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Tactile Space

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by

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Dedication

To Teri

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Abstract of the Thesis

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By

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As we enter the age of ubiquitous computing, where computers are worn, carried or embedded into the environment, we must be careful that the ideology the technology embodies is not blindly incorporated into the environment as well. As disciplines, engineering and computer science make implicit assumptions about the world that conflict with traditional modes of cultural production. Space is commonly understood to be the void left behind when no objects are present. Unfortunately, once we see space in this way, we are unable to understand the role it plays in our everyday experience. Space is never merely a neutral background for human activity; culture is built into its forms. This thesis introduces Tactile Space, an experimental location aware garment that seeks to address lacuna in the design process of computationally enhanced cultural artifacts and the spaces they inhabit.

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Chapter 1
Introduction

1.1 Overview

Tactile Space emerges from concerns regarding the manner in which the dominance of vision in Western culture affects the ways in which space is embodied and how it is experienced as embodied. The project's goal is to rebalance the senses, to re-embody visual experience. Technologies of representation and abstract systems have drastically altered our conception of vision, of what it is to see, and thus have drastically altered how we actually see. As our culturally dominant sense, vision not only constructs how we perceive space but how we embody space. In this paper, I would like to first briefly outline how abstract systems and technologies of representation alter visual perception. Then I would like to extend this notion more generally to spatial perception. I argue that the fields of computer science and engineering extend this tradition of abstraction of space and as we enter the age of ubiquitous computing, the dominance of abstract visual space in real space is potentially reified. A new approach to the design of computing systems is necessary to re-embody space. The social nature of the interface allows us to situate it within Henrí Lefebvre's notions of space. This provides new tools for thinking about how computing practice engages space and opens avenues to rematerialize the environment through embodied interaction. To conclude, I discuss the current Tactile Space implementation, which creates a tactile representation of a visual spatial analysis shifting the focus of attention back to the body as the locus of spatial perception.

1.2 Visual space

The philosopher Marx Wartofsky has argued for a radically culturalist reading of all visual experience. He concludes that "human vision is in itself an artifact, produced by other artifacts, namely pictures." All perception, he contends, is the result of historical changes in representation. (Jay, 5) Abstract visual representational systems are tacitly learned and internalized with repeated exposure.

For example, today the transparency of the photograph's direct influence on visual perception can be alarming. Susan Sontag warns of a mentality which "looks at the world as a set of potential photographs" and argues that "reality has come to seem more and more what we are shown by the camera." (Pallasmaa, 20) A poignant example of this phenomenon is exhibited in Ralph Weber's *On the Aesthetics of Architecture*. In the chapter on spatial form, he states that that people tend to overestimate the height of vertical objects by an average of 30 percent. Weber explains that this phenomena is why mountains depicted in paintings are "super-elevated compared to their actual condition." To illustrate this, he selects one of Cezanne's landscapes of Mount Saint Victoire and pits it against a photograph of the same mountain. (Weber, 134) What this example clearly illustrates is how technologies of representation alter the way that people believe that they see. In this case, the representation interpreted by a mechanistic visual system is taken as 'more real' than the human interpretation of the same experience. It is a common experience to snap a photo of a mountain, or of a full moon, hoping that you can capture the awe inspired by its size, only to be disappointed at how small they appear in the printed photographs. The idea that the experience is a perceptual or optical illusion presupposes a visuality that is external to lived human experience.

Photographic vision can be traced back to the visual paradigm created by Albertian perspective. Alberti's statement, "Painting is nothing but the intersection of the visual pyramid following a given distance, a fixed center and certain lighting" (Pallasmaa, 17) implies an equality between the image in perspective and visual experience that survives to this day.

> "The convention of perspective, which is unique to European art and which was first established in the early Renaissance, centers everything on the eye of the beholder. It is like a beam from a lighthouse–only instead of light traveling outward, appearances travel in. The conventions called those appearances reality. Perspective makes the single eye the center of the visible world." (Berger, 111)

Perspectival representation does not equate to the visual experience of two active, stereoscopic eyes; it is instead the experience of a monocular abstract point. The problem is that it claims, and is believed, to authoritatively represent reality. And that reality is that of the disembodied viewer "separated from the seen (the scene) by Alberti's shatterproof window." (Jay, 55)

Although the authority of perspectival systems of representation is presently almost ubiquitous, its history provides an example of how vision has changed. At its conception, it was not universally accepted as an accurate depiction of reality. To many of those schooled in vision of the fourteenth century, its acceptance came only gradually, and sometimes with misgivings. Brunelleschi himself is said to have even felt the contradiction between the system and the evidence of his eyes. (White, 206) Leonardo da Vinci invented a method of perspective that entailed foreshortening not only into the picture plane, but horizontally and vertically across it as well. Leonardo's synthetic perspective was concerned with the transference of the subjective appearances of the real world, both the physical and psychological, onto a flat surface. His method was based on curves rather than straight lines. Contrary to Alberti's plane intersecting the pyramid of vision, da Vinci favored a sphere, concave to the eye, intersecting the visual cone. (White, 207-208)

Interestingly, despite the obscurity of Leonardo's synthetic perspective, it seems much closer to what we now know of biological perception than does that of Alberti. Gibson notes:

> "if we combine all these two-dimensional projections of a three dimensional visual world into a single scene, we would obtain a two-dimensional space, in the geometrical sense, which is non-Euclidian. It would have the properties of the theoretical space defined by the

> surface of a sphere considered as a two-dimensional surface, i.e. it would be boundless yet finite, and it would return upon itself. The space composed of one's combined visual fields may be said to be a curved space in the sense that a point which traces a straight line will eventually come back to the position from which it started instead of traveling off endlessly in the same direction." (Gibson, 122)

Even though this model of vision has been at odds with experience since its inception it has survived and conquered Western culture as evidenced by uncountable ubiquitous photographic/filmic images. Linear perspective provides a precedent, or at least an initial mental picture for the abstract rationalization of space that is later fully articulated by Descartes. Cartesian notions of space continue to be the dominant view in Western culture. Hillier describes the dominant view of space in western culture as 'Galilean-Cartesian.' Following the reasoning of Descartes, space is defined as follows. The primary properties of physical objects are the measurable ones, called extensions, such as length, breadth and depth. These properties are objective and presumably do not rely on interaction with human observers. Space, it follows, is extension without objects. Space is merely the void left behind when no objects are present. This view seems to some to be quite natural. Unfortunately, once we see space in this way we are unable to understand the role it plays in everyday experience. Space is never simply the inert background of our material existence. It is more than a neutral framework for social and cultural forms. It is built into those forms. Human behavior does not just happen in space; it constitutes space. "Encountering, congregating, avoiding, interacting, dwelling, eating, conferring ... themselves ... constitute spatial patterns." (Hillier, 29) Cartesian notions of space only account for how it can be abstractly described, lived experience matters little within this conceptual framework.

In some ways, Cartesian space and the space of linear perspective are similar. With current technology it is possible to create a model of an inanimate object in a three dimensional, virtual Cartesian space and effectively render it as passable for a photograph of a similar object. The problem with both of these systems is a problem of the body. In linear perspective the viewer is merely a point in space, while in Cartesian space the body has been abstracted away entirely. The reason that these systems fail at a certain point is that we cannot begin to understand space without the body.

1.3 Tactual Space

The way the body senses is referred to as the tactual sense, which consists of the tactile sense and the kinesthetic sense. The tactile, or cutaneous sense refers to awareness of stimulation to the skin. The kinesthetic, or proprioceptive sense refers to the awareness of limb positions, movements, orientation and muscle tension. The tactual forms the basis of our ability for spatial perception. Consider this passage from Ashley Montagu's *Touching*:

> "What we perceive through the other senses as reality we actually take to be nothing more than a good hypothesis, subject to the confirmation of touch. Observe how often people will respond to a sign reading, "Wet Paint." Quite frequently they will approach and test the surface with their fingers for themselves." (Montagu, 100)

Even though ideas about vision have lost the body, “touch and visual spatial experiences are so interwoven that the two cannot be separated.” (Hall, 60) For example, texture is appreciated almost entirely by touch, even when it is sensed visually. “With few exceptions, ... it is the memory of tactile experiences that enables us to appreciate texture.” (Hall, 62) In fact, recent neurological research suggests an even deeper connection. In tests on monkeys it has been observed that “the premotor cortex contains neurons that discharge both when the monkey grasps or manipulates objects and when it observed the experimenter making a similar action.” (Rizzolatti & Arbib) There is part of the primate brain that directly connects the visual and the kinesthetic.

1.4 Towards the age of ubiquitous computing

Technologies are not mere exterior aids but interior changes of consciousness that shape the way the world is experienced. (Ong) We are currently in the midst of another collective change of consciousness – the age of the computer. The computer arises from Western scientific ideology which is built upon the assumption that the mind is separated from the body. The influence of this assumption is present at all levels of the technology, from the architectural level in the hardware/software split to the reduced set of body senses/movements engaged by its interface. This conflict between the abstract and the embodied is beginning to take the stage of the everyday as the digital/informatic realms, which have been inherently abstract, come directly into contact with cultural forms which have traditionally been inherently bodily processes. As we enter the age of ubiquitous computing, where many small computers will be worn, carried or embedded into our everyday environment (as computers 'disappear'), we must be careful that the values they embody are not blindly incorporated into the environment as well.

Early development in information technology followed the legacy of industrial interface design. In the early 20th century, as automation replaced humans in the workplace, its goal was to eliminate participation wherever possible. Consideration for the user has lagged behind the need to interact with computers. Computer science has a history of venturing blindly into disciplines, wielding the authority of the capital used to finance its research. For example, years of computer animation research were conducted before any computer scientists had any meaningful interaction with an animator. While research in human-computer interaction has been fruitful in certain areas, such as visual displays, it is not prepared to take on the design of physical spaces. In his book *Digital Ground*, Malcolm McCullough states, "Notions of what a computer is have not kept pace with realities of how digital systems are applied." The use of computers has evolved from its origins in mainframe computing and one computer for many users to the current age of desktop computing, with a one-to-one ratio of computers to users. Recent trends in computing have given rise to a third age of computing, where many, possibly thousands, of small computers are worn and/or embedded into the environment. In this age of ubiquitous or pervasive computing, the human/computer ratio jumps from 1:1 to 1:1000s. In some ways, it can be argued that the age of ubiquitous computing is well on its way. The average American already owns twenty or more computers, although most are devices that someone would normally not refer to as a computer. Televisions, VCRs or DVD players, microwave ovens, cell phones, as well as many components of modern automobiles (anti-lock brakes, fuel injection and climate control for example) contain information processing components. Even today, these computers, often referred to as embedded systems, are being produced at much higher volume (billions/year) than desktop PCs (millions/year). At the current moment, the vast majority of these computers act in isolation. However, in the future, an increasing number of computers embedded in the environment will be networked and communication, sensing and information processing will disappear into the environment. As information technology becomes part of the social infrastructure, it demands design consideration from a broad range of disciplines. Appropriateness now surpasses performance in importance in technological design. "Appropriateness is almost always a matter of context. We understand our better contexts as places, and we understand better design for places as architecture." (McCullough, 2-3)

Somewhat appropriately, 'context' is a popular topic in current ubiquitous or pervasive computing research. Most early papers, and even some recent ones, make a point to say that context is more than just location (see Abowd and Mynatt, 2000). What is included in context changes from researcher to researcher, but a couple of other typical variables are time, identity, identity of others, etc. Location is often an (x,y) or latitude, longitude if using GPS. Sometimes location is specified by building or room. The overwhelming majority of these research environments are for work settings and are focused on applications such as “How can we tell when a meeting is taking place?” so that presumably it can be recorded.

Although it is a step forward that computing has realized the importance of the social, and has begun in its own way and with the aid of interdisciplinary researchers to understand it in relation to computing, it is primarily focused on work environments. Social and spatial interactions as they relate to the production of capital are important, not the implications of technology on the everyday. However, computing has become part of the ambient, social, and local provisions for everyday life and as such it becomes important to look at the larger impact of computation on culture. Computing has revolutionized almost every discipline, and is continually increasing its presence in day to day life. However, it reifies an ideology which subordinates the body and physical experience.

1.5 The “engineering worldview”

As computers ‘disappear,’ care must be taken to avoid blindly incorporating the ideology they embody into the environment as well. The digital computer is constituted by the ideology of the discipline from which it arose, which, to reiterate, Simon Penny refers to as the “engineering worldview.” (Penny) Penny’s engineering worldview is an amalgam of capitalism, Western science and engineering. He argues that core ideas unite the scientific method, the logic of industrial production, and capitalism. Reductionism, the first of these ideas, allows a system to be rationalized into its individual components and logically maximized in terms of output.

Employed by industrialization, this method has generated a great deal of wealth and power which has consequently led to its privileged ideological position. The engineering worldview, or “the ideology of efficient production,” is constituted of:

> “a nineteenth and early twentieth century scientized approach to the world: that mind is separable from body; that it is possible to understand a system by reducing it to its components and studying these components in isolation (that the whole is no more than the sum of its parts); that the behavior of complex systems can be predicted.” (Penny)

Penny argues that these values find their purest expression in the digital computer. Evidence abounds for this assertion in computing, ranging from the architecture of the machine itself to its metaphorical usage in contemporary culture. The top-down hierarchy of the mind/body split is echoed in the division of computer systems into hardware that is controlled by software. The computer has also become a structuring metaphor for many human activities, up to and including the study of the mind. It is not uncommon to hear current researchers in cognitive and neuroscience describe the brain as a computer, and even model it as such (as discussed in Varela, Thonmpson and Rosch, 1993).

As the "(quintessential) product of the engineering," digital computers tacitly propagate this ideology with repeated exposure and interaction. The majority of research in human computer interaction has focused on the visual or aural modalities. Very little has been focused on the tactual senses. They are the farthest away from pure reason or thought, a belief upon which computing is founded: the mind/body split. The mind/body split has been challenged time and time again from all angles: philosophy, linguistics, biology, neurology, cognitive science, art, and even computer science (Dourish). However, embracing what embodiment means is difficult in a language that reifies the ideology. We talk of "my hand" or "my head" as if they are objects that we own, not inseparable parts of our being. To describe what is meant by embodiment, we must use neologisms such as the embodied mind, being-in-the-world, the life-world, etc. An embodied perspective that is not clouded by traces of duality is difficult, at best, in contemporary Western culture. In computer science, where the ideology is ingrained in the technology itself, it presents an even stiffer challenge. In order to re-embody notions of space, especially computer mediated space, there are two areas that must be addressed: the body and the interface. We have previously discussed the lack of the body in abstractions of space, but it is important to clarify exactly what is meant here by 'embodiment'.

1.6 Embodiment

The term ‘embodiment,’ as is used here, does not simply state the fact that humans have bodies. It is not a notion of an embodied mind that still clings to sacredness of consciousness or abstract rational thought, and thus still leaves them outside the realm of the physical body. It has been shown that even a change in posture, while maintaining identical sensorial stimulation, alters neuronal responses (Varela, 10). Embodiment is the relationship between meaning and action, and “the process of grasping a meaning is performed by the body.” (Merleau-Ponty, 153) Thus, the methods for making sense of action and the methods for engaging in it are the same methods. (Dourish, 79) This argument for embodiment comes from the philosophy of phenomenology, which focus on the world as it is lived in and experienced, not the world as it appears when we stop acting and start thinking about it.(Loren and Dietrich, 347) Understanding the world as the experience of an embodied mind creates a strong connection between person and their environment. From a biological perspective, Maturana and Varela have described this relationship as structural coupling. It is the process of an organism interacting with their environment where “the structure of the living system and the structure of the medium change together congruently as a matter of course.” (Maturana, 12) Therefore, the mind is inseparable from the body, and the body inseparable from the environment.

Chapter 2
Interface and Interaction

2.1 Introduction

How does the computer participate in the world it represents? This question illustrates the design challenge that results from the conflict between the "(quintessential) product of engineering" and all of the "spaces" that it inhabits. Computation is a fundamentally representational medium, and as the ways in which we interact with computers expands, so does the importance of attention paid to the duality of representation and participation. (Dourish, 20) The focus of this attention, and the place where this conflict is potentially best solved is at the interface, the point or area in which the person and computer come into contact.

The transition to ubiquitous computing means a change in interface. Most people are familiar with the traditional WIMP (Windows, Icons, Mouse, Pointer) desktop interface that came into being in the 1970s. Disappearing into the environment translates into many new interfaces. The difficulty of this design challenge should not be underestimated. The multitude of VCR clocks across the land blinking 12:00

is evidence of that. While commercial electronics manufacturers have spent a considerable amount of time and money developing interfaces for 'everyday' devices, their success has been moderate at best. When the interface is done correctly, the cultural impact can increase exponentially. Apple's iPod may be the best illustration of this point. Downloading music and portable mp3 players long predate the iPod. However, the devices were often complicated to use/navigate and were primarily purchased by early adopters. The iPod, with relatively few buttons and scroll wheel for navigating menus, proved to be intuitive to even the techno-novice. An intuitive interface coupled with a beautiful object resulted in a new cultural icon and a largely recognized change in the way that people listen to music. The examples of the VCR and the iPod demonstrate the importance of the interface on the overall cultural impact of a technology. [the VCR as a recording device was never widely utilized, Tivo (or digital video recorders) would be an example of a better interface to a functionality similar technology]

2.2 Taxonomy of interactive systems

(Sparacino, Davenport, Pentland 2000) have suggested a taxonomy of interactive systems. They do not claim their list to be exhaustive, but it may serve as a good starting point. They classify interactive systems as: scripted, responsive, behavioral, learning, and intentional. They consider their field of interactive systems to include multimedia communications, electronic art, (interactive) performance, and entertainment in general. Scripted systems use a central program to control the presentation of audio or visual material to the audience. The interaction modality is often restricted to clicking on a static interface in order to trigger more content. In this method, one has to carefully list and plan for all the combinatorics of possible interactions, such as breakpoints in the 'score' for input. Nothing happens unless you 'click on the right spot'. (Sparacino, 481) Responsive systems, in this taxonomy, are defined by a series of couplings between user input and the response of the system. Here, one-to-one mappings define a 'geography of responses' that shapes the user's experience. However, the same action by the participant always produces the same response by the system. As Sparacino has noted, "Many sensor based real time art applications are modeled according to this approach." Systems whose response is a function of the sensory input as well as its own internal state are referred to as behavioral. They provide a one-to-many mapping between the user's input and the response of the system. Sparacino, et al state that ideally, "the public should be able to narrate the dynamics of the encounter with a synthetic behavioral agent as they would narrate a story about a short interaction with a living entity, human, or animal." Then there are learning systems, which can learn new behaviors or modify existing ones. And ultimately, for Sparacino et al, are intentional systems, which adds a perceptual layer between the sensory data and the system response. This layer provides the agent with an interpretation of the interactor's intentions - a primitive "user model" of the system. They claim that the intentional approach more closely simulates the dynamics of a human encounter, such as the communication of emotion (Sparacino, 483).

While this taxonomy may be justified in looking down its nose at simplistic interactive art installations, it does not seem apparent that there is a place in it for systems that do not strive to interact with humans as other humans do. If one does not assume that they will be interacting with a human-like or anthropomorphized entity, the term ‘responsive’ is no longer derogatory. In describing human-to-human interaction a person who is described as ‘responsive’ is participatory, but not necessarily fully engaged. However, if the word ‘responsive’ is used to describe an object, or a landscape, it takes on a whole new meaning. Thus the word loses its pejorative tone in this conception of responsive media.

2.3 Responsive media and embodied interaction

There are two primary groups (although there is considerable overlap between the two) who have been experimenting with the computer interface: computer scientists/engineers and artists/designers. These disciplines, now more so than ever, rub together, intersect and/or overlap, but their goals and approach are generally different and thus still warrant separation. This discussion is best framed by two strategies that approach the middle of this emerging continuum rather than the extremes. Both strategies address the interface by challenging current models of interaction. The two are similar in that they look to phenomenology to remedy the problem of the body in computational media. Phenomenology is an appealing framework because it deals with direct experience, and the interface is, in many ways, the 'experience' of the system. We will start in the arts with the Topological Media Lab’s notions of ‘responsive media’ and ‘media-as-material’ and then return to computer science with Paul Dourish’s ‘embodied interaction.’

2.3.1 Responsive media and media-as-material

To create embodied computational media, a new design method is needed. One such method, practiced by the Topological Media Lab, is to view media as material. An analogy would be to manufacture cloth, rather than tailoring a jacket. For example, instead of assembling a group of video clips to be used as framed image objects for their representational or symbolic value, video is used as structured light for its plastic and luminous qualities (Sha, 42-43). This method allows for media to be transformed and combined dynamically in ways that would not be possible with an imposed script or structure (tailoring a jacket). Using media as material also shifts the focus from what the media represents, to how it behaves. Is it soft and pliant like clay, or brittle like shale? Does it swirl at the slightest touch like smoke or respond less enthusiastically like sludge? Media as gesturally shapeable and transformable 'stuff' links action and meaning at its core.

This method of creating responsive systems is not constrained by discrete rules. Materials in the world exist, have properties and behavior yet do not necessarily prescribe any action. A lump of clay may go unnoticed by one, used to make a sculpture by another, and be enjoyed by the feeling of it squeezing between their fingers by yet another. Either way, there is no puzzle to be solved, as is the case in many interactive artworks. There is nothing special that one has to do or figure out to 'make it work'. In the standard computer interface of monitor, mouse and keyboard, focus is always directed at or represented by a single point. One window is always active, and the mouse is always in exactly one spot. This implies a sequential organization for interaction. (Dourish, 50-51) Conventional linguistic techniques, such as narrative are not necessary to create a compelling experience. This approach provides an alternative to if/then logic and traditional linear script and score based work. There is also no need for syntax–there are no wrong movements (Sha, 41). Every movement/gesture is causally linked to a media response. Because of this, there is no reason to try to model the user's cognitive or emotional state (Sha, 26). For example, a violin neither knows nor cares if the person playing it is a novice, amateur, or virtuoso. If the player bows in a certain way, no matter their skill level, they will make the same sound. Similarly, the violin does not decide whether the person playing it is happy, angry or sad, but someone watching or listening may very well be able to.

How do responsive systems work? There are three main components: 'physicalistic' systems, hybrid space, and continuity. A small set of rules, or imaginary physics, are needed to determine the capabilities of the materials and how they work together. The rules do not necessarily have to mimic actual physics, and they surely do not have to behave as a physical simulation, thus the term 'physicalistic'. The rules need to causally connect the participant's actions with the response of the system. The system response will vary, dependent upon the desired overall affect. Rather than create a world from scratch, like virtual reality, responsive systems take advantage of real material space. For one, the real world enjoys higher resolution and lower latency than any computational simulation of it. More importantly it is also the only place where the participants are physically instantiated.

In this space, their movements and gestures are connected to both the physical and media environments. This leads to the last component, continuity. The everyday world of experience is continuous. Living consists of constant experience across the senses: visual, auditory, tactile, proprioceptive, etc... Every action in a responsive space stirs media processes in tandem with the physical material world. In this way meaning and action are connected to form embodied experience.

2.3.2 Embodied Interaction

While the Topological Media Lab's approach challenges traditional notions of interaction design and potentially how one may think about media or computationally rich environments, Paul Dourish has taken a more practical approach in the realm of computer science while sharing some of the same spirit. In his book, *Where the Action Is*, Dourish outlines 'embodied interaction,' a design methodology that emphasizes skilled, engaged practice in interacting with computers rather than disembodied rationality. This idea is culled from the examination of two current areas of research in human computer interaction: tangible computing and social computing. Among the goals of both of these programs is to make computers easier and more meaningful to use by addressing deficiency in current computing paradigms. Through a phenomenological lens, Dourish sees embodiment at the foundation of both of these programs and proposes embodied interaction as a response.

Tangible computing, which stems from Ishii and Ullmer's work on 'Tangible Bits' at the MIT Media Lab. Tangible Bits tries to tap into tacit knowledge that people have acquired about manipulating the physical environment and translate it into manipulating bits in the digital realm. By taking computing off of the desktop and situating it in physical space, interaction and attention are no longer by necessity serialized. Ambient information reinforces the importance of peripheral attention. Computable objects/actions are no longer confined to visual representation alone as they extend out into real space and time. While tangible computing does re-engage the body in interacting with computers, it stumbles due to the conflict inherent in trying to bridge the gap between the physical and the virtual, the abstract and the concrete. It is not always clear how to best map one to the other, and vice versa, without sacrificing some of the material benefits of either.

Dourish uses the term 'social computing' to refer to the design of computational systems accomplished with a sociological understanding. Although computers are often thought of as just a tool, a sociological understanding is useful when considering the context in which computing systems are used. Context can mean any number of things involving the both the user and system: the tasks to be completed, the setting for those tasks, etc… However, the context is as much social as it is technical.(Dourish, 56) Computation can be both a tool of and structuring force behind the relationships between people, institutions and practice. All interactions with computer systems are at some level a social activity. Even if one uses a computer in isolation, there is a social interaction present between the user of the system and the designer of the system. A user only knows how to use a computer system through a shared set of social expectations.

Tangible computing and social computing share a common foundation grounded in notions of embodiment, and it is from these notions that embodied interaction rises. Embodiment in this context is a property of interaction, not of the systems or technologies themselves. In this way embodied interaction runs counter to Cartesian approaches that separate mind from body and thought from action by emphasizing their duality. “We act in a world that is suffused with social meaning, which both makes our activities meaningful and is itself transformed by them. Our actions cannot be separated from the meanings that we and others ascribe to them.” (Dourish, 189) Embodied interaction’s foundation is described by six design principles: Computation is a medium; Meaning arises on multiple levels; Users, not designers, create and communicate meaning; Users, not designers, manage coupling; Embodied technologies participate in the world they represent; and Embodied interaction turns action into meaning.

Chapter 3
Towards Embodied Spatial Interaction

3.1 Embodiment and social space

Responsive media and embodied interaction provide conceptual tools for designing computer systems that emphasize the importance of the body in everyday experience. They provide ways of designing interactions that reinforce body knowledge and embedded social practice rather than forcing the user to adapt their actions to conform to larger abstract systems. How does this help us with the larger problem of space?

It is here that it may be helpful to look at the work of French, Marxist philosopher Henrí Lefebvre, most notably *The Production of Space*. Lefebvre believes that any attempt to understand the contemporary world that ignores spatial considerations are both partial and incomplete. The meanings that we attribute to space are inextricably bound with our understandings of the world in which we live. As has been stated prior, our basic understanding of the world originates from the sensory spatial relationship between our body and the world. Our understanding of space is directly related to our understanding of the space of our body, which has long been sundered in Western culture by the Cartesian duality. If we do not accept this separation, what is the resultant space?

Lefebvre confronts considerations of space that reside "comfortably enough within the terms of mental (and therefore neo-Kantian or neo-Cartesian) space." His central claim, that space is a social product, directly challenges the predominate "idea that empty space is prior to whatever ends up filling it." (Lefebvre, 15). Lefebvre's re-conceptualization of space is, at least partially, related to his conception of the body and its place in Western culture.

> "Western philosophy has *betrayed* the body; it has actively participated in the great process of metaphorization that has *abandoned* the body; and it has *denied* the body." (Lefebvre, 407)

Lefebvre describes the body, as he does many things, in the form of a triad: perceived–conceived–lived. Introducing a third term into the equation already destabilizes any notions of Cartesian duality. The body, as simultaneous subject and object, "cannot tolerate such conceptual division," (Lefebvre, 407) and can be liberated through a production of space. This occurs, in part, through the distinction between physical, social and mental space. Lefebvre states:

> Social space will be revealed in its particularity to the extent that it ceases to be indistinguishable from mental space (as defined by philosophers and mathematicians) on the one hand, and physical space (as defined by practico-sensory activity and the perception of 'nature') on the other. (Lefebvre, 27)

The unique properties of social space allow it to become the site for reconciliation between the physical and the mental, concrete and abstract.

3.2 Introduction

Social space can be broken down further into the triad spatial practice–representations of space–representational space. Lefebvre describes each as follows (Lefebvre, 33):

> 1. *Spatial practice*, which embraces production and reproduction, and the particular locations and spatial sets characteristic of each social formation. Spatial practice ensures continuity and some degree of cohesion. In terms of social space, and of each member of a given society's relationship to that space, this cohesion implies a guaranteed level of *competence* and a specific level of *performance*.
>
> 2. *Representations of space*, which are tied to the relations of production and to the 'order' which those relations impose, and hence to knowledge, to signs, to codes, and to 'frontal' relations.
>
> 3. *Representational spaces*, embodying complex symbolisms, sometimes coded, sometimes not, linked to the clandestine or underground side of social life, as also to art (which may come eventually to be defined less as a code of space than as a code of representational spaces).

Spatial practice is closely related to perceived space. It is the space secreted by society, recursively reifying it. It falls between daily routine and the infrastructure that allows it–the actual routes and networks that organize the daily routine. Ultimately, it is in spatial practice where the effects of ubiquitous or pervasive computing design will be felt and internalized. Computing is part of the infrastructure that organizes daily life.

Representations of space refers to conceived space. It is the space of scientists, architects, urban planners and all who privilege the cognitive over the perceptual or lived. It is the dominant space in our society, and it is the space of contemporary visual and computing cultures. It is a mental space separated from physical space, or abstract space imposed on concrete space.

Representational space corresponds to lived space, it is where meaning resides. It is "directly lived through its associated images and symbols." (Lefebvre, 38) It is the passively experienced space, which overlays physical space, which the imagination is able to change and appropriate. Representational spaces "tend toward more or less coherent systems of non-verbal symbols and signs." (Lefebvre, 38) Embodied interaction moves the design of computing systems from representations of space to representational space, from conceived to lived space.

These spaces are not always clearly differentiable, they overlap and intermingle in varying intensities. Lefebvre states that in order to understand these three moments of social space, one can map it to the body. The spatial terms (spatial practice, representations of space, representational space) are analogous to the bodily triad of perceived–conceived–lived. (Lefebvre, 40)

Physical	Mental	Social
Spatial practice	Representations of space	Representational space
Perceived	Conceived	Lived

Table 3.1 Lefebvre's spatial and body triads

Lefebvre seems to imply that these triads are in some ways analogous although different. If social space reconciles the duality of the mental and the physical with a nature that is both abstract and concrete, one may also argue that representational space holds a similar position between spatial practice and representations of space just as the lived does between the perceived and conceived. If all interactions with computer systems are social, and the social is the space of embodiment, where mental physical and mental co-mingle, this is the location in which embodied interaction will operate. The layered interfusion of spaces presented by Lefebvre provides a rich framework for thinking about the possibilities of embodied interaction as it extends into everyday space while simultaneously reflecting embodied interaction's careful negotiation between technology and human beings.

Chapter 4
Wearing Embodied Space

4.1 Introduction

Lefebvre's project reframes the everyday by making it appear unusual, in order to foster a deeper exploration and understanding of it. In a similar fashion, the Tactile Space project aims to take ordinary spatial experience and alter it so that it feels somewhat foreign. By making the usual unusual, the participant is encouraged to think about the aspects of their everyday spatial experience that typically go unnoticed in the background of their attention. Tactile Space is the first iteration of a larger project, of which looks at the relationship between the visual, the tactual, and everyday computing and spatial practices. This version looks primarily at the relationship between vision and the tactile in the functioning of built form. The goal is to rebalance or shift focus among the senses by taking the subtle visual cues that walkers subconsciously follow (Rana, 125) in the built environment and converting them into a conscious but peripheral tactile sensation. The tactile display emphasizes the body in the act of seeing with touch and vision inextricable bound. Visual space is nudged from out there to right here.

Why tactile? In an effort to create embodied spatial interaction, the body itself seems like the logical place to start. The majority of research in human computer interaction has focused on the visual or aural modalities; very little has been focused on the cutaneous senses (Tan). In this chapter, I propose that a combination of vibro-tactile displays and wearable computing is suitable to address lacuna in the design process of computationally enhanced cultural artifacts and the spaces they inhabit. First, a brief discussion about the importance of the skin, and why vibro-tactile stimuli are advantageous for use in human computer interaction. Next is a survey of tactual interfaces from early sensory substitution work in the 60s and 70s to contemporary work in wearable and ubiquitous computing. Then follows a brief discussion of how the skin senses vibratory stimuli, the dimensions that can be used for design/communication, and the perceptual effects that can be achieved. In conclusion, wearable vibro-tactile devices are discussed in terms of creating an embodied sense of space.

4.2 The skin

> "The skin is the largest organ of our body, yet only a small portion of it (i.e. the hands) is engaged in most human computer interactions." (Tan, 2001)

The mother of all senses" - touch is the sense which became differentiated into the others, and is the most ancient and largest sense organ of the body. The skin separates us from our environment and allows us to learn about the environment. (Montagu, pp. 1-3) The human tactual sense is generally considered to consist of the tactile sense and the kinaesthetic sense. The tactile sense refers to awareness of stimulation to the skin, while the kinaesthetic sense refers to the awareness of limb positions, movements, orientation and muscle tension. However

There are a number of tactile receptors that could be stimulated for use in wearable computing applications: thermal, pressure, electrocutaneous, humidity, air movement, vibrotactile, etc. The current state of the art points to vibrotactile as the modality for ubiquitous computing applications. Vibrotactile actuators are neither intrusive nor painful (problems that are possible with electrocutaneous actuators). They can be felt through clothing, are inexpensive, and have relatively low mechanical and power requirements. Since tactile interfaces have grown out of more general tactual display systems, a review of these along with current systems will place the research in a larger context.

4.3 Review of tactual interfaces

The use of tactual displays is rooted in the area of sensory substitution. Sensory substitution is the use of one sense, in this case touch, to compensate for visual or auditory impairment. More recently, tactual displays have been explored as a way of augmenting experience in virtual environments and they are slowly finding their way into wearable and ubiquitous computing.

4.3.1 Sensory substitution

The ability of the tactual sense to interpret large amounts of abstract information alone may have been originally realized with the invention of Tadoma in the 1930s. Tadoma is a method developed at the Perkins School for the Blind in Massachusetts for teaching a student with dual sensory impairments to both receive and produce speech. The student's thumb is placed on the speaker's lips and the fingers on the cheek and neck. The student feels all the physical aspects of speech, the air in the cheeks, the movement of the lips and the vibration of the vocal chords. Tadoma is difficult to learn, but experienced practitioners can sense details of speech as subtle as someone's accent.

The first tactual displays concentrated on language: written for the blind and spoken for the deaf. The "OMAR" system used motion, vibration and stiffness information as a cue to help the deaf understand speech. The "reverse typewriter," a kinaesthetic system developed by Bliss in 1961, was a pneumatic display with eight finger rests similar to the home position of a typewriter. Each finger rest was capable of moving in a fashion consistent with the movement of a typist's fingers while typing. Another kinaesthetic display, the MIT Morse code display worked by moving the fingertip of the user in a similar fashion to the ways one would move to send a Morse code message. (Tan)

The exploration of the tactile sense for language communication began with Linvill and Bliss's Optacon in 1966. It consisted of a small, handheld camera and a tactile display that fit under the tip of the index finger. The camera quantized a letter sized area into 144 black and white image points (24 rows and 6 columns) via photocells and then displayed them on a 24 x 6 array of vibrating pins, each pin vibrating according to matching a 'black' spot. Blind users were able to read between 10 - 100 wpm depending on the individual, the amount of training and experience. Users averaged about 30-50wpm. (Tan)

Geldard's Optohapt, (also 1966) was similar to the Optacon, but did not restrict the display to the fingertip, it was spread out over the entire body. A linear array of nine photocells vertically scanned text output by an electric typewriter to nine vibrators distributed across the body (one on each upper and lower arm, one on the torso, and one on each upper and lower leg). Raw letters were presented across the body surface. It was difficult for subjects to discern letters of the alphabet in this way, and it was suggested that there may be a set of more discernible symbols that could be used to represent the alphabet. (Tan)

In 1972, Bach-y-Rita developed the TVSS (Tactile Vision Substitution System) to transmit general visual images to the blind via an array of solenoid vibrators mounted in the back of a dental chair. A TV camera was used to capture the image and actuate the solenoids. Initial results showed that both sighted and blind subjects learned to recognize common objects and their arrangements in three-dimensional space. They also learned to perceive the sensations on their backs as being objects in front of them. Although subjects could distinguish shapes, it proved difficult to recognize any internal details or patterns.

The Kinotact (Craig 1973) was similar to the TVSS, but instead of general images it focused on printed language. It consisted of a 10-by-10 array of photocells linked by 100 switching circuits to a 10-by-10 array of vibrators mounted on the back of a chair. Subjects were asked to identify block letters of the alphabet based on the vibrating patterns they felt on their backs. Of interest in this experiment is that subjects performed almost equally well when the columns were ordered or randomized, as long as there was a one-to-one correspondence between photocells and vibrators. (Tan)

As mentioned above, tactual displays have been created to communicate sound to the deaf as well. Tactual hearing aids typically send the speech signal through an array of bandpass filters with increasing center frequencies. The outputs of these filters are used to modulate the amplitudes of an array of vibrators. A contemporary commercially available example is the Tactaid system produced by Audiological Engineering Corp. The Tactaid device comes with a microphone that can be clipped to the shirt or belt and an array of seven vibrators that can be worn on the forearm, chest, abdomen or neck. The device can be used during lipreading, increasing understanding by 10 -30%, as well as alone to provide information about environmental sounds.

4.3.2 Current examples of tactile displays

With few exceptions (Optacon, Tactaid), research in sensory substitution has focused on precise measurements that can be made in the lab and not on producing devices that could be of everyday use. Likewise, there has been significant research on tactual displays for virtual environments. Much of this has focused on the kinaesthetic sense (haptics), but there has been some research into the use of the tactile to provide peripheral awareness (van Erp, Yang). More recently, tactile displays have piqued interest from those developing wearable and ubiquitous computing applications. Unlike haptics in virtual reality or sensory substitution systems, tactile interfaces do not need to be concerned with direct transformation of visual or audio information. They can present coordinated tactile information that is not directly linked to visual or audio information, thus creating a new channel for human computer interaction. Tactile displays are beginning to be used in many places: alongside the desktop metaphor, augmenting voice and visual communications, as an aid in navigation, orientation and perception. and even in creative social and performance applications.

Some devices have been developed to augment traditional computer interfaces, such as TouchEngine (Poupyrev, 2002), a tactile display for handheld devices, and the iFeel mouse (Logitech) which give tactile feedback for screen based events (e.g. a bump is felt when the mouse crosses the border of a window). The interaction in this class of devices merely augments the standard interface paradigm and is not particularly applicable for ubiquitous or wearable computing.

Interpersonal communication is one area in which tactile interfaces are being explored. ComTouch (Chang, 2002) is a sleeve that fits over a mobile phone which augments voice communication with touch. When two people are talking and using the ComTouch system, hand pressure from one person's device is transformed into vibrational intensity on the other's, allowing users to communicate by touch as well as by voice. Super Cilia Skin (Raffle, 2003) is a computationally enhanced membrane that uses an array of actuators to display images or physical gestures. It is envisioned as both an input and output device to enrich interpersonal communication and children's learning. HyperMirror, a video conferencing system, has been augmented by a shoulder mounted, vibro-tactile device (Morikawa, 2000) to aid in communication between its users. In the HyperMirror system, all users see the same image, which is a composite of video captured of people in various places. After long- term use, the attention of the user often decreases, and they miss messages from other users who would like to communicate with them. The HyperMirror tactile display vibrates a tactor on the shoulder of a user when another's image overlaps theirs - which is understood as a tap on the shoulder to initiate communication. (Toney) has done more general research regarding shoulder inserts and vibro-tactile displays, offering design guidelines regarding perception and placement of actuators.

Tactile displays are also being used to aid perception in situations where other senses may be degraded (virtual environments, handicapped) or overloaded (pilots, drivers). POS T.Wear (Yang, 2002) uses an array of sixty vibrators in five circular rings spaced out in thirty degree intervals around the subject's torso to increase the "presence" of target interaction objects and support interaction with objects at a close range. The main proposed application for this system is a VR based motion training system where a 'ghost' guides your body from a first person perspective. (van Erp, 2001) van Erp has experimented with tactile actuators applied to the torso to reduce degradation in navigation, orientation, motion perception and object detection in virtual environments due to the lack of peripheral vision. More recently, he has developed a multi-purpose tactile vest for astronauts in the International Space Station. Long periods of time in zero gravity can cause discomfort due to sensory deprivation of the proprioceptive system. Van Erp's tactile vest provides orientation information, so that astronauts can keep a sense of the subjective vertical as well as the location of their limbs in space. (Van Erp, 2002) NASA has also developed a tactile vest, the TSAS (Tactile Situation Awareness System), to aid pilot's situational awareness and orientation in navigation and combat. (NASA)

Tactile interfaces are also being used in more ordinary real spaces. The Carnegie Mellon University Wearable Group has developed a general purpose tactile vest for developing and testing tactile displays. Their initial efforts were customized for wayfinding and navigation applications (Gemperle, 2001). Ross has tested wearable displays to aid the visually impaired in crossing the street. They found that a tactile interface (vibro-tactile tapping on the shoulders) gave the best results in terms of performance and subject preference. Tan and Pentland have created a tactile directional display, also called the 'rabbit' display, which takes advantage of sensory saltation (to be described shortly). The display consists of nine vibrators arranged in a three-by-three matrix in the back of a chair. Pulsating the vibrators in different sequences and at different rates has been shown to effectively communicate direction and simple geometric shapes. (Tan, 1997)

There have also been a few creative applications of tactile displays, which offer a glimpse of some of the possibilities of the technology. Kuenen describes a system for visceral interpersonal communication, which combines a vibro-tactile display with temperature change in a wearable device which is controlled by sensors that monitor the user's heart-rate and communicate it to other nearby users via a wireless network. The resultant effect is being able to feel the collective body state of the shared space. (Kuenen, 2002) Eric Gunter has developed a system, Cutaneous Grooves, for aesthetic explorations of the sense of touch. His system allows for the composition and perception of musically structured spatio-temporal patterns on the surface of the body and has tactors located on the arms, legs and torso. Gunther also makes a first attempt at a compositional language for touch, by describing the perception of various parameters.

4.4 Tactile communication

There are several techniques that can be utilized for tactile communication. In trying to create a tactile experience akin to music, Eric Gunther has investigated the dimensions of tactile stimuli that can be used as the underpinnings of a language for tactile composition. The parameters that he highlights are: frequency, intensity, duration, waveform or spectral content and space. Frequency: The range of the skin's vibrotactile response is roughly 20-1000 Hz, with maximal sensitivity at around 250 Hz, and it is relatively poor at frequency discrimination. Intensity: Gunther remarks that the amplitude envelope can be varied to create a wide range of perceptual effects. For example an abrupt attack will feel like a sudden tap, whereas a more gradual attack seems to rise up out of the skin (Gunther). Duration: Stimuli of duration of less than 100 ms are perceived as taps or jabs. Longer pulses are perceived to be smoother. Also, stimulating an area for an extended period of time can result in adaptation. Waveform or Spectral Content: Although subtle variations cannot be perceived, larger differences are perceived as smoothness or roughness. (a sine wave being smooth and a square wave being rough). Space: In terms of spatial resolution, touch is second only to vision. Glabrous skin has more receptors than hairy skin and may therefore be better suited to finer grains of vibrotactile stimulation. Spatial acuity varies greatly over the surface of the body. The lips and fingertips have a high spatial acuity, whereas the back's spatial acuity is relatively low.   However, as the back/torso has a much larger area than that of the fingers, and is not as frequently needed for other purposes, thus being a good potential location for certain kinds of vibrotactile displays.

A perceptual illusion, sensory saltation, holds promise for use in vibrotactile displays. Sensory saltation occurs across the senses resulting in the perception of apparent motion. Tactile sensory saltation was discovered in the early 1970s by Dr.

Frank Geldard at the Princeton Cutaneous Communication Lab. In a typical setup for eliciting tactile sensory saltation, three mechanical stimulators are place equidistant from each other on the forearm. The stimulator closest to the wrist delivers three short pulses, followed by three more at the middle stimulator, and finally three more at the last stimulator. Instead of perceiving three pulses at each of the stimulator sites, the observer perceives that all of the pulses are distributed with approximately uniform spacing from the site of the first stimulator to the site of the third. The sensation is described as if a tiny rabbit was hopping up the arm from wrist to elbow, and is sometimes called the "rabbit" effect or the "cutaneous rabbit." An important feature of this illusion is that it is able to simulate higher spatial resolution than the actual number of stimulators, yet create the impression of a dense stimulator array, thus potentially reducing the overall weight and power consumption needs of a wearable device.

Using variations in these parameters in different spatio-temporal patterns has uncovered a group of concepts which can be perceived through the tactile sense. For example, a single point can be perceived as a direction. (van Erp, 2001) Tactors arranged spatially on the body can create a relationship akin to vision where the ego center is perceived as one point and the stimulus at another, thus creating direction. Taking advantage of sensory saltation, lines can be perceived, as can their length, straightness, spatial distribution and smoothness. (Cholewiak, 2000) There is also some more recent research (TNO Human Factors) that suggests planes and three dimension forms can be perceived. Tactors on the body can create a 360 degree “field of touch" where lines and forms can be perceived not just on the surface of the body, but through the body. Finally, the tactile systems that have been discussed are very easy for users to learn, and require practically no training.

4.5 Conclusion

Wearable vibro-tactile devices, especially those designed for the torso or entire body, are a rich medium for embodied communication with computational devices. Tactile displays shift attention, either focal or peripheral, to the body, which is an area that computing often ignores. The predominately visual nature of the computer interface mirrors the dominance of vision in Western culture. The dominance of vision can be traced back to the same ideological roots of computing: the separation of mind and body and thought from experience. Tactile interfaces may be an avenue for computing to embrace the body and work towards a rebalancing of the senses in design. Wearable vibro-tactile displays have been shown to "enhance environmental awareness" (Cholewiak, 2000) and help maintain spatial awareness in unusual environments (van Erp, 2000). When this becomes an area of focus and concern for computing,, the design of computational cultural artifacts that foster an embodied experience is possible.

Chapter 5
Tactile Space Implementation

5.1 General description

5.1.1 Description of experience (original)

"Culturally and socially, space is never simply an inert background of our material existence" (Hillier). Tactile Space is a large scale tactile installation that examines the influence of wearable computational media on the ways in which people perceive, understand and use space. Participants put on a vest outfitted with a wearable computer/global positioning satellite receiver and are instructed to wander about a space as they like. While exploring the area, participants encounter changes of vibrotactile texture dependent on their location. Some phenomena seem to move, suggesting an unseen presence or palpable waves. Others are more static and may be perceived as gradients or landmarks. The everyday experience of space is augmented with an invisible tactile landscape, where one navigates less by vision and more by feel. New boundaries and thresholds are encountered as tactile textures move across the body shaping the experience of bodily orientation and navigation. tactile/space challenges the participant to think about the role other senses play in everyday spatial experience in a culture dominated disembodied technologies.

5.1.2 Description of experience (current/future)

Using a GPS linked to a torso tactile display, Tactile Space transforms the subtle visual cues in the built environment that influence its function into vibrotactile textures that allow one walking through the city to feel its diverse and changing spatial forms.

A participant goes to a designated location to check out the equipment and begin the experience. Once there, they would be briefed about the project by staff on hand, and/or given a leaflet that explains the project in more detail. Choosing to try out the experience, the participant would be asked to exchange their ID for the system, to be returned upon the system's return. A staff member would turn the system on, wait until a GPS signal was acquired, and then give the vest to the participant to put on.

The participant may be given a map that shows location and the boundaries of the coverage area (but with no other details), which she/he may or may not use as a reference, and is instructed to walk about the city however they would like and 'feel' the space of the city. As the participant wanders, she/he encounters vibrotactile rhythms and textures depending upon the spatial configuration of the current location. Closed spaces have different rhythms than open ones, major thoroughfares have more energy and a smoother texture than back alleys. As tactile patterns shift back and forth between focus and periphery, the participant is engaged to think about the relationship between their visual understanding of space and their bodily understanding of space.

5.2 Technology

The system is currently being developed using the following hardware: GPS board from OKW Electronics, PIC16F873 micro controller, two PAK Vc chips from AVC that allow 8 independent hardware pulse-width modulation outputs simultaneously, and thin disc shaped pager motors. The micro controller receives serial data from the GPS, parses it for the location and orientation, and maps it to the campus grid. The campus has been translated into a grid of textures determined by space syntax analysis. Space syntax is a set of techniques for the analysis of spatial configurations. It was originally conceived of by Bill Hillier and his colleagues at University College London in the 1980s as a tool to help architects simulate the likely effects of their designs. (see Appendix A.) The analysis was performed using Isovist Analyst 1.1, an extension to popular GIS software ArcView, written by Sanjay Rana. Once the location and texture are determined, the micro controller sends the appropriate control messages to the PAK Vc chip to drive the motors and create the resulting tactile texture.

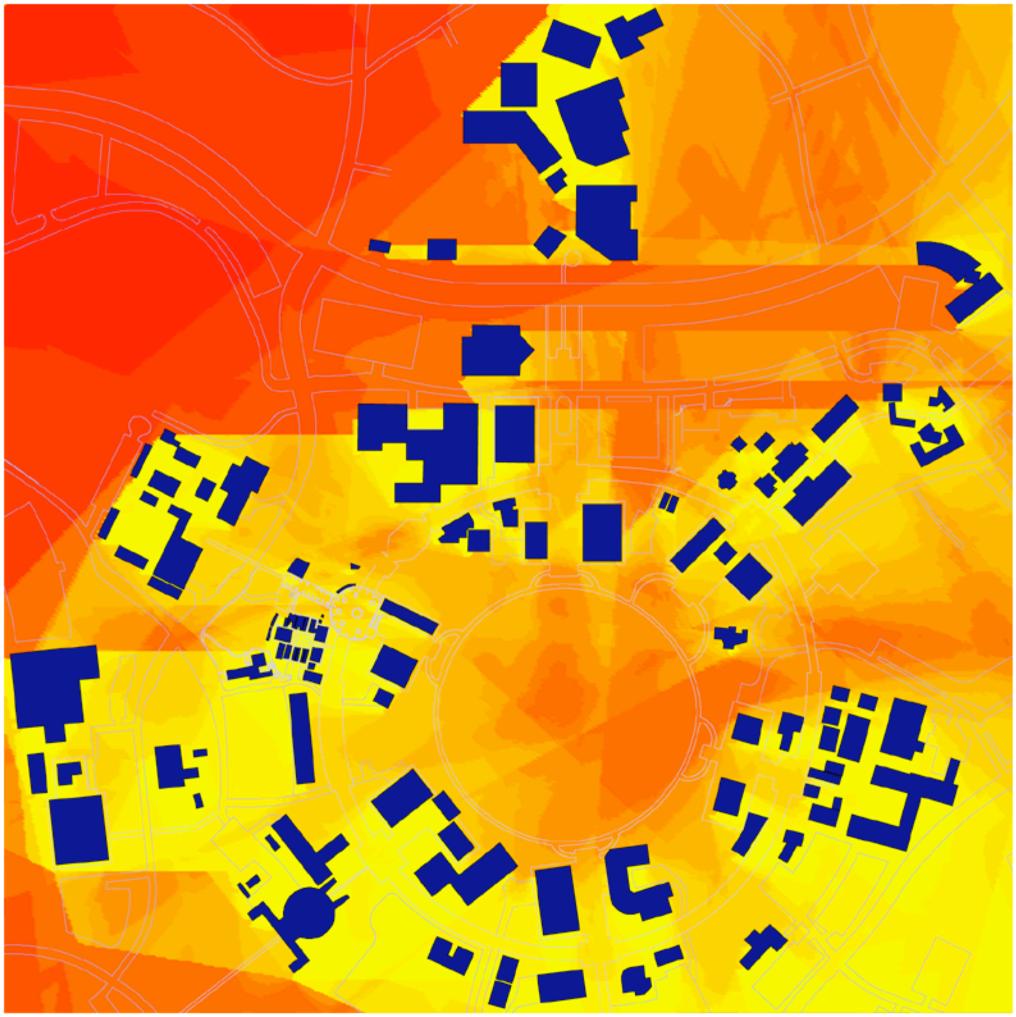

Figure 5.1 Campus isovist area graph (excluding Aldrich Park) An isovist, as defined by Michael Benedikt is "the set of all points visible from a given vantage point in space."

5.3 System diagram

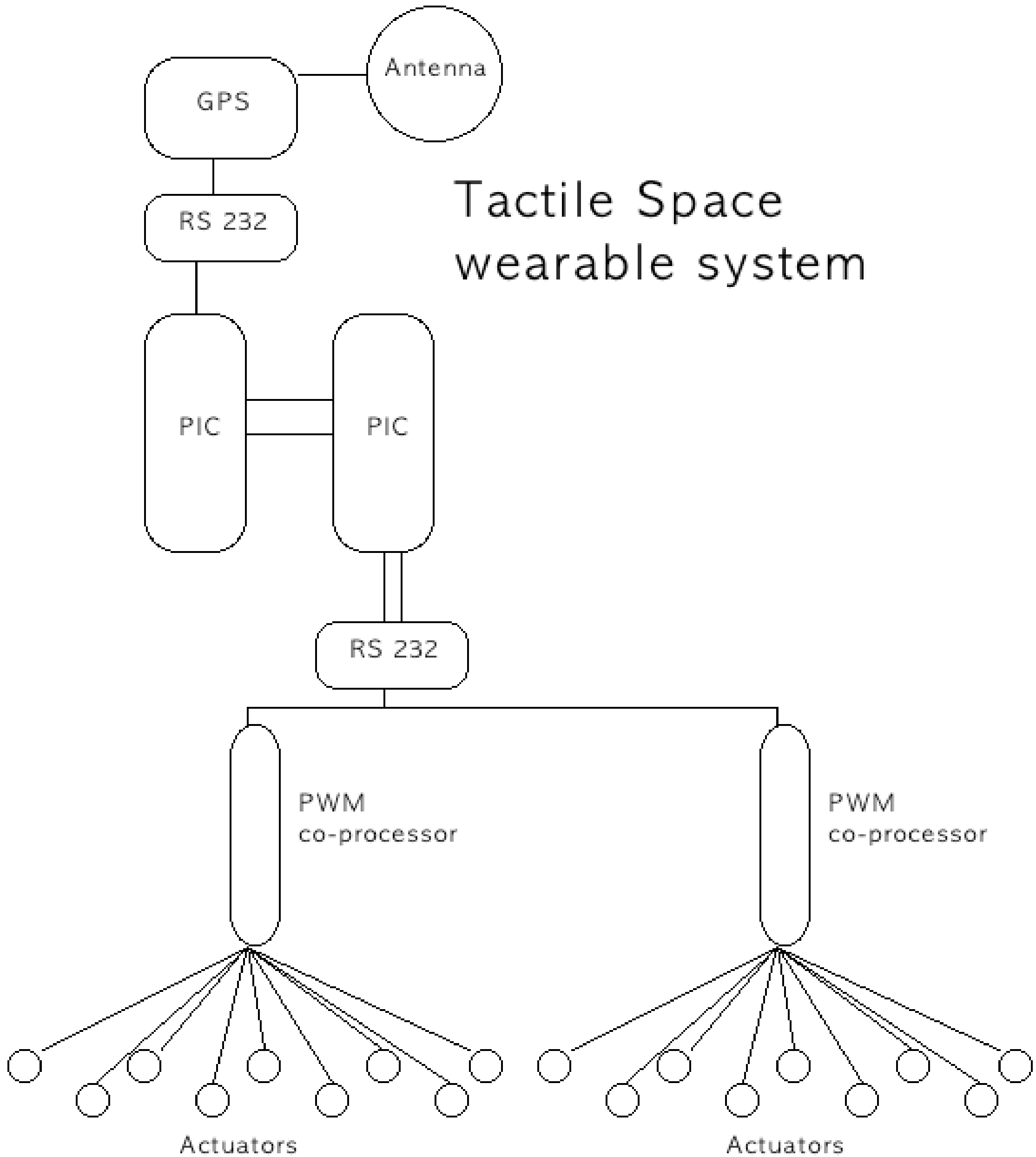

Figure 5.2 Tactile Space system diagram

5.4 Modeling and specification

5.4.1 Models

The most appropriate model of computation for the Tactile Space system is the Communicating Finite State Machine Model (CSFM). One could break down the design into three FSMs communicating asynchronously. FSM1 receives data from the GPS, and if valid, sends control data to FSM2. FSM2 receives data from FSM1, interprets the data and sends control data to FSM3. FSM3 receives data from FSM2 and sends the appropriate signals to the vibrating motors. The whole process is essentially sequential, from the input GPS location data – mapping location to vibrotactile patterns – output to actuators. The GPS could be viewed as a FSM machine in itself, however for our purposes here we are treating it as an external device as it is not necessarily device specific.

5.4.2 Specification scheme for design intent

The specification scheme for design intent provides a framework for establishing and evaluating the varying requirements of the system. It outlines the functional necessities of the system, and provides a reference for validation of the final system. The system design is broken down into several categories: behavioral, structural, timing and communication, programming elements, and non-functional properties. The specifications of each of these categories must be met for a successful system design.

The behavioral specification outlines how the system should interact with the user. The system must have two states: on and off. When on, one LED should light to indicate that the power is on and another should light to verify that valid GPS data is being received. When operating the system should output various vibrotactile patterns based upon the user's location. For example in location A, there is one vibrotactile pattern and intensity and at location B it changes to a new pattern. If one returns to location A, the original pattern should be output again.

The structural specification describes the physical architecture of the system, and consists of two main components: the GPS receiver and the main processing unit. For the GPS component, an on board solution was originally desired, but due to communication problems a consumer GPS (Garmin eTrex Legend) had to be substituted. The GPS will reside in one of the vest pockets and communicate via serial cable to the main unit. The main unit shall reside in the other vest pocket. It consists of two PIC micro controllers and two PAK IV PWM chips. One RS232 chip is used for serial communication between the GPS and one of the PICs, while another for communication between the second PIC and the two PAK IV chips. The PAK PWM chips are connected to the vibrating motors using telephone cables with jacks as connectors. The motors are fastened inside the upper torso of the vest.

The timing and communication specification describes the interface between the two parts of the system. Since both the GPS and the PAK IV chips communicate via RS232, a common baud rate of 9600 should be used for all communication. The GPS is able to output serial data in several formats. The system can use standard NMEA format, or the Garmin Text format.

The programming elements specification assures interoperability of code in the design of the system. The PIC chips will be programmed using PIC BASIC and the PIC BASIC Pro compiler.

The non-functional properties specification, while difficult to quantify, are often the ultimate determining factor in the success of an embedded computing system. This embedded system should be a light, unobtrusive wearable that generates tactile patterns relative to the users location on campus, fostering awareness of non-visual modes of spatial perception. It needs to be easy to set up and turn on, as untrained gallery attendants will equip users. It must be able to run continuously for at least an hour (preferably longer) and it must be easy to change the batteries (again to be done by gallery attendants). Users should be able to turn the device off if desired. It should be fairly rugged, so as not to break or suffer broken connections under the stress of regular bodily movement and being put on/taken off multiple times and by multiple users.

5.5 Hardware/Software Co-design

The boundary between hardware and software is not always clearly defined when designing and developing a system that is comprised of both. Some design problems can be solved with either hardware or software, with the best solution determined by a number of factors, such as cost, speed, time to market, etc. In this section the various possibilities in hardware/software codesign are outlined.

Considering hardware/software codesign for this system, it would be possible to repartition this system either more so in the direction of software or hardware. It would be possible to implement the system primarily with off-the-shelf hardware with minimal custom hardware. There are many possible solutions in this area, with the PocketPC + GPS card one of the more popular options in locative media. This option would have made programming and evaluation much easier, as there are more powerful programming environments as well as simulation software available for the PocketPC. By using commercial hardware and doing more of the work via software, the system would potentially be easier to extend and ultimately more flexible.

The choice was made to build custom hardware for several reasons. First, the PocketPC platform is overkill in terms of features and processing power. No screen is needed for this embedded system and its processing requirements are modest. Also as far as size and durability, I held the belief that I would be able to make a device much smaller, and much more rugged. There would be no screen to inadvertently damage, and the external serial connection, which would be needed to control the motors, is very fragile on current PocketPCs.

It would be possible to implement more functionality in hardware if it was necessary. For example the GPS could be fully integrated into the device, rather than being an external device. As mentioned previously, this was the intent of the original design, but unforeseen problems and known deadlines forced a switch to a different solution. In its current state, I believe that it would be possible to implement much of the internal logic in hardware. Since this is a prototype, reprogrammability is essential, thus the design as currently implemented.

5.5.1 *Software Issues*

The software for this embedded system can be divided into two parts: [1] software for creating maps for tactile landscapes and [2] software that runs the inter-system communication and translates the map into tactile textures that can be perceived by the participant. The mapping of the space is done prior to the system being deployed. Spatial analysis, using Space Syntax techniques (see Appendix A), is performed with the Isovist Analyst (versions 1.0 –1.2) extension, written by Sanjay Rana, to the ArcView 3.2 Geographic Information System (GIS) software. After a visibility graph was constructed, large, similar sections were extracted and converted into areas measured by latitude and longitude.

The system software reads the incoming latitude and longitude data from the GPS receiver and compares it to the regions extracted from the map. Once the region has been determined, a 4 bit code is transmitted from one PIC to the next the signal the proper tactile output. In the current design of the system, there are six possible tactile outputs, three modes each with two different timings/intensities, as outlined in the table below.

Spatial configuration	Mode	Timing/intensity
Closed – less visible area	Tapping	Fast
…	Tapping	Slow
….	Pulsing (front to back)	Fast
…	Pulsing (front to back)	Slow
…	Pulsing (diagonal)	Fast
Open – more visible area	Pulsing (diagonal)	Slow

Table 5.1 Tactile Space output mappings

5.6 Design Tradeoffs

Some of the design tradeoffs were discussed in the Hardware/Software codesign section, such as the choice to try to implement the system with custom hardware vs developing an application for an existing mobile platform, like the PocketPC. As mentioned above, this system is still in development, and its final form is still a bit amorphous. However, there are some tradeoffs that have been made for the sake of time that make obvious extensions for version 2 of the system. First, the GPS should be incorporated into the device. This was part of the original design, but had to be switched for an external model during production. Second, as this was all being assembled by hand and a bit on-the-fly, designing a more efficient circuit board as well as having it printed would decrease the size of the electronics a great deal. One major problem in building the system was finding a solution from keeping the connection between the wires in the vest and the motors from breaking. A more rugged and less obtrusive system may be able to be obtained through the use of conductive fabrics. This would allow the flexibility that is required from a garment and relieve some of the stress on the electrical connection. For simplicity's sake, only eight actuators were incorporated into the prototype design. Future versions of the system could easily accommodate 16 to 24 actuators and provide much greater coverage and resolution.

5.7 Future Directions

Aside from the above mentioned future improvements, more research and testing needs to be done in the creation of vibrotactile patterns. For this purpose, it may be useful to create an interface for a device like the PocketPC, much like the Mobile Bristol Toolkit has done for locating sound in space with a PocketPC. <*http://www.mobilebristol.co.uk/flash.html*> This would allow myself, or other artists or designers to create vibrotactile pattern/space relationships on the fly through an easy to use GUI.

If the system can be engineered to be cheaper and easier to reproduce, it would be very interesting to network the devices. In this way Tactile Space could be used to explore social relationships. One possibility would be being able to feel the movements of people in your group, no matter where they are physically located. Other possibilities include play/games or communication. Tactile cues could be sent over the network as a low resolution communication medium or could be employed for games like tag.

Besides networking, it would also be interesting to include various sensors into the garment, to add the possibility of reacting in real time, to light, temperature, sound, radio (wi-fi/bluetooth detector), wind, or any number of other elements. Currently, the system relies on a pre calculated map of spatial relationships, but it would be possible to explore other relationships that could be computed in real time.

In conclusion, I believe that wearable vibrotactile devices, especially those designed for the torso or entire body, are a rich medium for embodied communication with computational devices. Tactile displays shift attention, either focal or peripheral, to the body, which is an area that computing often ignores. Tactile interfaces may be an avenue for computing to embrace the body and work towards a rebalancing of the senses in design. Wearable vibrotactile displays have been shown to "enhance environmental awareness" (Cholewiak, 2000) and help maintain spatial awareness in unusual environments (van Erp, 2000). When this becomes an area of focus and concern for computing, the potential for re-experiencing the everyday via computational media becomes much more interesting

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Appendix A – Space Syntax

Space syntax is a set of theories and techniques for the analysis of spatial configurations of all kinds, from buildings to cities. It was originally developed by Bill Hillier, Julienne Hansen and their colleagues at The Bartlett, University College London in the late 1970s and early 1980s, as a tool to help architects simulate the likely effect of their designs. One technique that practitioners of space syntax employ is Visibility Graph Analysis, which is a method of analyzing the inter-visibility connections within a space. Visibility graphs are constructed by computing isovist measures for a uniform number of points in a space. An isovist, as defined by Michael Benedikt is "the set of all points visible from a given vantage point in space." To compute an isovist, one starts at a vantage point and extends a straight line until it comes into contact with a barrier (interior wall, building), then recording that point in space. One then rotates a given amount, depending on the desired resolution, and repeats this process for 360 degrees. At the end of this process a polygon is created that comprises the visible field from that vantage point. From the geometry of the isovist, many features can be extracted that can be used to assess perceptual qualities of the space as well as possible usage of it.