at least one of their working or storage piles spread so that it touched an edge of the table.

8.6.4.2.2 Corners

Another goal of the study was to examine the impact of corners on the utilization of working surface real estate in direct manipulation user interfaces. Corners have previously been observed by Stott et al. (Stacey D. Scott, M. Sheelagh T. Carpendale et al. 2003) as storage spaces on the table. Applying on table reach envelopes to predict workspace segmentation from overlapping reach disagrees with Scott et al.'s observations. Application of on table reach envelopes predicts that, as space reachable by adjacently seated participants, corners should form group spaces on the table. The table usage observed in the study disagreed with both predictions. Study participants showed reluctance to use the corners at all, leaving on average an approximately 20 cm x 20 cm wedge of unused but reachable space at the corner of the table between the two subjects.

8.6.4.2.3 Storage and Sorting Areas

As expected, all of the subjects fanned out the LEGO™ over the table so the pieces could more easily be searched. When participants discovered pieces of possible later use, they were moved to storage areas closer at hand. As these areas held a small number of pieces, they could be visually scanned frequently and only reached into to store or retrieve specific pieces. Areas of low table usage were observed on either side of the working space (Figure 84). These regions were approximately 26 cm by 12 cm deep (312 cm^2) and corresponded to the storage spaces for specific pieces the participant had previously set aside. The formation of this dead space supports the prediction that the storage space (S_S) will form in areas reachable by only one hand (S_R - S_{RB}).

8.6.4.2.4 Where is the preferred working area or "Sweet-Spot"?

The highest usage area fanned out in front of the users to a mean maximum depth of almost 50 cm. Over 90% of the recorded table usage was constrained to within an approximately 12 cm wide and 34 cm deep (410 cm^2) region in front of the participant. This area corresponded to the core of the observed assembly area.

The average planar distance between the wrists over the course of the study was 48.97 cm with a variance of 13.26 cm. This corresponds to an average bounding area for the manipulation area of 1,275-3,873 cm^2 (mean at 2,398 cm^2). During assembly, the inward bending of the fingers and hand can act to significantly reduce this distance, but this measure indicates an absolute maximum working volume a deployed user interface would have available if it was supporting the study participants. These observations support the hypothesis that working space (S_W) is primarily contained within the area of bimanual reach (S_{RB}) or bimanual action (Toney and Thomas 2007).

8.7 Simulating "Reachability"

Simulation enables the impact of a large number of changes to be easily compared, providing insight into how small changes in usage context alter usage of the working surface. Iterative simulation resulted in several significant observations.

8.7.1 Modeling "Reachability"

The models of reach discussed in Chapter 7 describe the reachable space on the working surface and its segmentation into areas of overlapping reach and uniquely reachable space. As the models of Chapter 7 were binary, only describing sets of points currently reachable by the user, description of reachable space derived from application of these models is also binary. Extending these binary models to describe attributes of the reachable space extends their ability to describe the usage of reachable space.

The binary ZCR model for reach introduced in section 7.3.2 was used as the basis for a model describing "reachability" of space. The new models assumes that there is an ideal working distance (R_{IDEAL}), and that "reachability" linearly increases with distance from the shoulder rotation point to R_{IDEAL}, after which point "reachability" decreases to zero at the maximum reach (R). The model is presented in Table 11. Reachable space for the model is constrained within a maximum and minimum horizontal adduction and abduction angles (NASA 1995; Wang, Das et al. 1999). These angles are used to constrain the model, limiting the motion of the arm to a fraction of the hemispherical shell.

Distance	Reachability
$D \leq 0, D > R_{IDEAL}$	0
$D < R_{IDEAL}$	D/R_{IDEAL}
$D \geq Reach_{IDEAL}$	$1-((D- R_{IDEAL})/(R- R_{IDEAL}))$.

Table 11 Reach attenuation based on distance

8.7.2 Simulated users

All simulated users were anthropometrically representative of 50th percentile females (NASA 1995; Donelson and Gordon 1996; Paquette, Gordon et al. 1997) seated 17cm the tables edge. A distance of 17cm was derived in earlier research by the author to be the average comfortable working distance from the table (Toney and Thomas 2007). The simulated users were given a shoulder width of 36cm, a shoulder to elbow distance of 33.49cm, and elbow to wrist distance of 24.1cm and a palm length of 9.9 cm. All users were simulated to be the same size and gender to minimize artifacts arising from differences in gender or size from confounding the initial testing. Future work is needed to examine the impact of differences in size and reach on workspace utilization.

8.7.3 Simulation results

The reach simulations conducted for this thesis reflected the general shallowness of reach observed in section 7.4.1. This shallowness appears to make workspace utilization sensitively dependent to table size. Simulation revealed the impact of table size and shape on the interactions that occur on them.

8.7.3.1 The Impact of Table Size

Workspace utilization for direct manipulation user interfaces is sensitively dependent on table size (Ryall, Florlines et al. 2004). In Figure 85, an increase in the table size by only 10cm on a side is shown to cause the loss of the comfortable communal group region ($S_G = \cap S_R$). The simulation in Figure 85 illustrates that increased table size discourages direct physical collaboration between all participants at the table. As the table's size is increased, the collaboration space at the center of the table (S_G or $\cap S_R$) becomes less accessible. As a result, larger tables show preference to lateral "shoulder-to-shoulder" collaboration. This effect is seen in the clustering patterns observed by Ryall et al. (Ryall, Florlines et al. 2004) and Scott et al. (Scott, Carpendale et al. 2003).

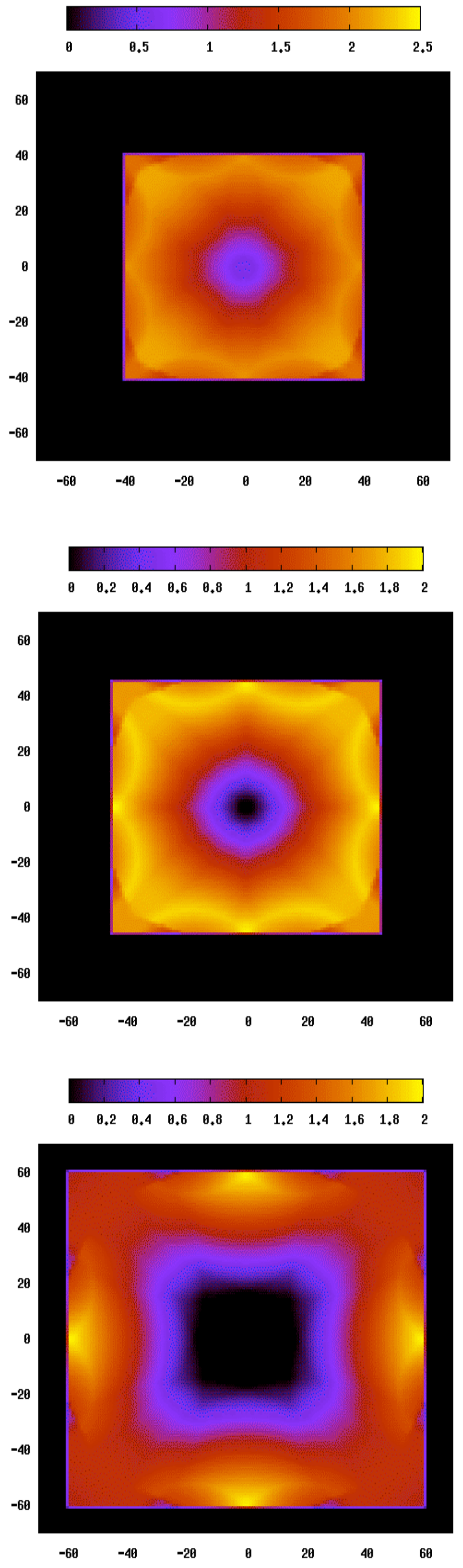

Figure 85 Predicted reachability for user centered at 80, 90, and 100 cm square tables

8.7.3.2 The Impact of Table Shape

A change in table shape can have a dramatic impact on the usage of the table. For example, a curved table's edges allow for inner sagittal plane angles that less then 90°. As the angle between the sagittal planes of collaborators decreases, the total amount of reachable space on the table ($\cup S_R$) decreases, while the overlapping reachable spaces ($\cap S_R$) increases. This decrease is shown in the simulated reach shown in Figure 86. For this reason, under some conditions, round tables, or tables with a convex edge, are better suited to shoulder-to-shoulder collaboration then tables with straight contour. Tables with a convex edge begin to have problems when the inner sagittal angle between collaborators is decreased too far, causing the users arm to prevent their collaborators access to their shared space. Future work is needed to extend the presented models to predict how overlapping reach congests access to shared space.

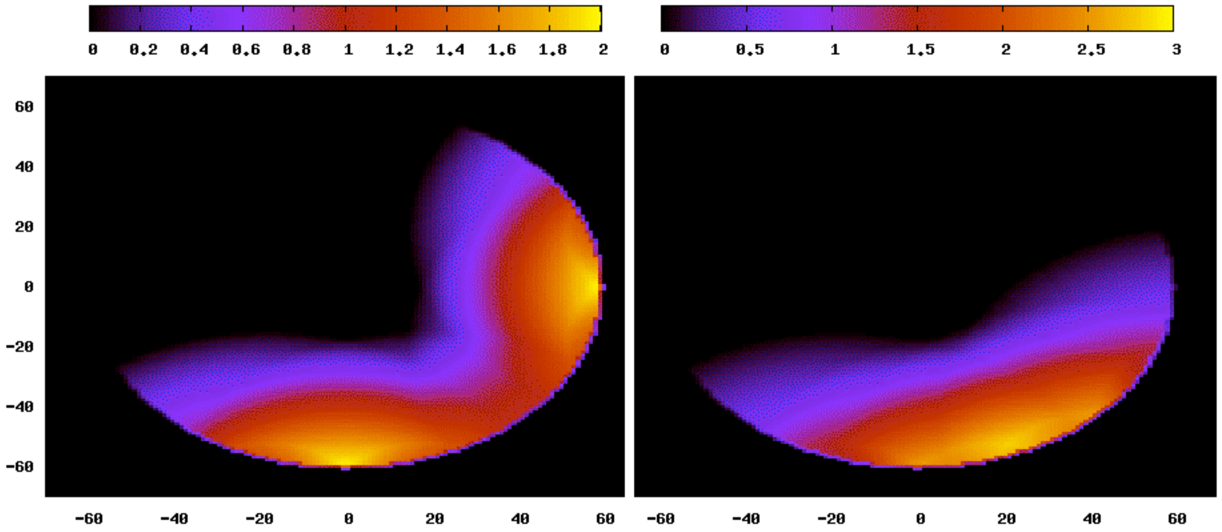

Figure 86 Predicted on-table reach probability for seated participants with an inner sagittal plane angle of 90° (left) and 45° degrees (right).

8.8 Simulating Deployment

The technology required for projecting a large high-resolution display onto a working surface, and tracking the gesture of users, has not yet been demonstrated in a package suitable for use in a deployable device. Currently available options are still too large and power hungry for the type of deployable device envisioned by this thesis to be constructed.

Since deployable devices do not yet exist, researching device deployment necessitated the construction of a simulated deployable device and application. A simulated deployable device enabled observing deployment and users interacting with a deployed application. Since the models concerning deployment developed for this thesis described attributes of multi-party interaction, such as table segmentation and territoriality, the simulated application was developed to support multiple simultaneous users.

8.8.1 Simulating a deployable device

The deployed devices were simulated as having the ability to project a display into their users' environment, and track gestures made with handheld objects to control the user interface. The simulated device deployment was conducted in a pre-instrumented and calibrated environment. Users deployed the simulated device onto a rectangular desk, with collaborators seated adjacently.

An EPSON EMP-X3 short-throw projector projected the simulated display. The projector was suspended in scaffolding above the desk, calibrated to project a display right up to the desk's edge. While top down projection does not have the shadowing artifacts discussed in section 8.5.2, the users' hands and body can still obscure sections of the deployment surface.

The EBeam[25] virtual whiteboard system was used to provide the tracking required to simulate both the initial device deployment and the deployed device's inputs. The EBeam system consists of four special pens and an eraser that can be ultrasonically tracked and identified by a proprietary sensor module. Depressing an EBeam device powers its internal transmitter, enabling the EBeam sensor pod to determine the position and identity of the depressed device. The sensor pod is mounted in the upper left corner of the area to be tracked as shown by Figure 87. The sensor pod tracks an approximately 90º wedge on the table, and is connected via USB to the computer running the simulation software. To simulate deployment, a pen was tapped within a tracked area of the table and then set down at that location. This first pen represented the simulated deployed device, and a display wedge was projected from the base of the pen to the edge of the table. This wedge of display area represented the display that a deployed device would project on the deployment surface.

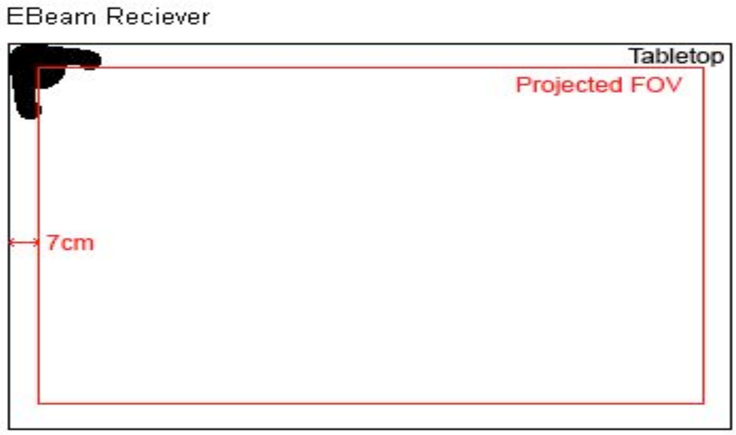

Figure 87 e-Beam on table

The deployment pen was left at the apex of the projected display after deployment, enabling redeployment of the display by depressing the pen at a new location on the desktop. The

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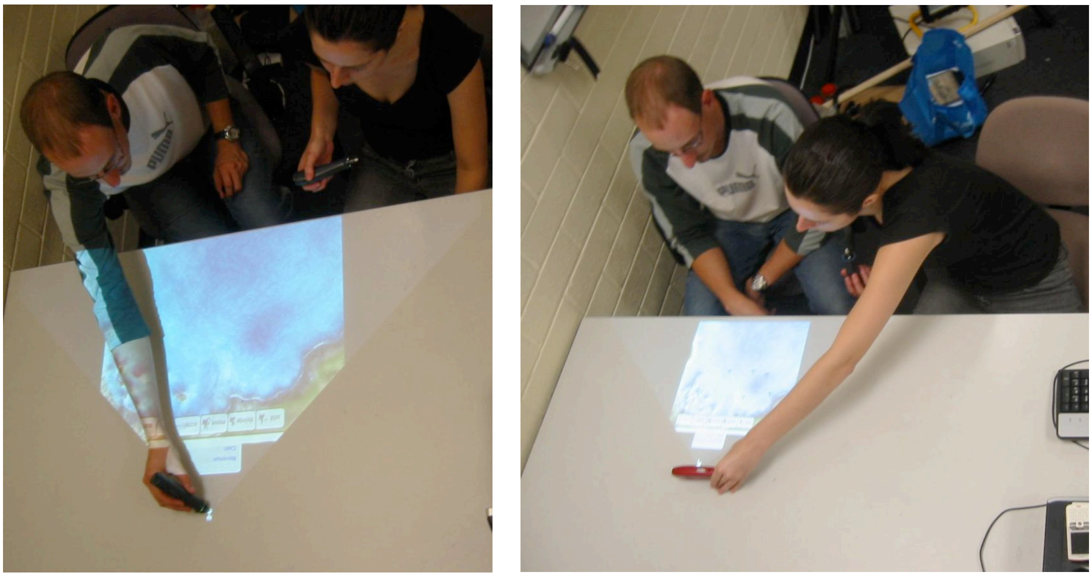
[25] Luidia, Inc – 125 Shore way Rd. Building D. San Carlos, Ca 94070 - Phone: 605 413 7500 URL: www.ebeam.com

projected user interface was automatically scaled to reflect changes in the size of the display area based on redeployment. An example of both deployment and redeployment of the simulated user interface is shown in Figure 88.

The region in which the users are able to deploy or redeploy is demarked by a red rectangle projected by the same projector that is used to simulate the deployed device's display. The rectangle is clearly visible in Figure 89, which depicts the simulated user interface as displayed by the projector. The deployable region runs to within seven centimeters of the left and right edge of the desk on which the device is deployed. A minimum deployment depth was determined by the minimum depth at which the dynamically scaled user interface labels would still be readable. The maximum deployment depth was determined to be the minimum of the maximum comfortable reach depths derived in Chapter 7, ensuring that either subject should be able to be able to reach the deployed device for redeployment.



Deployment Redeployment

Figure 88 Deploying and redeploying a user interface

The EBeam system was also used to simulate the user interface for the deployed device. The goal of the simulated user interface was to provide the functionality that would be available if the deployed device was tracking the hands of the people near the table interpreting gestures used to control the application. To achieve this, each user interacting with the deployed devices was given a pen with a distinct ID. Users tapping, or tapping and dragging, user interface elements controlled the simulated deployed application.

8.8.2 Deployment scenario

The simulated deployment scenario was chosen to model two businessmen representing collaborating companies meeting to prepare for an important meeting at a neutral location. In the tested scenario, one businessman was representing an oil company, and the other a subcontracting company that had won a bid to manage the oil company's ocean drilling platforms. This provided a context with incentive for collaboration, but one in which the goals and information of the collaborators would not be entirely homogeneous.

The subcontractors were told that their company received performance based rewards, so they were concerned with both the operating cost of the individual wells and the total oil generated by the well. The meeting was working on planning the location of five new wells in a recently discovered undersea oil field. While both parties were told they had a direct stake in the profits from running the wells, both representatives had their own private goals and information guiding their choices of acceptable well location. The oil company's representative was concerned with maximizing oil production, while the representative of the subcontracting company was concerned with minimizing the operational cost of the wells.

Their collaboration task was to find five candidate locations for new wells that were acceptable to both companies. All values were single digits, representing the number of hundreds of thousands of dollars per hour that operating the oilrig within the indicated cell would cost, and the revenue value was indicated in the number of hundreds of thousands of dollars of oil that would be generated per hour at that location.

8.8.3 Conducting the study

Each study section began by giving the users a tutorial on how to use the simulated application. The subjects were assigned their role in the study, as either a representative of the oil company or the subcontracting company operating the wells, and given a sheet to brief them on the expert information that their company possessed. This information consisted of a map of values indicating either the predicted cost of operating an oil well at a given location or the expected revenue from placing a well at that location. Subjects were given five minutes to study their respective packets.

Subjects were allowed to study the grid data for up to five minutes before the study was conducted, after which time the sheets were taken away from the users and the study commenced. The expert values were presented on a 16 by 16 grid. The grid data given to the subjects are shown in Appendix D (figures Figure 101 and Figure 102, respectively). A grid with a high degree of granularity was used to prevent the subjects from just memorizing the expert information; instead the high granularity forced the participants to try and remember the general regions of high and low value within their own respective maps, resulting in the testing of many areas looking for a collaborative optimum placement. During the collaboration, this enabled the participants to quickly converge on regions with gross gestures, and then make a large number of fine gestures within the candidate high value areas.

8.8.4 The simulated deployed application

The simulated deployed application is pictured in Figure 89. A map was displayed by the application corresponding to the newly discovered oil field about which the users had been previously briefed. Subjects were presented with six buttons for manipulating the deployed application. The commands were triggered from a menu bar located at the bottom of the display area. The menu bar contained six control buttons – add, delete, move, scroll scale, and reset were located on the bottom of the projected display.

Three buttons, add, delete, and move, were provided for controlling the placement of oil wells. Users were able to add up to five oil wells anywhere on the map. Users also had the option of moving or deleting a well once it had been added. Projected revenue and cost was calculated for each oil well based on its location, and the total cost and revenue for all currently placed wells was displayed at the top of the projected area.

Scroll and scaling functionality enabled a much larger virtual display to be presented within the available physical space for the projected display, and enabled the user to zoom in and out on the map being displayed. Being able to zoom and scroll the user interface area helps the users to compensate for differences between deployment on different tables, and shallow deployment onto counters and small tables when no deeper surfaces are available.

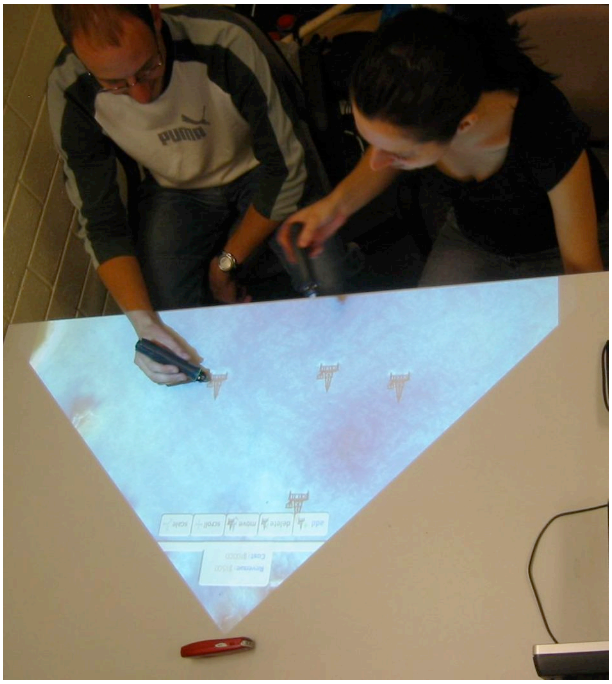


Figure 89 Early version of the deployed application in use

8.8.5 Observations about deployment

Seven pairs of subjects were observed using the simulated deployed application. The users exhibited a wide range of behaviors in how they interacted with the technology, resulting in the following observations.

8.8.5.1 Proximity affording ownership

Work presented earlier established that group space forms in preference to personal space in jointly reachable areas. Most of the observed dyads deployed in a position that resulted in the majority of the deployed interaction space being jointly reachable, and thus tend to collaborative use. The deployed application was designed with no private storage or working areas making the entire displayed area afford use as collaborative space. Despite these strong biases against ownership, users were observed negotiating access to space in close proximity to other users. Requests such as “I might grab that one and shuffle it over here” were a common precursor to moving a well. Future work is required to determine how physical proximity to the user implies ownership of space, and to determine the impact of proximity on the preferred formation of group space over personal space.

8.8.5.2 Passenger effect

In several of the observed subject dyads one user was observed to be clearly dominant. This type of user was termed a Passenger. While passengers were comfortable providing the other user with instructions, such as "Just delete that one", "Go a little bit lower", or "Move it a little bit more", they had almost no interaction with the deployed user interface themselves.

8.8.5.3 Fatigue

Even though the entire deployed display interaction area tended to be reachable, users were observed taking turns, and affording ownership of regions farther away to their collaborator. For example one user was observed saying "you do it - it is too tiring" – after making a number of small actions near the full extension of their reach.

8.8.5.4 Deployment impacting reach

Rather than redeploy the device to improve access to the deployed application; some users adjusted their body, twisting their torso to face the user and the deployed device. The twisted torso reduced the reachable space on the working surface. Over a long period, the twisted torso resulted in the user resting their arm on the table, further limiting their reach.

8.8.5.5 Scaling of the UI

Device deployment relies on objects discovered in the user's environment to provide the working surface. As a result, the size and dimensions of the working surface available to a deployed device can not be guaranteed to be known in advance of deployment. One deployment may be on a 12 inch deep counter at a coffee shop, and the next could be a two-meter square conference table. The simulated application demonstrated a deployable application dynamically scaled its user interface elements based on the available deployment space. Deploying the simulated device creates a wedge of display space, with the deployed device at its apex. Shallower deployment results in a smaller display wedge requiring the software to scale its interface.

Early versions of the software located the menu bar in its classic position at the top of the display; but this is the area most impacted by dynamic scaling to account for shallow deployment. After experimenting with the deployed user interface under conditions of shallow deployment, similar to what a mobile user will occasionally find, the user interface's menu bar was moved to the bottom of the display wedge. This maintained usability for the minimum possible deployment depths. Figure 88 and Figure 89 show an earlier version of the software with menu bar located at the top, rather then the final configuration at the bottom of the screen shown in Figure 100 in Appendix D.

8.8.6 Subject Response

At the end of each study session, both subjects were asked to fill out a questionnaire. The questionnaire contained a number of statements and users were asked rate their agreement on a seven point Lycart scale. Appendix D - provides a copy of the post trial questionnaire provided to the users on completion of the study. The averaged results for the exit interview questions indicate strong agreement that the group worked well together, could comfortably access all of the display areas, felt free to add and remove elements anywhere on the displayed map, that the map was a comfortable working size, and that a projected display was well suited for the task.

The most interesting results was that users strongly agreed that they would feel comfortable using a projected user interface for an important meeting but only slightly agreed that they would feel comfortable using the display in a public space such as a coffee shop. Since the envisioned use of deployable devices, is that they be used in public places this response is a significant point for any future research into deployment to investigate.

8.9 Summary

This chapter has shown how the models of reach presented in Chapter 7 could be applied to predict high-level table usage. For an individual, the applied models were shown to predict the utilization of reachable space on the working surface, and for collocated collaborating users the applied models were shown to predict territoriality and the segmentation of the working surface into private and common areas. It was shown that reach could be used in assessing the impact of table shape, size, and the relative location of users on the utilization of the working plane. Overall, the application of reach models is shown to be a powerful design tool, enabling the creation of direct manipulation user interfaces that are actively tailored at runtime to their user's physical characteristics.

Deployment was formally introduced in this chapter as a new usage context for mobile devices. Examples were used to contextualize the models of table segmentation for use by deployed applications, and design issues of affordence and shadowing of the working surface were discussed as they impacted deployable devices. Several trial studies were conducted to inform the design of a formal study of workspace utilization. The study was used to validate the application of reach-based models predicting table usage, for deployable devices.

A small study was run in order to able to observe the use of a simulated deployed device and application. Study participants reported deployment as being a generally positive experience, and one that they believed they would use again.

9

Someone: "It is a pity he shot himself in the foot."
Peter: "Well, that is what you have two feet for. You make your mistake and you try again."
Peter Hutterer – Conversation in the lab.

Chapter 9 Conclusion

The work of this thesis contributed to a broad range of topics concerning mobile devices and their user interfaces. The resulting research contributions can be broadly summarized as; developing techniques for minimizing the negative social consequences of using mobile technology, developing "bring your own support" strategies for ensuring the mobile user's access to ubiquitous computing resources, and using observations and models of the user to inform the design and actions of mobile applications. While the contributions cover a diverse range of topics, they are all chipping away at different fundamental problems of supporting the mobile user. In aggregate, the practical application of the contributions of this thesis will enable future generations of mobile technology to be less socially and physically invasive, be uniform in their support of the user, and to anticipate and respond to their own use.

9.1 Research Contributions

The work of this thesis resulted in contributions in seven areas of research. The contributions are outlined in the following subjections.

9.1.1 Social weight

The concept of device social weight was developed in this thesis to measure the degradation of social interaction that use of a device or interfaces causes. This work was the first to formally model the negative social consequences of using technology (Toney, Mulley et al. 2002). The resulting model, and techniques for quantitatively scoring the models components, allows social weight to be measured for both mobile devices and their user interfaces.

A formal quantitative model for social weight is integral to the design of mobile devices (Toney, Mulley et al. 2003). Being able to comparatively assess the social weight of differing designs enables the designer to iteratively refine their designs, minimizing the negative social consequences that will arise from its use. Runtime application of models of reach by an application can minimize social weight by subtly guiding usage, to control usage through device or interface escalation.

9.1.2 Garment integration of technology

Construction of the prototype garments used in this thesis required techniques to be developed that resulted in three contributions to the state of the art in garment integration.

Bedding: The technique of "bedding" wires to form a fabric backplane bus was developed to integrate a bus for distributing power and data within a prototype garment (Toney, Mulley et al. 2002).

Cloth conduits: In order to prevent the integrated bus from altering the fit and hang of the garment the technique of running the bus free floating within a series of cloth conduits within the prototype garment was developed (Toney, Mulley et al. 2002; Toney, Mulley et al. 2003).

Integration into interfacing: Interfacing and removable inserts provide a location in which to integrate technology that minimizes the physical invasiveness of the integrated technology. By locating the technology within pre-existing volumes created by padding and stiffening agents that are already used to provide tailored garments with their final tailored shape, integration of the technology results in a minimal alteration to the garments unintegrated hang and fit (Toney, Dunne et al. 2003).

9.1.3 Garment integrated user interfaces

The e-SUIT was constructed out of necessity in order to have a garment containing integrated covert user interfaces for formal study (Toney, Mulley et al. 2002). No garments suitable for this type of study are available commercially. As a whole the devices integrated into the e-SUIT made a minor yet significant contribution to garment integration, demonstrating for the first time the design of garment integrated devices designed to minimize resultant social weight arising from their use.

Following up on the promise demonstrated by the e-SUIT's single actuator vibrotactile display, a series of multi actuator prototypes were constructed and formally evaluated with a user study (Toney, Dunne et al. 2003). These displays were a major contribution of this thesis. The formal development and evaluation of the displays provided an initial pad sizes, actuator layouts, and pad construction suitable for use in developing multi actuator displays for garment integration.

9.1.4 Smart garment management

The work of this thesis was first to recognize that moving from a small number of intelligent garments, to a wardrobe consisting of mostly if not exclusively intelligent garments would require a smart garment management system (Toney, Thomas et al. 2006). The smart garment management system developed in this thesis consisted of two types of components: a collection of smart hangers and a smart wardrobe.

The smart garment management system developed in this thesis was the first to demonstrate the use of augmented coat hangers to manage smart garments. Augmenting the hanger enabled charging and synchronizing garments with integrated technology with minimal impact to the care of conventional garments.

Using multiple smart hangers, the developed smart garment management system was the first to demonstrate a smart wardrobe capable of providing its user with a single interface for managing all of their smart clothing. Instead of having many different devices to track and manage, the smart wardrobe essentially turns the user's collection of clothing into a single distributed device. This feature enables the system to help guide the user's daily choice of outfits to ensure that the desired minimum level of support is always available from the currently worn garment integrated devices.

9.1.5 Available on table space

For direct manipulation user interfaces, reachable space dictates the maximum space usable for inputs in the user interface. If the user is unable to reach a user interface element, then they cannot manipulate it. The work of this thesis was the first to recognize that existing models of reach used for industrial design could also be applied to the design and evaluation of on table user interfaces (Toney and Thomas 2006). As part of this contribution a new statistical model of user reach, measured under conditions that closely resembled the use of on table user interfaces, was developed (Toney and Thomas 2006; Toney and Thomas 2007). The new statistical model included the first study derived data describing comfortable table working heights and working distances from the table for use of on table user interfaces. Collectively the adaptation of existing models from other domains, along with the derivation of new models under more appropriate conditions, enables the development of tangible and direct touch user interfaces that dynamically scale and respond to their current users reach (Toney and Thomas 2006; Toney and Thomas 2007).

9.1.6 Algorithmically predicting table segmentation and territoriality

The developed models of a user's reach were used to predict the user's gross table usage, and use of overlapping reach for multiple users to predict private and collaborative regions on the working surface. This application of the models explained previously reported observations of workspace usage in the literature, and the results of several informal user studies. The demonstrated ability of applied models of reach to predict utilization of the working surface enables the creation of applications that dynamically tailor their user interfaces to their users.

9.1.7 Device deployment

Device deployment was proposed as a new usage context for mobile devices. Deployed devices allow users to temporarily instrument their environment with powerful devices, not suited for being worn or garment integrated. Deployment provides a way to fills the gap between the functionality that can be garment integrated or worn, and the level of functionality expected from a preinstalled pervasive or ubiquitous computing infrastructure. Collectively the developed models of reach and predictive use of the working plane were researched as part of answering the question "where and how can a user deploy?" The user studies, trials, and simulated deployed user interface provided observations about how deployed devices will be used. These observations are essential to the informed development of the first deployed devices.

9.2 Future Work

While there were many areas of possible future work suggested by the research of this thesis, there were four areas in particular in which I personally hope to conduct further research. These areas of research are recapped in the following subsections, and are respectively social weight, Garment integrated vibrotactile displays, Adaptive user interfaces, and device Deployment.

9.2.1 Social weight

After constructing the initial model of social weight, I was exposed to the work of Gottman and Murray (Gottman, Murray et al. 2003) on the mathematical modeling of marital interactions. They demonstrated techniques for developing and testing nonlinear models of human behavior that are directly applicable for the development of more robust models of social weight. The next step in researching social weight will be to develop new models of social weight that are more generally applicable and less constrained.

In researching social weight, it was often necessary to describe subtle differences between two or more complicated and similar social interactions. Out of necessity, my thesis advisor and I developed a graphical notation system, akin to Feynman diagrams, for describing the nuances of the social interactions we were describing or comparing. While I decided not to include the diagrams in this thesis, or publish them elsewhere, I found them an invaluable tool for clarifying my thoughts on social weight. As part of future research into social weight, I wish to develop the social notation system, and publish it as a tool usable by others.

9.2.2 Garment integrated vibrotactile displays

Testing the vibrotactile displays developed for this thesis showed the displays were able to communicate at a higher bandwidth then initially expected. Integrating the displays into garment inserts and interfacing makes them suitable for integration into a wide range of garment types worn by both genders. Further refining the actuators types used, reevaluating the two-point threshold values used for the shoulder, testing with male subjects, and testing stereo pattern detection and discrimination is warranted.

9.2.3 Adaptive user interfaces.

Models of user reach were shown to predict high-level usage patterns occurring on the working surface. For tangible and direct touch user interfaces the ability to predict usage has direct and immediate potential for creating applications that better respond to their users actions. Both the LEGO™ user studies, and the study of simulated deployment, illustrated that further research of table usage was required to refine the usage models to account for non-anthropometric user characteristics. Based on the research conducted in this thesis, it seems hat the most significant contribution will come from longitudinal studies conducted to test the models of reach built from multiple observations of the user.

9.2.4 Deployment

Initially the primary goal for my thesis work was the construction of a deployable device. Early on, it became clear that before a device could be constructed that possessed the functionality I desired, a number of research problems would need to be addressed and overcome. It was addressing these problems that lead to the work of this thesis applying models of reach to predict the usable space on the table and how that space was likely to be used.

A deployed user interface was simulated, rather then constructed, for the tests conducted in this thesis since as the research problems surrounding deployment became clear, it was obvious that constructing a deployed device and building applications to run on it would have been the work of multiple Ph.D. thesis. The next two steps in researching device deployment will be the construction of a refined simulated user interface that can recognize the types of gestures expected of a deployed devices, and testing the projection of the display from the point of the deployed object. After this research, the way should be clear for the construction and formal testing of an actual deployable device.

9.3 Closing Remarks

My research conducted for this thesis preceded along multiple lines all working to support the mobile user. The devices convergent from my work will soon become not only commercially available, but commonplace. In part, these devices will emerge out of the evolution of mobile devices such as smart phones and portable music players. They will also emerge from the development of entirely new classes of mobile devices and smart clothing. There are many open questions still to be researched to make these convergent devices a reality. It is my sincere hope that the work of my coming career will continue refining the new areas of research presented in this thesis such as social weight or device deployment.

A

"I ran out of creativity mid way through my thesis outline. The rest was patched together with stimulants and the promise of sleep if I just wrote a little bit more."
Lost and confused Ph.D. Student (1974 -...)

APPENDIX A - OBSERVED MAXIMUM REACH DEPTH

This appendix section contains the raw data gathered for the minimum, comfortable, and maximum reach depth derived from the user study presented in Chapter 7. Reach data was gathered at three subjective table heights, the heights that subjects reported to be the minimum, comfortable, and maximum table heights. Reach depth was observed at 11 angles spaced evenly at 15-degree increments. The gathered data, presented in Table 12, was used to generate Figure 71.

	Table working heights					
Angle	Minimum (cm)		Comfortable (cm)		Maximum (cm)	
15°	32.19757	42.93489	37.35197	46.79108	35.01329	46.46991
30°	58.80025	44.29406	57.41596	46.16348	60.31399	44.11173
45°	54.98029	44.353	56.99652	45.29048	55.68089	44.78104
60°	50.97896	43.75072	52.44458	45.55908	51.22234	45.06383
75°	47.09807	44.50887	49.17894	46.22515	47.49705	46.689
90°	44.72875	45.37373	46.75406	46.99869	45.81227	48.58671
105°	43.46536	47.39749	45.54011	49.33731	44.70633	49.62391
120°	43.79013	50.79033	45.01551	52.98232	44.34858	53.44568
135°	44.01721	54.67907	45.46857	56.95062	44.32055	57.71078
150°	42.42901	56.97578	41.68549	55.67552	44.75261	60.47628
165°	44.73378	33.21432	43.5404	32.36612	42.38597	42.95071

Table 12 Maximum reach depths

B

"Maybe someday I'll get to where you are--with your snazzy Captain Capacitor uniform, wielding your mighty soldering iron to defeat evil-doers--but for now I'm digging the cool stuff I can buy off the shelf..."
Jason Black, Personal Correspondence

APPENDIX B - SCHEMATICS

This chapter presents schematics for the majority of the hardware developed for this thesis. Schematics where only included for designs where the development of the hardware itself presented a research challenges. The author is happy to supply interested parties with schematics for any of the projects not listed here.

Schematics are provided for two projects. Schematics for the JTAG programming adapter used by all four projects is also provided. The presented projects are the “Controller box” described in Chapter 4, the SmartTag described in Chapter 5, and the one wire master and smart hanger schematics described in Chapter 6.

B.1 Shoulder Pad Testing Hardware

The development of the vibrotactile displays of Chapter 4 required the construction of two pieces of custom hardware, a handheld “button box” and a computer controlled “controller box”. All of the prototype displays used DC motors as their actuators. The prototype displays used a standard nine pin connector, allowing for one ground connection and for connections to up to eight motors. Both the “button box” and the “controller box” were designed to connect to the standard nine pin connectors.

The “button box”, shown in **Figure 30**, enabled testing of individual motors in a prototype display. A 4×4 grid of buttons enabled the “button box” to control the firing of up to the maximum of 16 possible motors present in both a left and right shoulder pad. Schematics are not included for the “button box” as they are trivial. Pressing one of the buttons completed a circuit between the motor, ground, and batteries integrated into the button box.

A “controller box” was created to allow computer control over the motor firing. Custom software running on a desktop PC, combined with the motor “controller box” was used to run the formal studies of the developed prototypes. Computer control enabled consistent testing of complicated vibrotactile patterns, varying in vibration pattern, duration, an inter vibration delay. Schematics for the controller box are provided in Figure 90, Figure 91, and Figure 92.

The “controller box” was designed to have both a serial connection to a controlling computer and to allow for wireless connection to future prototypes. A Maxim MAX3221 3V to 5.5V RS-232 level shifting transceiver was used to provide a buffered RS232 serial connection to the controlling computer. The MAX3221 was chosen as it provided an indicator of a valid serial connection, which was connected to both the core microcontroller (P1.5), and provides an indicator of a valid serial connection (LED1) for debugging. To allow for later development and testing of a wireless shoulder pad, a Linx[26] TR-916-SC-S radio transceiver was also included. The included transceiver provided for a 9600 baud half duplex wireless serial connection. All transceiver components were laid out on a separate board and headers JP1 and JP2 reflect the mating connectors used to attach the transceiver board to the core board. Schematics for all the IO components are provided in Figure 91.

The core board housed the Texas Instrument’s MSP430F449 microcontroller, which communicated with the control program and drove the motors based on the pattern indicated by the controlling computer. Schematics for the core board are provided in Figure 90. A series of Darlington amplifiers, diode protected against kickback, were used to buffer the output lines of the MSP430 used to drive the motors. Schematics for the buffers are provided in Figure 92.

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[26] Linx Technologies, Inc – 159 Ort Lane, Merlin, OR 97532 USA – Phone 541 471 6256

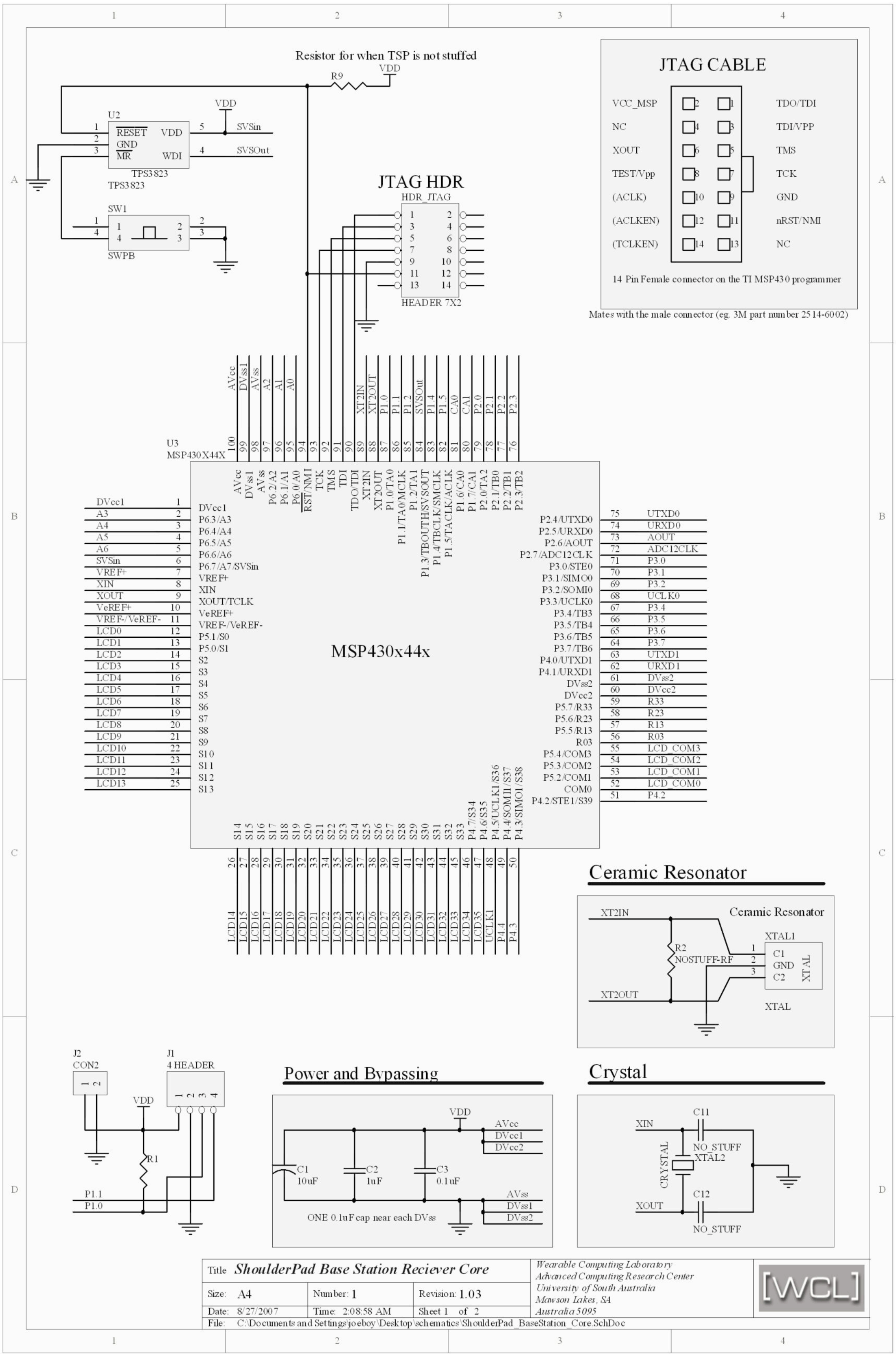

Figure 90 Shoulder pad core

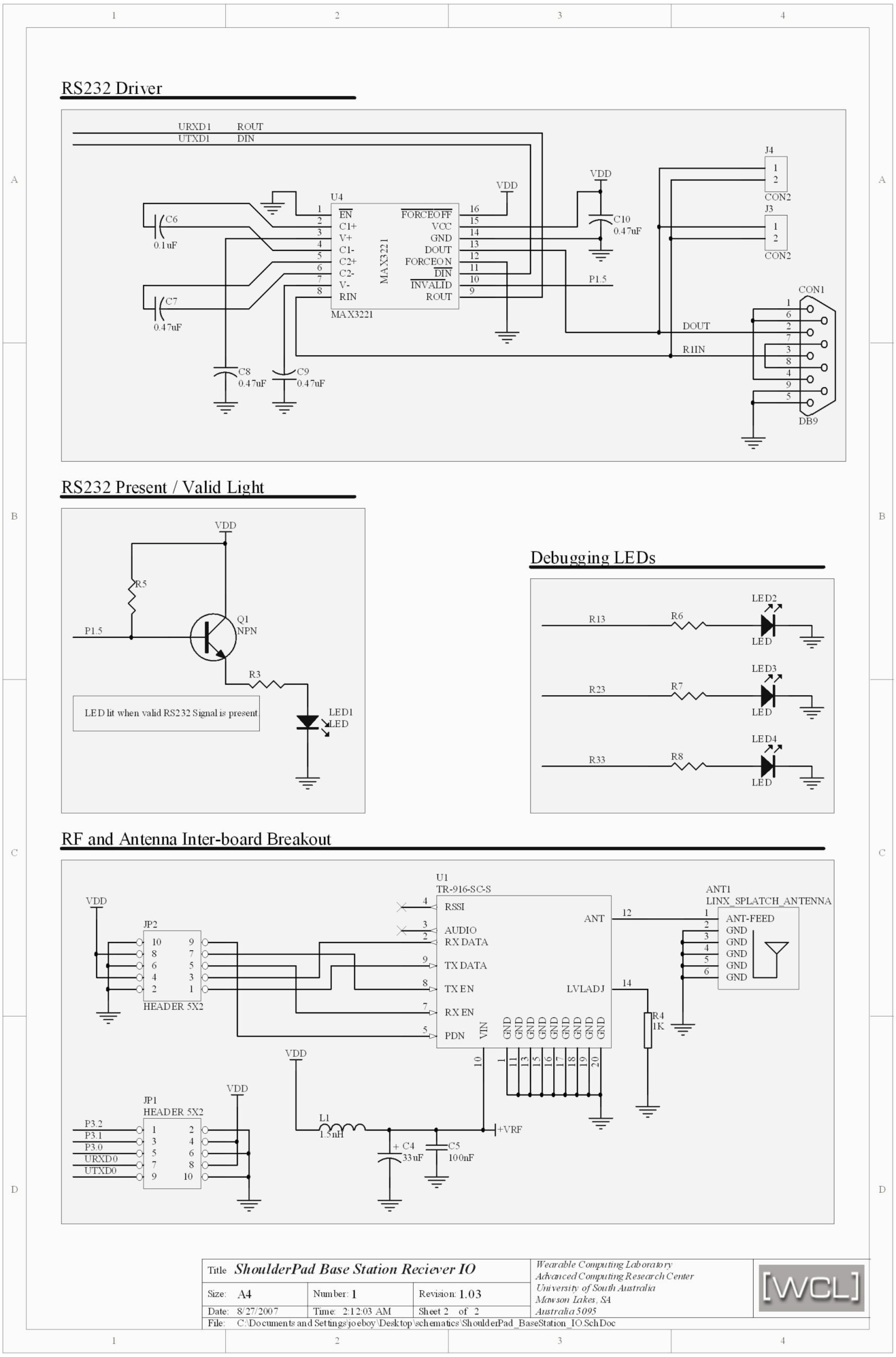

Figure 91 Shoulder pad IO

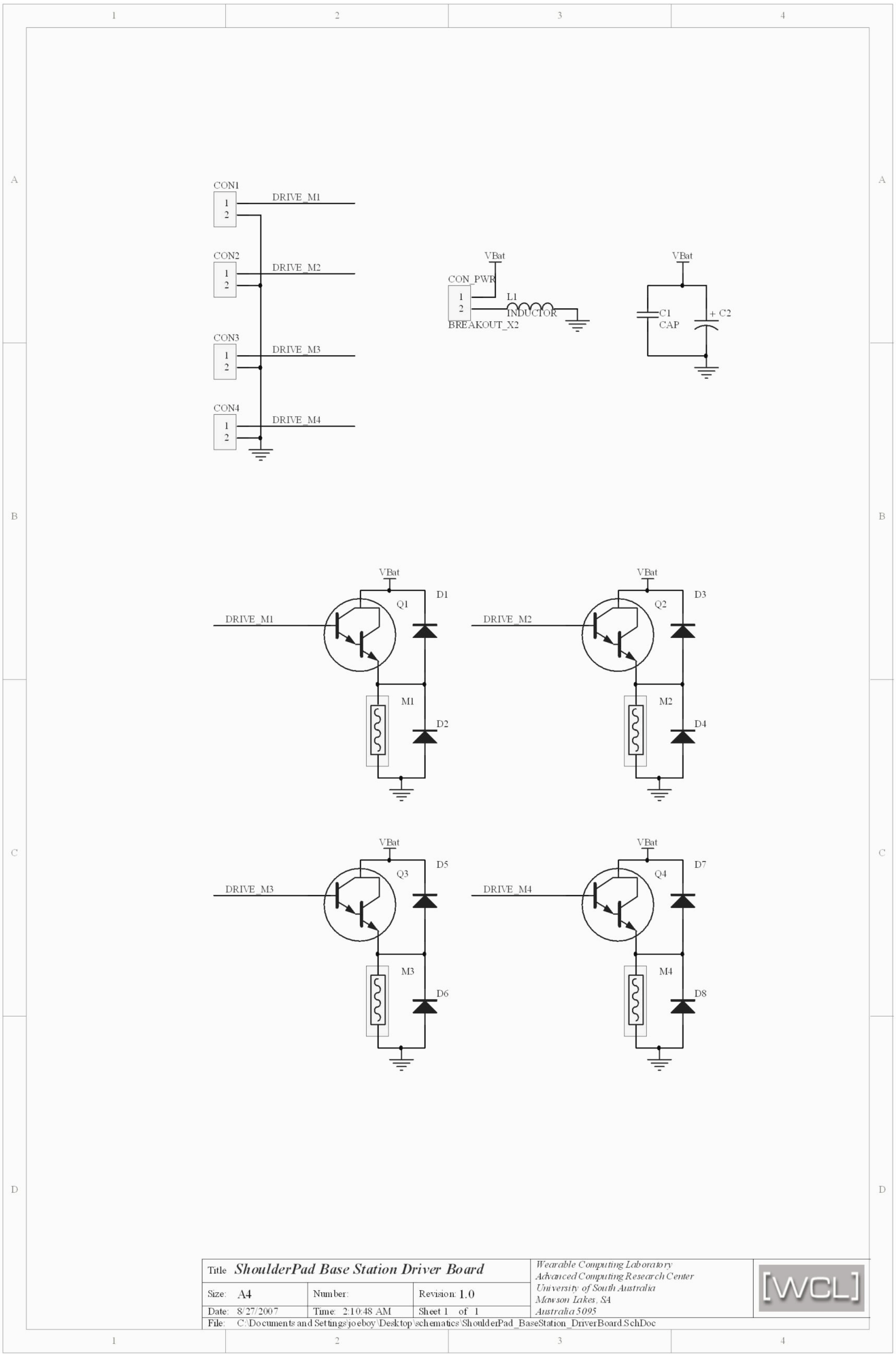

Figure 92 Shoulder pad driver

B.2 JTAG Pin Reduction and Serial Breakout

Microcontrollers of the MSP430 line are programmed through a JTAG connector. The official programming and debugging dongle breaks out to a 14-pin JTAG connection. Using a SIP-100 connector with a standard 100 mil pitch between the connector pins, the connector provided with the official programming dongle mechanically consumed 0.24 square inches of area on each side of the board. As the prototypes developed for this thesis began to require increasingly smaller boards, such as for prototyping the circuitry integrated into the clothing or their hangers, the area consumed by the connector became increasingly costly. While the JTAG connector provided for fourteen pins, only eight pins, including power and ground, were required to program and debug the microcontrollers. This enabled using a custom adaptor to reduce the pin count required by the programming and debugging connector.

A breakout board was used to provide the adaptation between a custom ten-pin connector, and the standard fourteen pin JTAG connector. Using two additional pins, beyond the eight pins required by the JTAG connection, enabled adding standard serial diagnostics and debugging features to my designs. A DIN-9 serial connector and a Maxim 3232C 3V to 5.5V RS-232 level shifting transceiver were added to the adaptor board. Powered through the adapted connection, the transceiver enabled the design to be connected to any standard serial connection. Connecting the hardware to a serial connection exposed generated status information, and allowed for control over the running program. This repeatedly proved a useful feature when testing mobile prototypes away from the lab and its more sophisticated resources. When lower level debugging was required, the exposure of the JTAG connection enabled the user of lower level debugging tools to monitor the internal microcontroller state.

Readers implementing the illustrated custom adaptor should be aware that the total cable length, with adaptors, should be less then ten centimeters when using the official programmer supplied by Texas Instruments.

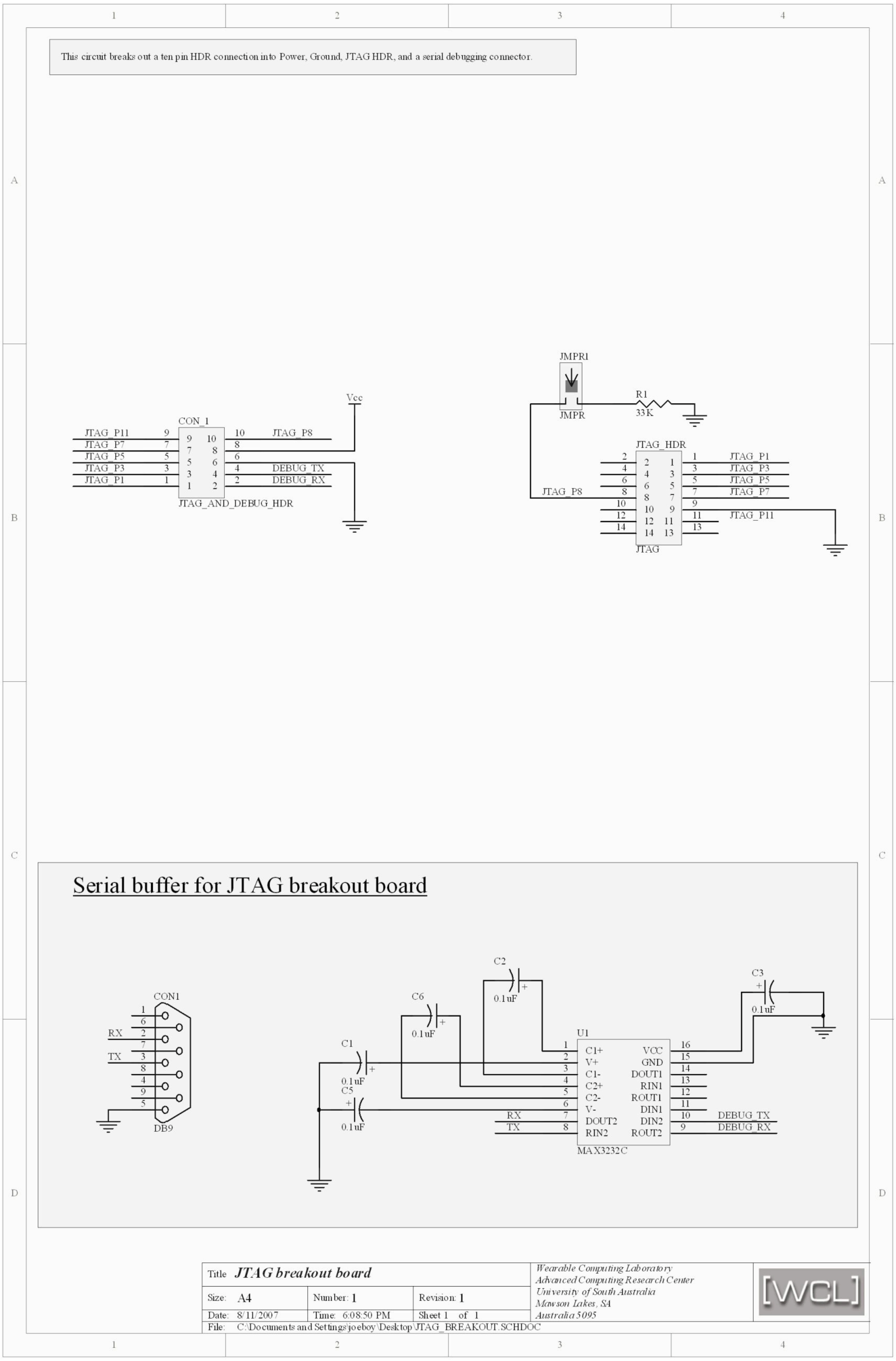

Figure 93 JTAG adaptor and serial breakout

B.3 One Wire Bus Master

The smart garment management system described in Chapter 6 consisted of three components: a number of Smart Hangers, a computer running management software, and a one wire bus master to allow bidirectional communication between the computer and the hangers. Schematics for the one wire master are provided in Figure 94 and Figure 95.

The core of the one wire master controller was a Texas Instruments MSP430F1232 microcontroller. A Maxim TPS3223 watchdog was used to ensure clean resetting. Power regulation was performed by a Texas Instruments REG104 high-current 3.3 Volt low dropout voltage regulator, a Maxim MAX3232 3.0V to 5.5V RS-232 level shifting transceiver was used to provide a buffered RS232 serial connection to the controlling computer. Transistor Q1 was used to buffer the microcontroller pin driving the bus, and diodes D3 and D4 provided protection against kickback when a large number of devices loading the bus made it a large reactive load. Resistors R7 and R8 enabled provided the microcontroller with an analog measure of bus voltage on P3.7, to complement the digital sensing of the bus on pin P1.1.

In order to allow for a high-speed wireless connection to the managed prototypes, a Lemos[27] PROMI-ESD-02 Bluetooth module was included in the bus master. Figure 94 provides schematics for the core hardware, and Figure 95 provides the schematics for power regulation and the serial buffering and level shifting.

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[27] Lemos International – Suite A-12 1275 Post Rd Fairfield, CT, 06824 – Phone: 866-345-3667

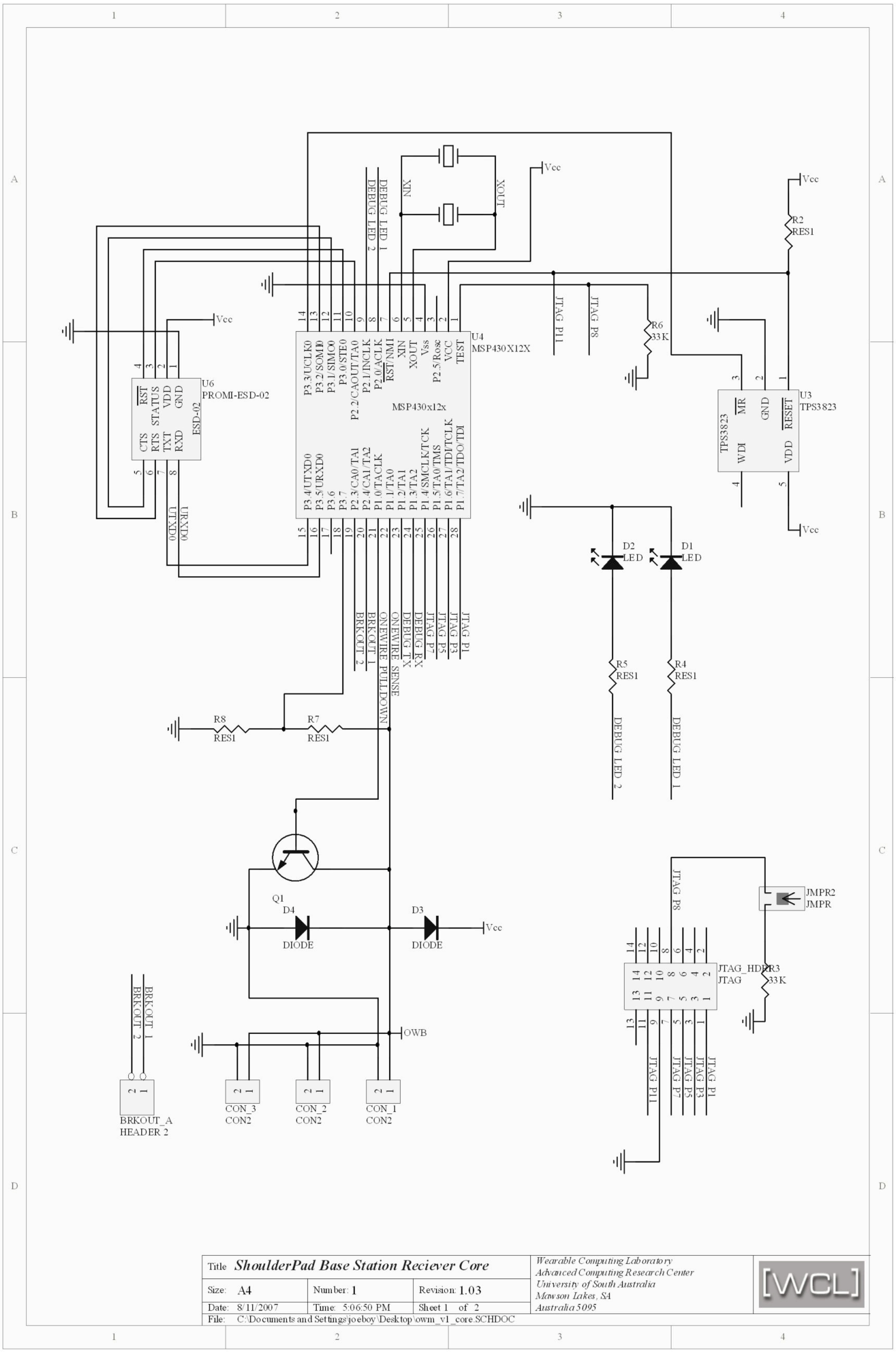


Figure 94 One Wire Master Core

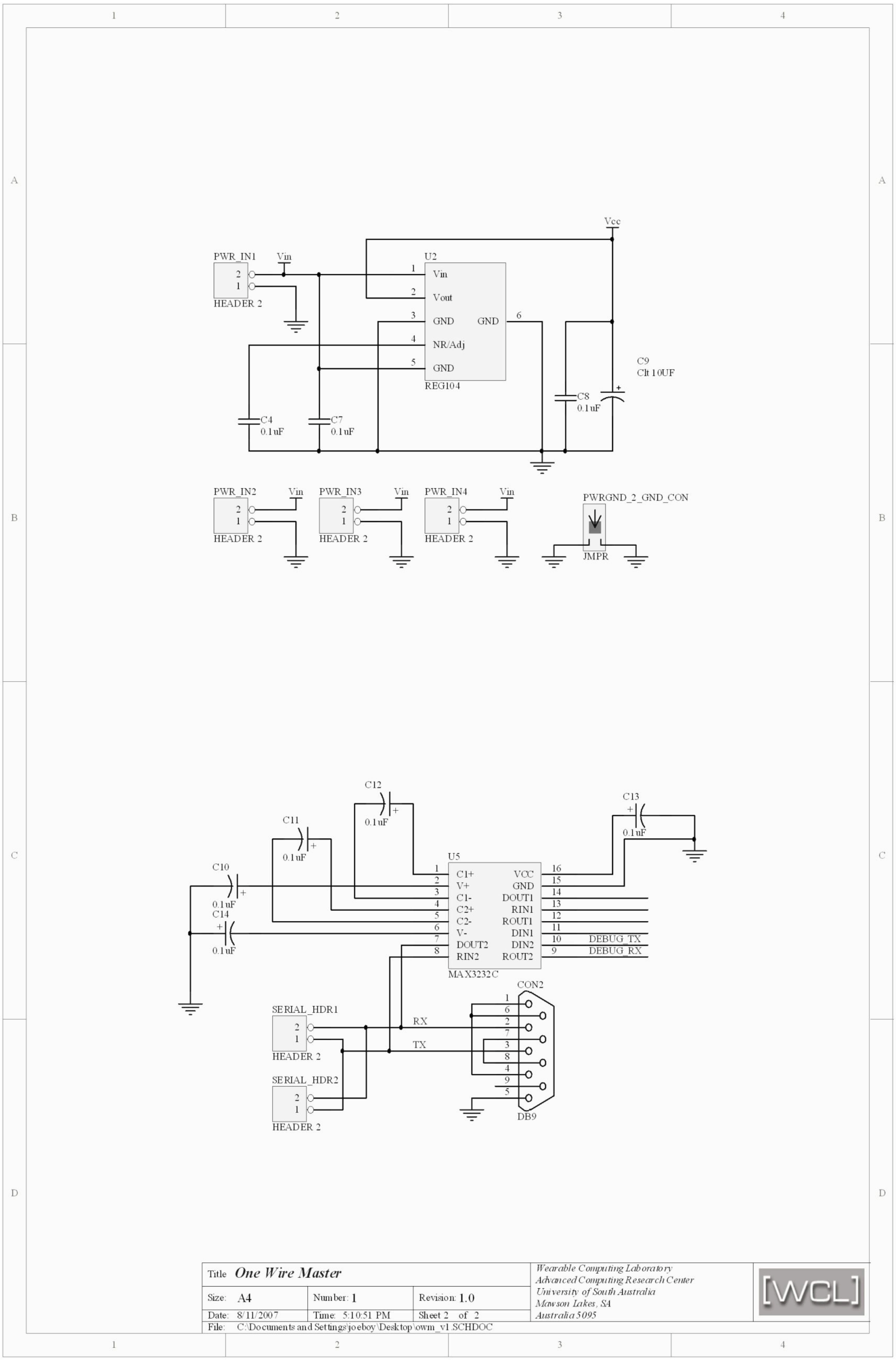


Figure 95 One Wire Master Serial and Power

B.4 Smart Hangers

The most recent hanger design is pictured in a hanger constructed by Mr. Marais, shown in Figure 55. The center panel of the hanger contained a chamber containing the electronics. An earlier prototype hanger is show with its front panel removed, and the electronics exposed, in Figure 96.

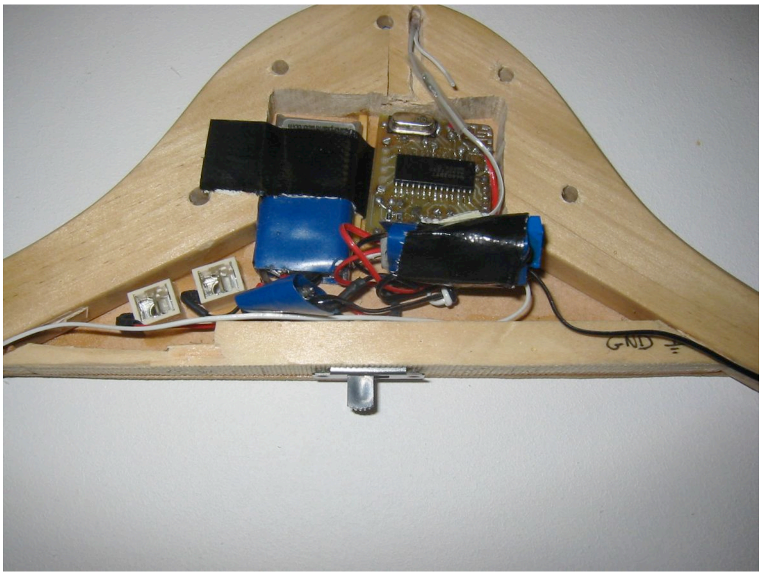


Figure 96 Smart Hanger Internals

Each hanger contains a 3.7 Volt Li+ battery and electronics used by the hanger. Schematics for the electronics contained in the smart hanger and presented in Figure 97 and Figure 98. The IO for the smart hanger is presented in presented in Figure 97. The hangers and the one wire master shared the same hardware, described earlier, to talk on the one wire bus. Components D5, D6, D7, C3, C4, and R5 of Figure 97 were part of an early experiment for running the hangers off of 1 farad super capacitors. Diode D5 was normally not stuffed, and was only used when externally charging the capacitor by hand. Under normal operation, C3 and C4 were charged through R5 and discharged through D7. While the approach bears revisiting, it was abandoned as the level of work required in further debugging and development was entirely outside of the research focus of this thesis. A core design for the microcontroller, watchdog, and power regulation was standardized as art of the iterative hanger prototype development. Figure 98 depicts the core module. An MSP430F1232 microcontroller, a TPS3823 reset power watchdog, and a REG104 power regulator composed the core.

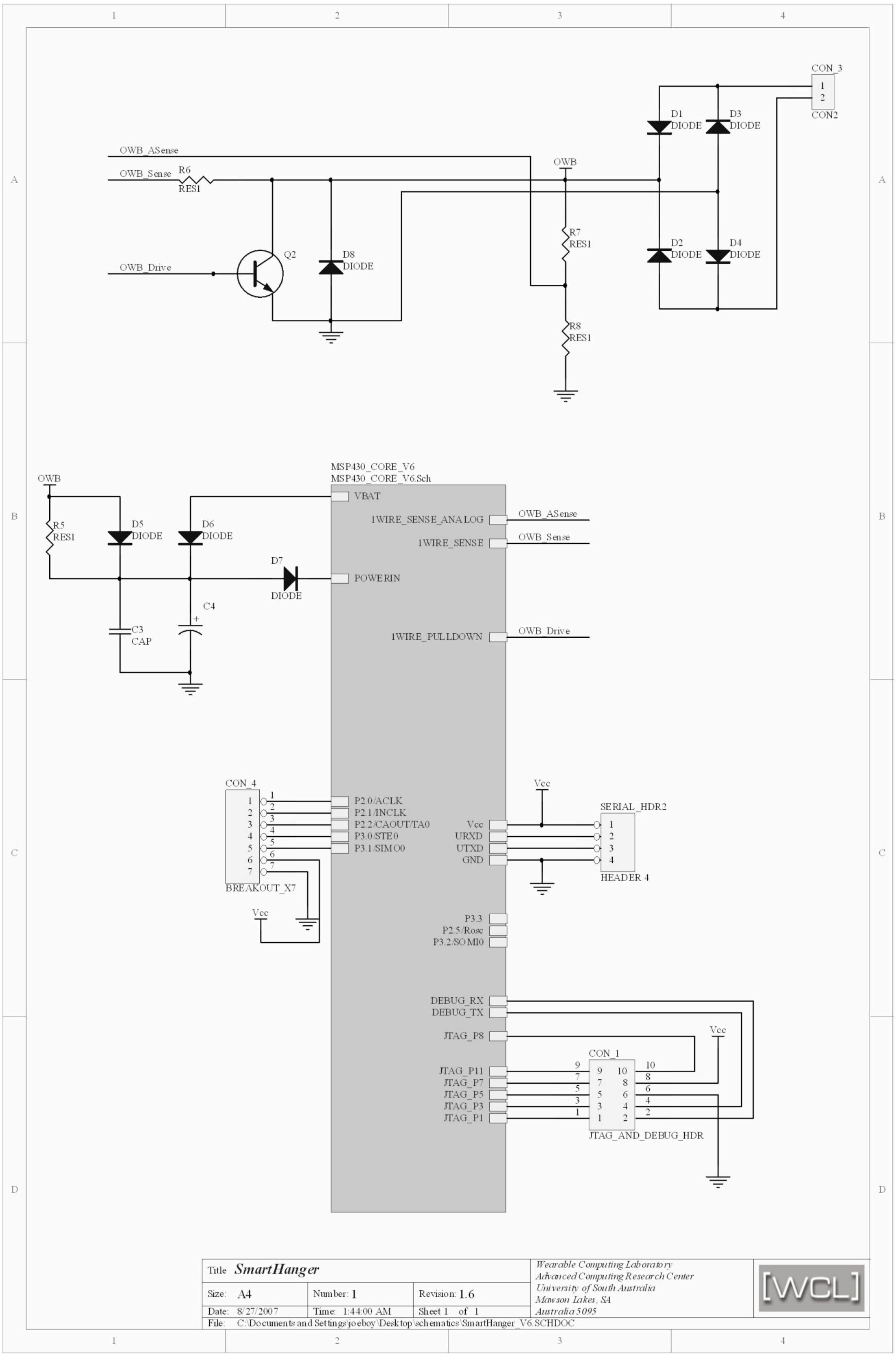


Figure 97 Smart Hanger

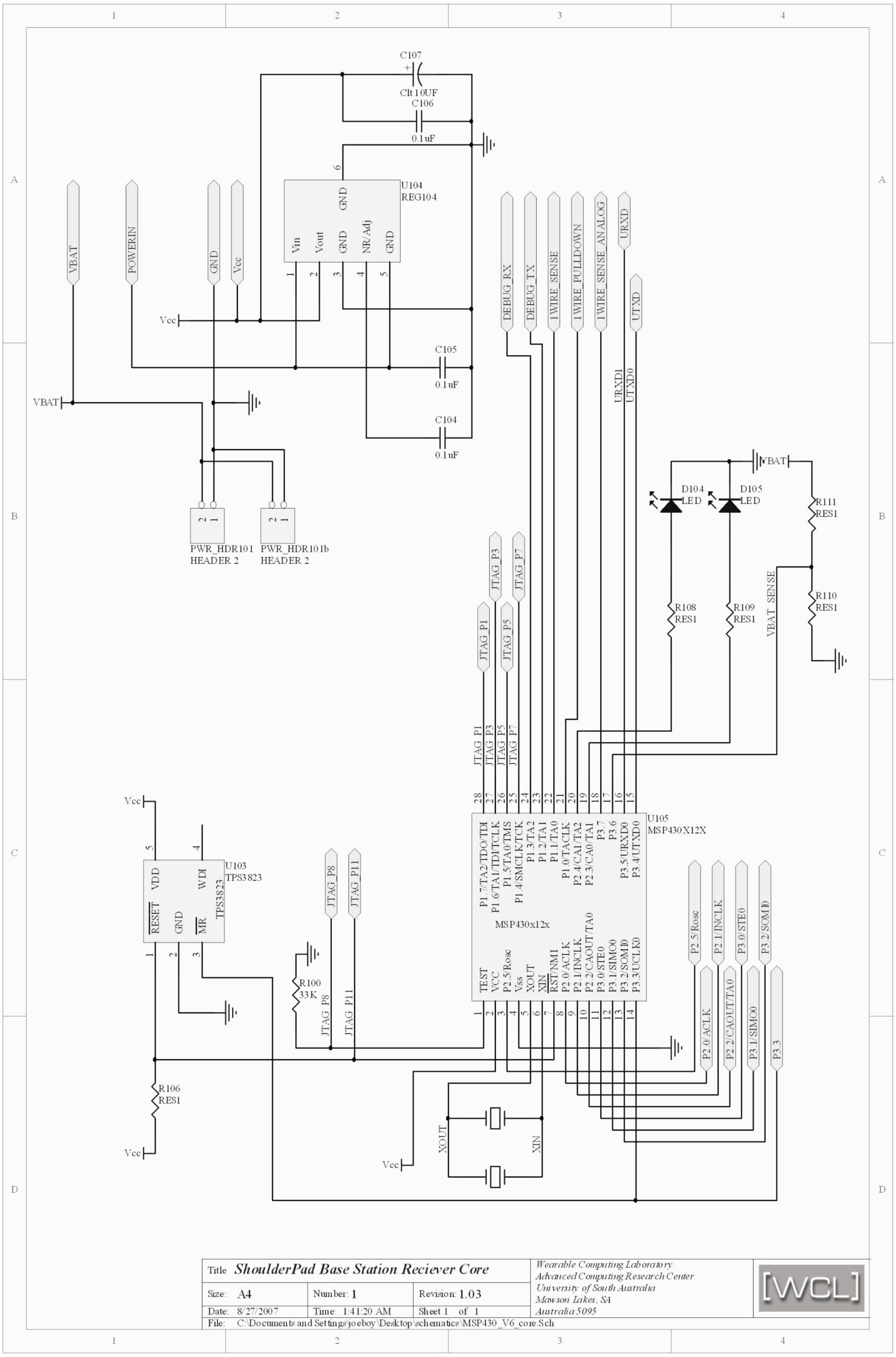
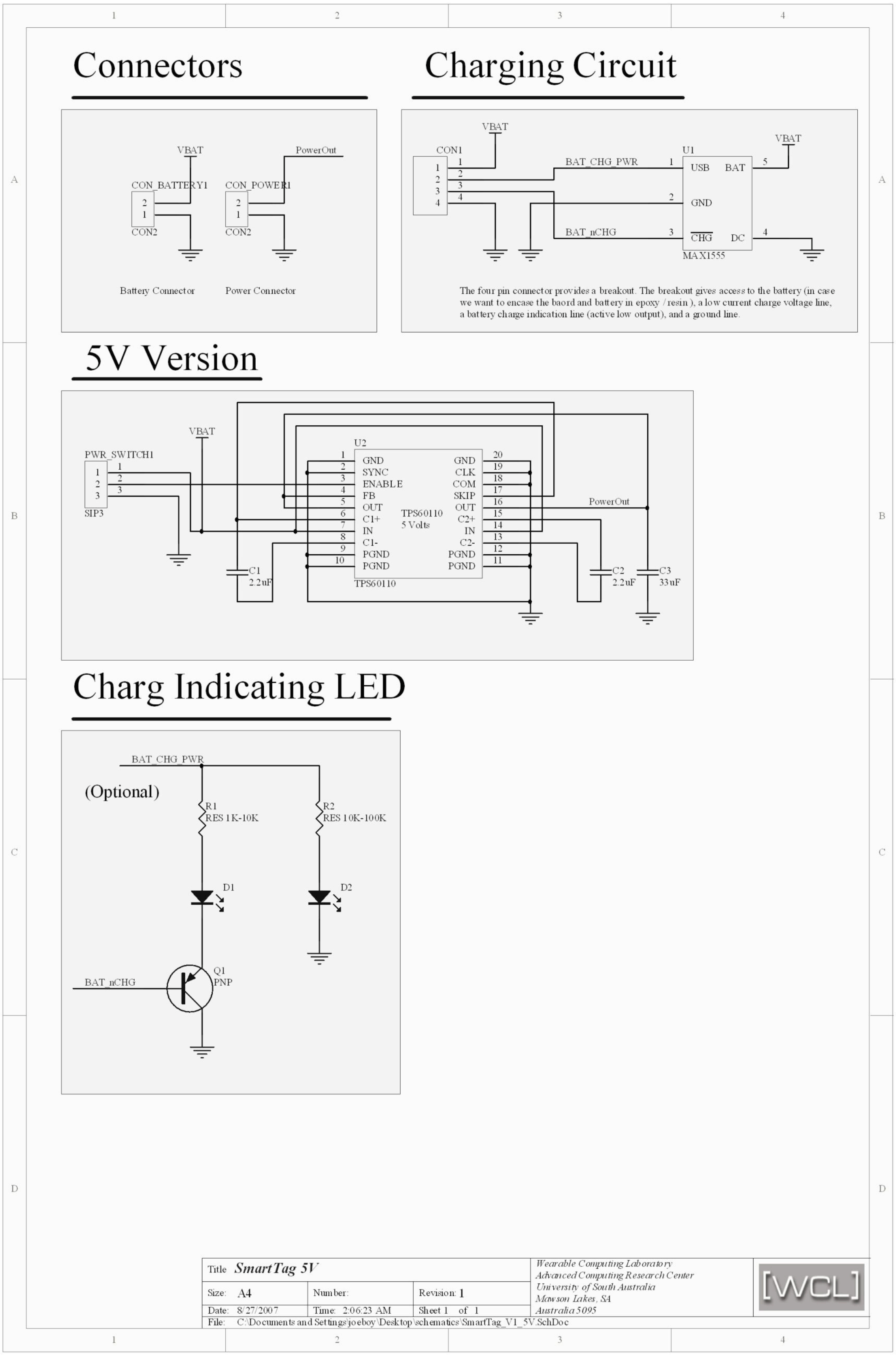


Figure 98 Smart Hanger core

B.5 SmartTags

The SmartTag described in section 5.5.3.2.3 was developed as a demonstration of smart tagging, a modular smart garment prototyping technique. The demonstration SmartTag board was designed to be connected to a Li+ Battery, to manage both its charging, and the power derived from the battery. The battery was charged using a Maxim MAX1555 charger. Designed to charge batteries from the power available from a USB connection the MAX1555 internally limited the charge current to a maximum of 100 mA. The Texas Instruments TPS60110 DC/DC converter was used to regulate the voltage available from the battery, ensuring it remained constant independent of the battery voltage. The SmartTag board contains two diagnostic LEDs that can be seen in Figure 37. One of the LEDs is powered on the presence of charging power, and the other indicating that they battery is currently being charged. The schematics for the SmartTag board are provided in Figure 99.



The four pin connector provides a breakout. The breakout gives access to the battery (in case we want to encase the baord and battery in epoxy / resin), a low current charge voltage line, a battery charge indication line (active low output), and a ground line.

Title *SmartTag 5V*
Size: A4
Number:
Revision: 1
Date: 8/27/2007
Time: 2:06:23 AM
Sheet 1 of 1
File: C:\Documents and Settings\joeboy\Desktop\schematics\SmartTag_V1_5V.SchDoc

Wearable Computing Laboratory
Advanced Computing Research Center
University of South Australia
Mawson Lakes, SA
Australia 5095

Figure 99 Power Regulating Smart Tag

C

"Well, on the bright side I now know just how much
my reach exceeds my grasp."
Ph.D. student.

APPENDIX C - EQUATIONS DESCRIBING TABLE

This appendix summarizes the equations and observations put forth in Chapter 7 and Chapter 8, describing the formation of different types of spaces on the table in terms of user reach. The equations are presented generically and can be applied using either statistical or kinematics based models of reach.

Area reachable by a single hand	A_L, A_R
The area reachable by the left hand, or left-handed reach, is indicated by (A_L), while the area reachable by the right hand, or right-handed reach, is indicated by (A_R). Both mathematical and statistical models describing these reachable areas are presented in Chapter 7. Suitable statistical models are also provided in Appendix A.	

Reachable Space	S_R
For a given posture, the reachable space (S_R) is, by definition, the total space reachable by the left and right hands ($A_L \cup A_R$).	

Bimanual reach	S_{RB}
For a given posture the area of bimanual reach (S_{RB}), or the area reachable by both of an individual's hands, is defined by definition ($A_L \cap A_R$).	
Observations	
Unless driven by the task or interface presented to the user, highest table usage tends to occur in areas of bimanual action (S_{RB}), while lowest usage tends to occur in areas reachable only by one hand (S_R - S_{RB}), or (A_L+A_R).	

Usable space	S_U
For a given posture the usable space defines the set of all points usable by directly manipulated elements of the user interface.	
Observations	
(1) Models that describes S_R also describes a superset S_U (where $S_U \in S_R$) describing the	

<table>
<tr><td>set of all points currently usable by the directly manipulated elements of the user interface. The usable space, S_U, is constrained within the intersection of available working space and the reachable space ($S_U \in S_R \cap S_{WS}$). Given quantitative descriptions of both the working surface and a user's reach, this relationship allows programs to dynamically generate a quantitative description of their maximum potential usable space.

(2) For a moving user, the set of all points usable by the directly manipulated elements of the user interface over some window of time ($S_U |_{t=t_{start}}^{t=t_{stop}}$) is contained within the union of the sets of points reachable by the user during that time; $(\bigcup_{t=t_{start}}^{t=t_{stop}} S_R)$. ; $(S_U |_{t=t_{start}}^{t=t_{stop}} \in \bigcup_{t=t_{start}}^{t=t_{stop}} S_R)$. This allows discreet algorithms segmenting the table accommodate user motion by repeated application, without requiring alteration of the algorithms.</td></tr>
</table>

<table>
<tr><th>Communal or group space</th><th>S_G</th></tr>
<tr><td colspan="2">The communal space for a group is contained within the intersection of its member's reachable spaces. For a group of collaborating users k, the available collaborative space is contained within the intersection of the reachable spaces for each member of the group ($S_G \in \bigcap_{i,i\in k} S_{Ri}$).</td></tr>
<tr><th colspan="2">Observations</th></tr>
<tr><td colspan="2">(1) As the table's size is increased, the collaboration space at the center of the table (S_G or $\cap S_R$) becomes less accessible.

(2) Unless driven by the task or interface presented to the user, for co-located users in an equal power relationship group spaces tend to for form in preference to personal spaces.</td></tr>
</table>

<table>
<tr><th>Private space and affordance of ownership</th><th>S_P</th></tr>
<tr><td colspan="2">For a group of collaborating users k, the available private space for the n^{th} member of the group, their uniquely reachable space, is their reachable space complement the rest of the group's reachable space $(S_{Rn} - (\bigcup_{i\in k, i\neq n} S_{Ri}))$.

Affordance of ownership can be achieved for groups in a similar fashion, by using the union and intersection of its member's reachable spaces. For a group of users k that is a subset of a larger group of users, l, ownership of a user interface element can be afforded either to the group k or to one of its members. To afford ownership to a subgroup the element can be placed in the area uniquely reachable by that group: $((\bigcup_{i\in k} S_{Ri}) - (\bigcup_{j\in l, j\notin k} S_{Rj}))$. This relation also holds for the individual, as that is just a subgroup with a single member.</td></tr>
</table>

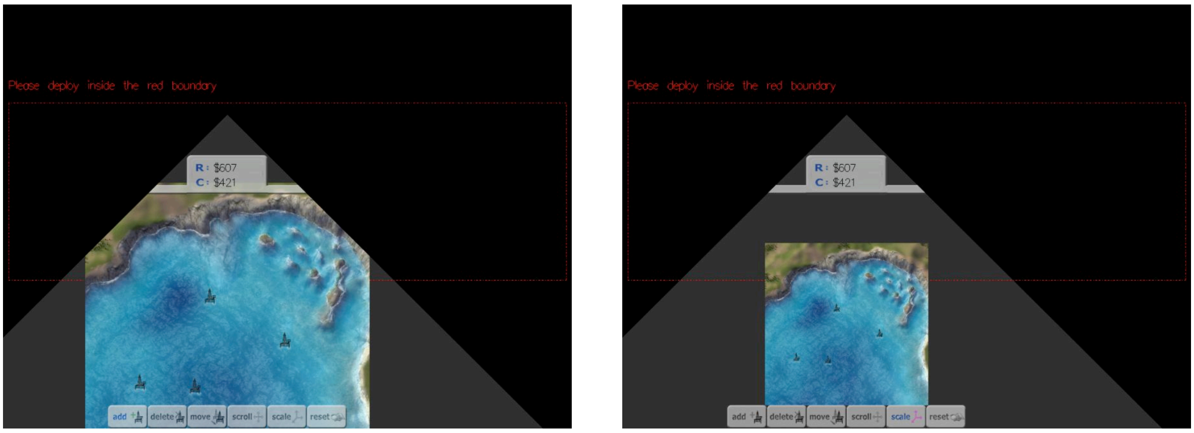
D

"I am finished. Do I get to drive the trains now?"
Ex-Ph.D. student.

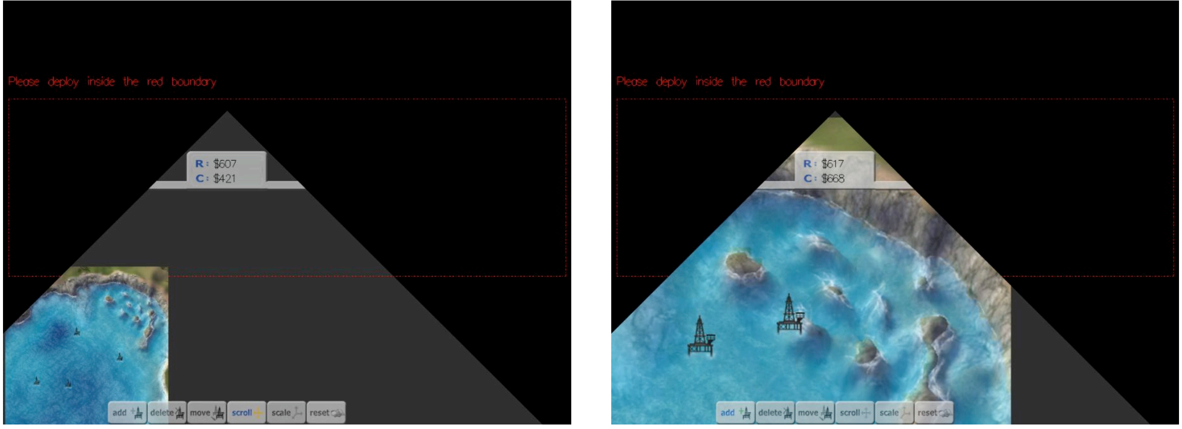
APPENDIX D - DEPLOYMENT STUDY

The simulated deployed application described in Chapter 8 provided users with a scenario represented the incomplete sharing of information between collaborators, a common occurrence in the business world. Each of two users is given a value grid mapping value onto a shared map. After being given time to study the value maps, the maps were collected and the users were asked to find five locations maximizing both their individual and group scores. The reason that this type of incomplete sharing is common in business is that full disclosure is not always possible. A simulation scenario demonstrating incomplete sharing was chosen as it would encourage the users to collaborate across a large working area, encouraging both scrolling and scaling the interface to distinguish local from global score maxima.

The simulated scenario had the users looking for places on an area of coastline to place oilrigs. Users were able to perform four actions with the display space: (1) add or remove elements, (2) scale or (3) scroll the display, (4) reset the display to its default location and size. Examples of actions 1-3 are provided in Figure 100.



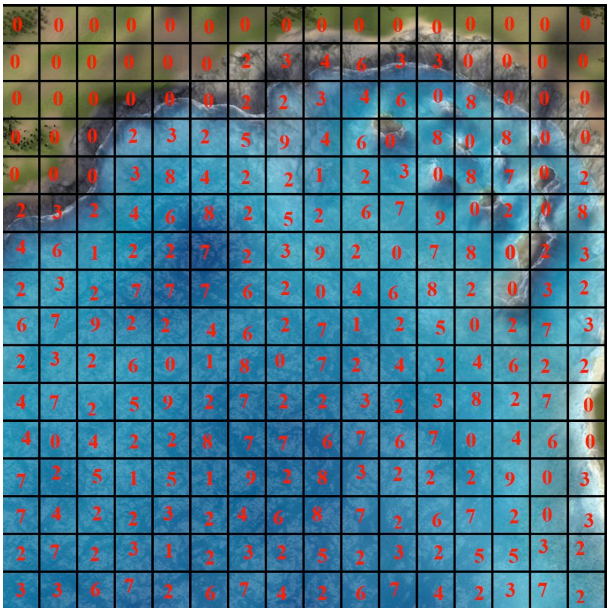
Adding or Removing Scaling



Scrolling Scaled and Scrolled

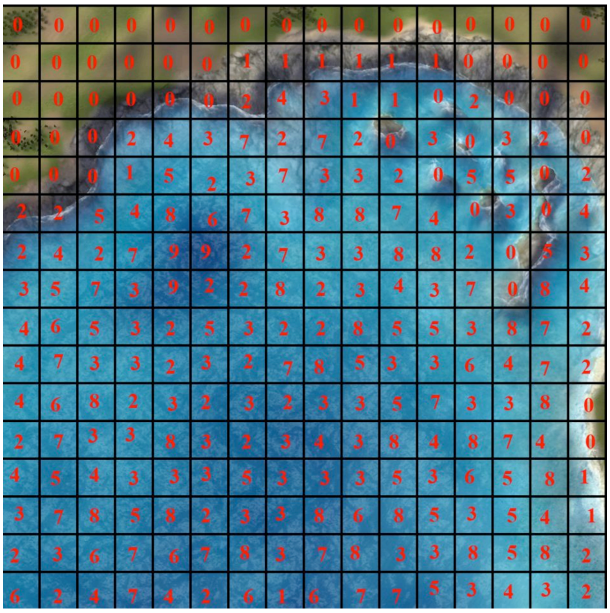
Figure 100 Deployment study application options

The value grids provided single digit values representing either the number of hundreds of thousands of dollars per hour that operating the oilrig within the indicated cell would cost, or the number of hundreds of thousands of dollars of oil that would be generated per hour at that location. The value fields given to each of the subjects are shown in Figure 101 and Figure 102 below.



0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	2	3	4	6	3	3	0	0	0	0
0	0	0	0	0	0	2	2	3	4	6	0	8	0	0	0
0	0	0	2	3	2	5	9	4	6	0	8	0	8	0	0
0	0	0	3	8	4	2	2	1	2	3	0	8	7	0	2
2	3	2	4	6	8	2	5	2	6	7	9	0	2	0	8
4	6	1	2	2	7	2	3	9	2	0	7	8	0	2	3
2	3	2	7	7	7	6	2	0	4	6	8	2	0	3	2
6	7	9	2	2	4	6	2	7	1	2	5	0	2	7	3
2	3	2	6	0	1	8	0	7	2	4	2	4	6	2	2
4	7	2	5	9	2	7	2	2	3	2	3	8	2	7	0
4	0	4	2	2	8	7	7	6	7	6	7	0	4	6	0
7	2	5	1	5	1	9	2	8	3	2	2	2	9	0	3
7	4	2	2	3	2	4	6	8	7	2	6	7	2	0	3
2	7	2	3	1	2	3	2	5	2	3	2	5	5	3	2
3	3	6	7	2	6	7	4	2	6	7	4	2	3	7	2

Figure 101 Revenue by location



0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0
0	0	0	0	0	0	2	4	3	1	1	0	2	0	0	0
0	0	0	2	4	3	7	2	7	2	0	3	0	3	2	0
0	0	0	1	5	2	3	7	3	3	2	0	5	5	0	2
2	2	5	4	8	6	7	3	8	8	7	4	0	3	0	4
2	4	2	7	9	9	2	7	3	3	8	8	2	0	5	3
3	5	7	3	9	2	2	8	2	3	4	3	7	0	8	4
4	6	5	3	2	5	3	2	2	8	5	5	3	8	7	2
4	7	3	3	2	3	2	7	8	5	3	3	6	4	7	2
4	6	8	2	3	2	3	2	3	3	5	7	3	3	8	0
2	7	3	3	8	3	2	3	4	3	8	4	8	7	4	0
4	5	4	3	3	3	5	3	3	3	5	3	6	5	8	1
3	7	8	5	8	2	3	3	8	6	8	5	3	5	4	1
2	3	6	7	6	7	8	3	7	8	3	3	8	5	8	2
6	2	4	7	4	2	6	1	6	7	7	5	3	4	3	2

Figure 102 Cost by location

Upon completion of each session both subjects filled out a questionnaire containing the “post trial questions” shown on the following three pages. The questionnaire contained nineteen statements for the user to rate their agreement on a seven point Lycart scale, and two short answer questions.

Post Trial Questions

Subject Number____________ Date _______________

Please answer the following list of questions by placing an X in the box corresponding with your answer. Each of the questions is a statement. Your answer should indicate the level which you agree or disagree with the statement. Below is an example of a statement and an answer that indicates some disagreement with the statement.

0. This is a statement that I somewhat disagreed with.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
		X				

At the completion of the study please answer the questions below.

Questions to be answered at the completion of the study						
1. I believe that my group worked well together.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
2. I could comfortably access all of the display area.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
3. I felt free to add elements anywhere on the displayed map.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
4. I felt free to remove elements anywhere on the displayed map.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
5. I was more likely to use space reachable by both hands.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree

6. I felt more comfortable using closer areas of the display.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
7. At some time I felt that I owned a section of the display area.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
8. At some time I felt that my collaborator owned a section of the display area.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
9. I was comfortable reaching into the entire area of the projected display.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
10. I was free to redeploy the projected display.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
11. Overall, I felt equally represented when interacting with the display.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
12. It was hard to find the areas of the map I wanted.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
13. Overall, it was hard to reach the areas of the map I wanted.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
14. Overall, the map was at comfortable working size for both myself and my collaborator.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree

15.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
16. Overall, I felt that a projected display was well suited for the task.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
17. I would feel comfortable using a projected user interface for an important business meeting.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree
18. I would feel comfortable using a projected display in a public space, such as a coffee shop.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree

If the projected display was moved, or “redeployed” during the study please answer the following questions.

If the display was redeployed during the study						
1. Redeployment during the study was a positive experience.						
Strongly Disagree	Disagree	Somewhat Disagree	Neither agree or disagree	Somewhat Agree	Agree	Strongly Agree

Suggested Improvements: If there are any improvements you would like to suggest for the study please comment in the space below.

General Comments: If there are any general comments you wish to make about the study pleas provide them in the space below.

Refs

"I sound smarter the more other people are saying the same thing I am."
Ph.D. Student

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