PROTOTOUCH

A SYSTEM FOR PROTOTYPING UBIQUITOUS COMPUTING ENVIRONMENTS MEDIATED BY TOUCH

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Submitted to the program in Media Arts and Sciences, school of Architecture and Planning, in partial fulfillment of the requirements for the degree of Master of Science at the Massachusetts Institute of Technology

September 2011

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ABSTRACT

Computers as we know them are fading into the background. However, interaction modalities developed for "foreground" computer systems are beginning to seep into the day-to-day interactions that people have with each other and the objects around them. The Prototouch system allows user interface designers to quickly prototype systems of ubiquitous computing devices which utilize touch and gesture based interactions popularized by the recent explosion of multitouch-enabled smartphones, enabling the user to act as container, token, and tool for the manipulation and transportation of abstract digital information between these devices. Two versions of the system utilizing different network topologies have been created, and several example applications utilizing the system have been developed.

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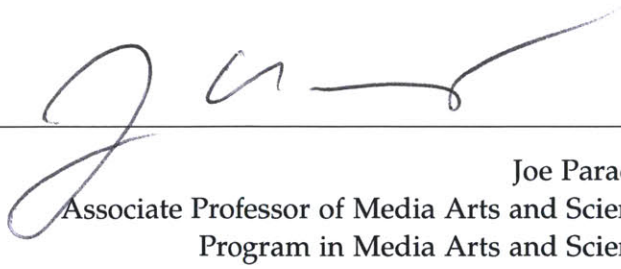

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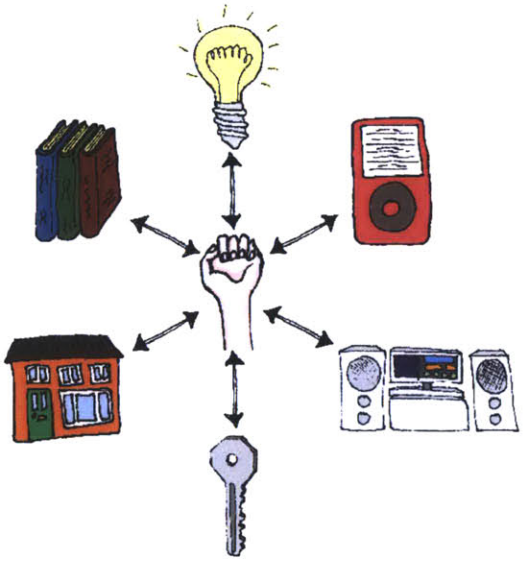

A System for Prototyping Ubiquitous Computing Environments Mediated by Touch

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1

INTRODUCTION

Embarking on the journey of casting off the constraints of windows, icons, menus, and pointing devices[33] has opened a veritable Pandora's Box of theoretical, technical, and even sociological questions for HCI researchers. When user interfaces truly become "places we go to get things done [73]," how can we as interface designers empower users to become physical interlocutors of the ethereal swirl of information that permeates modern existence, enabling them to shape it to affect their desires upon the world?

When we consider the almost weedlike proliferation of smartphones, tablet computers, and LCD screens as embodying the portents of pads, tabs, and boards foretold in the same essay, it becomes clear that the realization of the dream of ubiquitous computing is rapidly accelerating. However, the problem remains that there is not yet a good solution for commanding the flow of information amongst our devices and information appliances. The ways in which we manipulate digital information is still mostly constrained to the digital world, and in some cases more cumbersome than the physical counterparts they were meant to replace. For example, wireless computer accessories help to maintain cleanliness of desk areas, but it remains difficult to coerce them into to pairing with our own computers, and not with the computer down the hall.

Although the concepts of smart appliances, considerate technology, and tangible user interfaces are not new topics of exploration in the development of HCI, the sheer number of touch-gesture enabled devices (projections estimate 1 billion smartphones in the field by 2013 [34], or about 15% of the earth's total population) in use today represents a quantum leap forward in bringing the world of post-desktop computing to fruition; a significant portion of humanity are regularly engaging in direct tangible interaction with digital information via the oldest and most natural method of transacting information in the physical domain - by touch.

Because of their newfound ubiquity, touch interfaces represent a very interesting yet incompletely explored path for furthering the development of the devices which will allow us to naturally bridge the gap between the spheres of digital information and physical reality by utilizing technology and interactions already well known to the general population. If people have truly integrated the interaction methodologies provided by the current explosion of touch-gesture enabled devices into their day-to-day realities, it follows that we should

be able to incorporate these methodologies as design considerations in the creation of new systems of well-designed smart appliances. I have thus designed and implemented a system which assists researchers in prototyping ubiquitous computing devices, appliances, and environments mediated by touch.

2

BACKGROUND AND MOTIVATION

As advances in technology provide us with increasing amounts of computation enabled objects distributed about the physical environment, the need for means of moving information between them becomes more urgent. This is a difficult problem to address due to the fundamental differences in the ways which we interact with objects in the physical world versus the the ways in which we interact with abstract digital information[31].

Johnson et. al. have done work to categorize several recent trends in the design of user interfaces, categorizing them into the framework of *reality-based interfaces*. These interfaces leverage users' already-entrenched skills and expectations about the real world to make more seamless and intuitive interfaces[33]. If we extend this framework to encompass the gestural vernacular which has entered the public consciousness as a result of the proliferation of touch-gesture enabled devices, perhaps we can work to design augmented objects[41] which are more considerate as well as more functional within their expected affordances[56] by utilizing these types of interaction methodologies.

From an engineering standpoint, the design and subsequent installation of such systems could be greatly eased by leveraging the ubiquity of devices with conductive surfaces in the form of capacitive touchscreens and the low cost of creating objects with conformal sensors which can serve as inputs and outputs of digital information into the users themselves for transportation around physical space.

2.1 TANGIBLE USER INTERFACES AND CONTAINERS FOR DIGITAL INFORMATION

Fitzmaurice et. al.'s Graspable User Interfaces project[20] and Ishii's and Ullmer's subsequent work on Tangible User Interfaces[31] introduced the notion of tightly coupling informational constructs with everyday physical objects in order to allow user interface designers to "take advantage of natural physical affordances to achieve a heightened legibility and seamlessness of interaction between people and information"[5, 31]. This work concentrates on going beyond the pads, tabs, and boards of Weiser's vision[73] by augmenting the affordances of the very physical objects that we interact with in the natural world, as opposed to concentrating on making computer terminals of varying sizes and locations to suit every interaction need[31].

The question of how to make the transfer of abstract digital information between devices more tangible and interactive is an ongoing topic of research within the field of HCI, and the subfield of tangible user interfaces in particular. Holmquist et. al. describe a schema of three types of physical objects which can be linked to digital information: *containers*, *tokens*, and *tools*[28].

CONTAINERS are objects used to physically move digital information between devices.

TOKENS are used as pointers to abstract information.

TOOLS are physical intermediaries which can be used to manipulate digital information.

musicBottles[32] are an example of a physical container for abstract digital information, as they are ordinary-looking glass bottles which appear to contain sound. When the stopper is taken out of one bottle, the user hears the sounds of one instrument in a band. When another is opened, a second instrument appears to join the playing of the first. In the Invisible Media project[48], IR beacons are used as tokens to access information associated with the parts of a car engine when the user points at a specific part. Pick-and-Drop[64] introduced the concept of multi-computer direct manipulation[29] by utilizing a tool, embodied as a pen, to move digital content between a variety of computer systems.

Furthermore, the user themselves can be utilized as a container, token, and/or tool for the storage and transfer of abstract digital information through the use of touch interfaces and intrabody communication.

2.1.1 *User as Container*

Recently, work has been done into investigating leveraging the user themselves as a container for abstract digital information. SPARSH is a design exploration which allows a user to move digital media between devices by touching to copy and paste, conceptually storing the information inside the user themselves[50]. For example, a user could receive a text message of the address of a party, touch the address, and then touch the screen of a traditional computer terminal to load a map to that address from Google Maps.

2.1.2 *User as Token*

The most common application of user as a token appears in authentication schemes. Fingerprint readers, handprint identification systems, and other forms of biometric security systems are widely employed to

provide secure access to buildings, computer systems, cellular phones, and automatic teller machines[35].

2.1.3 *User as Tool*

Most users carry with them at all times a well characterized set of tools which can adeptly manipulate a wide variety of physical and digital objects - their hands.

One much of the most prevalent "user as tool" interfaces present in the current consumer electronics landscape are the gesture sensing surfaces available in the form of smartphones and computer touchpads. A number of often-overlapping gestural languages have been implemented to control these devices. Many smartphones and tablets utilize pinching, rotating, sliding, and flicking motions to allow user to interact with the information on their screens.

With the latest release of Mac OSX(version 10.7), Apple has taken steps to integrate the touch-gesture based interaction system of many currently-available smartphones with the user experience of its flagship operating system. For users of computers equipped with a touchpad, pinch-zoom, rotational, natural direction scrolling, and other gestural grammar is available to provide a more unified experience between device types[2].

The use of touch as a physical input is further discussed in section 2.4.1.

2.2 IMPLICATIONS FOR UBIQUITOUS COMPUTING

The concept of utilizing users themselves as links to digital information has interesting implications for HCI research as well as the engineering problems of building ubiquitous computing systems. Additionally, much of the psychological and technological infrastructure is already in place for the real-world implementation of systems which augment everyday objects and interactions to afford the invisible[57] transmission of information between them mediated by the user.

The above three examples of utilizing the user themselves as a link to abstract digital information are unified by the fact that they all rely on some kind of touch interface to transact information. Users can become interlocutors of physical and digital information through careful augmentation of pre-established physical interaction patterns by utilizing an interaction modality which allows users to naturally control the input and the output of both.

Every day, we tangibly manipulate objects and devices, using gestures and grasps to interact with the information they contain. Many

devices have touch interfaces already, providing a perfect communication channel for direct manipulation of informational constructs. The multitouch screens on the ubiquitous electronic devices which we carry with us and interact with every day are made with conductive surfaces, and can thus be used to transact digital information to and from devices that the user already carries on their person. Additionally, the gestural language which they employ for manipulation of information on their screens has become ubiquitous as well; it is not uncommon to hear stories of young children attempting to perform "pinch to zoom" gestures on the surfaces of normal photographs[42].

This is not to say that the solution to interaction within ubiquitous computing environments is to simply stick touch-gesture surfaces on everything; rather, the point being made is that we can use this pre-existing infrastructure of technology and widely accepted interaction methodologies to investigate new modes of interacting with technology by making it easier for users to learn new concepts by tying it to ones with which they are already familiar[26].

2.3 UBIQUITY OF TOUCH INTERFACES

Since the introduction of Apple's iPhone, multitouch surfaces have been an increasing topic of interest amongst the general population[5]. Figure 1 shows a Google Trends analysis of of searches for "multitouch" between 2004 and 2011.

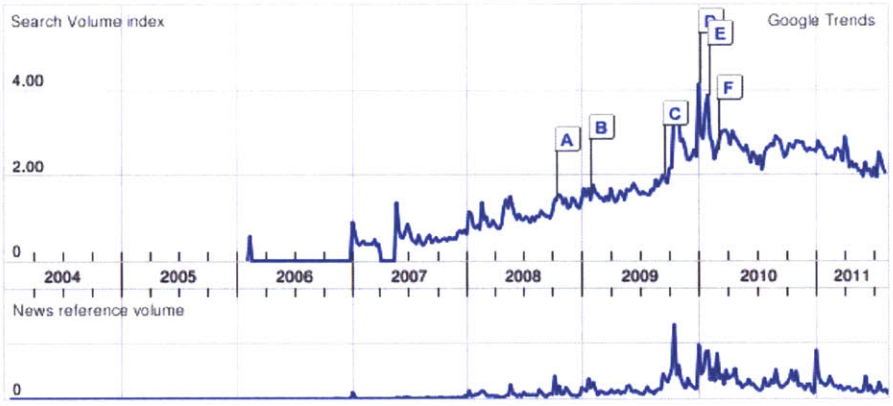


Figure 1: Google Trends analysis of "multitouch"

The above figure shows the number of searches for this term over time as compared to the average number of searches during January 2004. It reveals an increasing amount of searches for "multitouch" worldwide since around early 2006. Additionally, the fact that nearly 15% of humanity will be using smartphones, many of them multitouch enabled, by the year 2013[34] is a testament to the degree to which this type of interaction has been absorbed into the daily life of everyday technology users.

Widely available consumer electronics, pads, tabs, and boards sporting multitouch surfaces in the form of tablet computers, smartphones, and touch-enabled televisions and whiteboards[71] are undeniably a phenomenon which are rapidly making a sizable dent in the sales and use of traditional keyboard-and-mouse based computers. In 2010, America's largest electronics retailer Best Buy reported that sales of tablet computers had cannibalized their sales of laptops by as much as 50%[4].

2.4 TOUCH AS INPUT AND OUTPUT

Touch is uniquely suited to the design of interfaces which allow users to bridge the gap between their devices because it is a channel which affords two way communication. In the following sections, the four information transmission cases implied by this fact are discussed.

2.4.1 *Touch as Physical Input*

Touch inputs are found on devices ranging from fighter jets to music controllers. They can be implemented via resistive[5], capacitive[69], or even optical[24] sensing methodologies. Obviously, multitouch interaction is a well-known topic of great interest in the HCI literature. There is a wide variety of research into integrating this interaction modality into the fabric of ubiquitous computing, with good reason; it is physically and computationally inexpensive to implement [17, 75], and it provides the appearance of direct interaction with informational constructs via the natural human tendencies of reaching, touching, and grasping[17].

In addition to multitouch interaction, there has been much work into utilizing the way in which users grasp and manipulate objects themselves to intuitively control electronic devices. The Graspables project [70] aims to investigate how a generic electronic device indistinguishable from a "bar of soap" can determine what function a user wants to perform with it by the way in which the user is holding it. Several other interaction modalities were explored during the Graspables project; one particularly relevant to this thesis was the use of sliding touch gestures on the Bar of Soap to control a Rubik's cube computer game. interface a The Tango[40] is a whole-hand interface for manipulating onscreen 3D objects. OnObject [11] is a system which allows the user to easily and quickly create tangible user interfaces by "tagging" objects with gestures and linking those gesture/object combinations to trigger sound and graphical events from a host computer. ReachMedia [19] is a system which uses a accelerometer and RFID reader equipped wristband to classify objects that the user is holding and provide just-

in-time audio augmented reality information about it selected by the user's hand gestures.

2.4.2 *Touch as Physical Output*

Physical output via touch can be accomplished via a number of different means. Peltier junctions which utilize the thermoelectric effect[12] can allow electronically enabled objects to adjust their temperature, such as shown in the Haptic Doorknob[46]. The apparent texture of surfaces can be modulated using tiny vibrating pins pressed against the users' finger[3]. Surface-acoustic waves can be used to modify the apparent friction of a surface[54]. Additionally, ultrasonic vibration can be utilized to put shear force on a user's finger, giving them the feeling that the surface is "pushing" it around, as demonstrated via the Shiverpad[10] project.

2.4.3 *Touch as Digital Input and Output*

Since the initial discovery that information could be transmitted through the human body [62], quite a bit of work has been done to characterize the ways in which signals propagate through the body [22, 23, 67]. In addition to healthcare applications [44], many interesting HCI projects have been implemented with varying interaction modalities and transmission speeds using this technique. Touchtag [72] is a system which functions much like an RFID system, involving passive tags that can be powered up long enough to do a small amount of computation when touched by a body with a transceiver attached. The researchers behind the Wearable Key project [47] have developed an body-attached transceiver which implements frequency shift keying and can achieve transmission speeds of up to 9600 bits per second in order to allow users to seamlessly authenticate to and set desired environment variables in public computer terminals. Touch and Play [59] is a project which allows users to link various consumer electronics devices with each other by simply touching both of them. For example, a user could hold a digital camera in one hand, pull up a picture of interest on it, and then touch a printer to transmit the photo data through the body to the printer where it would then be printed out. The system described in the Touch and Play paper can reach data transmission of up to 1 megabit per second using non-return to zero encoding. The GestureWrist and GesturePad project [65] implements a system of a bracelet which uses intrabody capacitive coupling as well as coupling to patches of conductive fabric to allow for creating clothing-based control surfaces for electronic devices.

2.5 DESIGN IMPLICATIONS

Clearly, the ubiquity of touch interfaces and the variety of information transmission modes they afford make them an interesting choice for exploring the design of ubiquitous computing ecosystems.

The system presented in this thesis allows interface designers to utilize three of the four above stated information transfer techniques when experimenting with touch-mediated ubiquitous computing environments by utilizing capacitive sensing for physical input from the user, and intrabody transmission for digital input and output through the user.

In the following chapters, I present three design explorations into augmenting everyday objects and interactions with invisible information interaction features were carried out during my course of study, followed by a technical description of the development of the ProtoTouch toolkit and several example applications it makes possible.

3

TOUCHKNOB

To explore the concept of designing object everyday objects which provide technological benefit completely seamlessly to the user, I completed a design exploration entitled "Touchknob." Schematics and PCB artwork can be found in Appendix A.

Figure 2: Touchknob

Touchknob is a object which demonstrates the possibilities of transparent interaction design afforded by patterning sensor electrodes on surfaces of objects and programming them to respond in natural ways based on the users' natural interaction pattern with a normal doorknob.

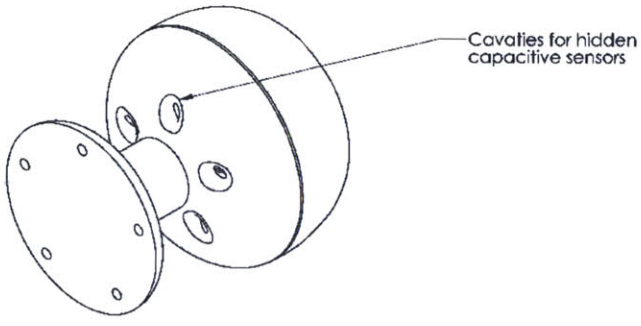


Figure 3: Diagram of Touchknob

Originally envisioned as a prototype grasp-based security interface, it inspired further discussion within the group toward transparent human-mediated exchange of information amongst smart devices.

3.1 INTRODUCTION

We interact with many technologically augmented security devices throughout the day. Keys, keypads, card scanners - their benefit to the world is clear, but the problems with lost keys or even the break in concentration required to satisfy such a system to one's credentials can be annoying and time-consuming. Touchknob was created as an interaction design sketch to explore the possible functionality and ergonomics of a touch-sensitive doorknob which detects a user's grasp. If turned into a finished product, it could be mounted in tandem with an electronic door lock such that when a user attempts to open the door in the usual way, it is unlocked or locked if the user is authorized or unauthorized to pass through the door.

In order to facilitate a truly seamless interaction, Touchknob was designed to utilize only the natural affordances of a normal doorknob. In an installed system, feedback would simply be manifested in the form of a locked or unlocked door, but as this is a design sketch, colored LEDs are utilized to make the doorknob glow as feedback from the user's grasp.

3.2 SYSTEM OVERVIEW

The system itself consists of a plastic doorknob with touch sensors hidden on its back side which are connected to a control PCB hidden in the body of the doorknob. When the user grasps it in different ways, it displays different visual output. If it is touched in a particular way, it glows green; otherwise it glows blue.

(a) Green glow (b) Blue glow

Figure 4: Output states of Touchknob

3.2.1 *Hardware and Firmware*

The body of the doorknob itself was designed in SolidWorks and printed on a 3D Systems InVision printer. It consists of two parts; one is the hollow "knob," which contains the control PCB and battery, and the other is the "stem" of the doorknob onto which the capacitive sensing pads are located. The two parts fit together via magnets mounted in each side.

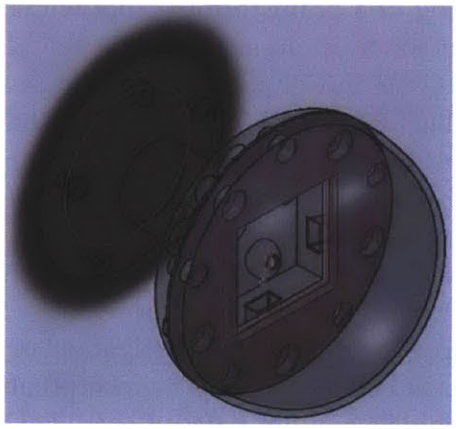


Figure 5: CAD model of Touchknob

The electronics consist of an ATMEGA328 loaded with the Arduino firmware connected to a MPR121 12 channel capacitive sensing/LED driving IC, and 6 tri-color LEDs. Wires are routed from a header on the board through channels in the stem of the knob to connect to strips of copper tape which serve as sensing pads. Tri-color LEDs serve as both output indicators and as mechanical locator pins for the snap fit of the two sides of the doorknob. The system is powered by a Polymer Lithium Ion 110mAh battery.

(a) Vinyl cut board (b) Assembly (c) Finished product

Figure 6: Build process of Touchknob

The build process became unexpectedly complicated with the discovery of a bug in the physical design of the PCB which necessitated the addition of some external transistors and support components to drive the LEDs. Rather than spending the additional cost of remaking the control board, a small flexible circuit board was produced on the machine shop's Roland vinyl cutter, populated, and encased in

electrical tape such that it could be stored in the hollow cavity of the doorknob.

3.3 DISCUSSION

Touchknob was shown at many lab open houses. It was demonstrated informally to around 100 people over the course of about one and a half years. Because of its nature as an evocative visual aid, it became used as something of a brainstorming tool within the group about grasp-based interaction in general. One of the ideas most relevant to this thesis to come out of the lab open houses and the internal discussions was the idea of having the doorknob be able to detect user credentials not just by grasp, but by reading a tag transmitted through the user's hand from a device worn on their person. This would reduce the computational cost (and thus monetary cost) required by the system by avoiding the design challenges presented by performing reliable grasp detection, yet still allow for seamless natural interaction. This idea prompted the further investigation of human-mediated information transfer between devices by incorporating intrabody data transmission terminals to other types of everyday objects.

4

SHAKEONIT

To explore the concept of adding digital information to a physical communication channel, I completed a design exploration entitled "ShakeOnIt[14]." It is important to note that the paper that was published describes an early version of the system. A completely wireless version was designed from the ground up when the original demo broke; this thesis describes the technical details of the latest version. Schematics and PCB artwork can be found in Appendix B.

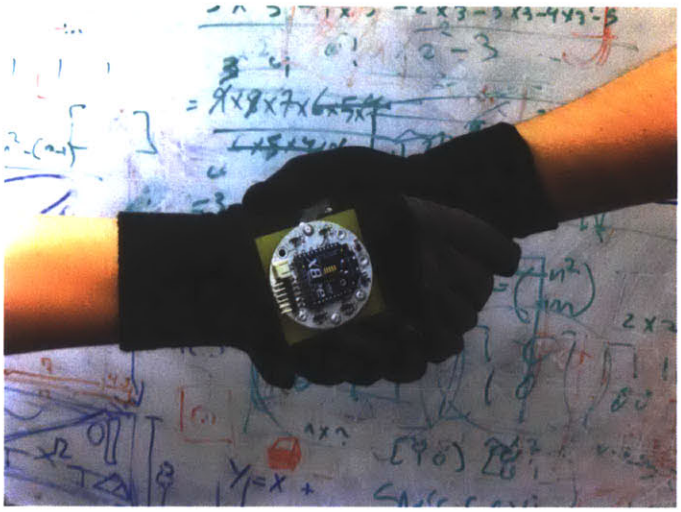


Figure 7: ShakeOnIt

ShakeOnIt is a system which utilizes a pair of sensor-outfitted gloves to test for the performance of a series of multi-person gestures known as a "secret handshake." The fact that a new user of the system is required to rehearse the handshake performance with someone who is already experienced in performing it adds a novel layer of security to digital information access which is inherently social because it augments users' pre-existing interaction patterns.

4.1 INTRODUCTION

Members of many social groups use specialized interaction methods known as "secret handshakes" to greet and identify one another [45]. These handshakes can be simple or complex, ranging from a basic clasping of hands to an elaborate series of gestures [45]. Similarly, a user of a computer system may be required to identify themselves to the system in order to access certain information by providing

credentials through the use of a password, biometric, or other access control system.

However, unlike the learning of a password or the adding of fingerprint data to a biometric database, the process of learning to perform an elaborate secret handshake includes non-transient periods of practice and interpersonal tangible communication with one or more members of the "approved users" group. Additionally, because a secret handshake requires the presence of two performers in order to be performed causes it to be, by definition, a social activity.

A computer system which tests for social integration would add a novel dimension to information access. In order to investigate this idea, a pair of sensor-outfitted gloves which can demonstrate a test for the successful performance of an elaborate secret handshake between two users was created.

4.2 RELATED WORK

The iBand [39] is a device demonstrated by researchers from Media Lab Europe and the University of London's Institute of Education which facilitates information transfer between two users shaking hands. The device itself consists of a wristband outfitted with LEDs, an accelerometer, and an infrared transceiver which facilitate the automatic transfer of personal information when two people wearing iBands shake hands.

Patel et al. [60] have done work regrading using gesture as an authentication scheme. In their system, a single user authenticates to a public computer terminal by performing a series of gestures with a personal device that is known to the system to belong to the user. In this way, the user can prove their identity to the terminal without the use of a password.

There have also been papers published in the literature which detail the use of synchronous and cooperative gesturing as an interaction and information sharing framework [27, 52]. Morris et al. discuss cooperative gesturing amongst a group of users in order to send a single, combined command to a system [52]. Hinckley describes methods by which a combination of users and displays can bump the displays together in different ways in order to share information amongst them [27].

The goal in creating ShakeOnIt was to combine elements from these projects in order to explore the possibilities of leveraging a computer mediated authentication scheme with a socially accepted cooperative gesturing system.

4.3 SYSTEM OVERVIEW

The system itself consists of two form-fitting gloves outfitted with conductive patches which allow it to sense nine different gestures which are displayed on the screen of a host computer.

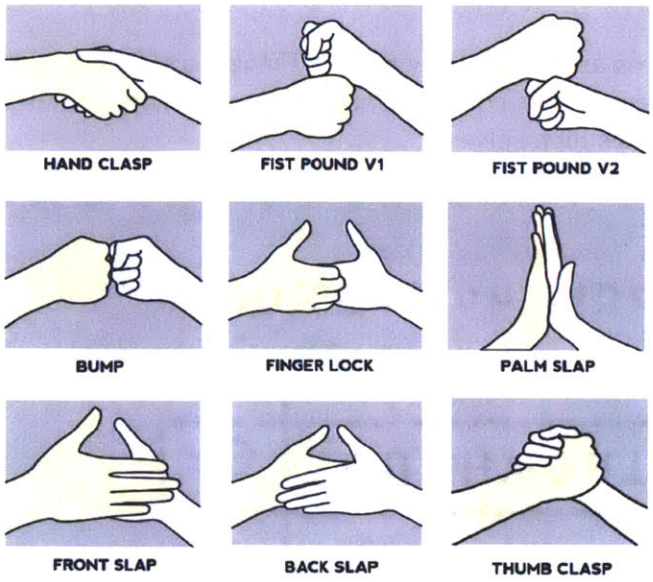


Figure 8: Secret handshake gestures

4.3.1 *Soft Sensors*

Each glove is outfitted with six patches of iron-on conductive fabric in the following locations: the front of the fingers, the palm of the hand, the back of the fingers, the bottom of the hand, and the top of the hand.

Figure 9: ShakeOnIt gloves

These patches are connected to the microcontroller by means of conductive thread sewn into the gloves which are crimped to snap connectors to improve mechanical impedance matching with the control boards.

4.3.2 *Hardware and Firmware*

Both gloves are outfitted with an STM32F103x based control board with soldered connections to snap connectors which mate with those on the gloves themselves.

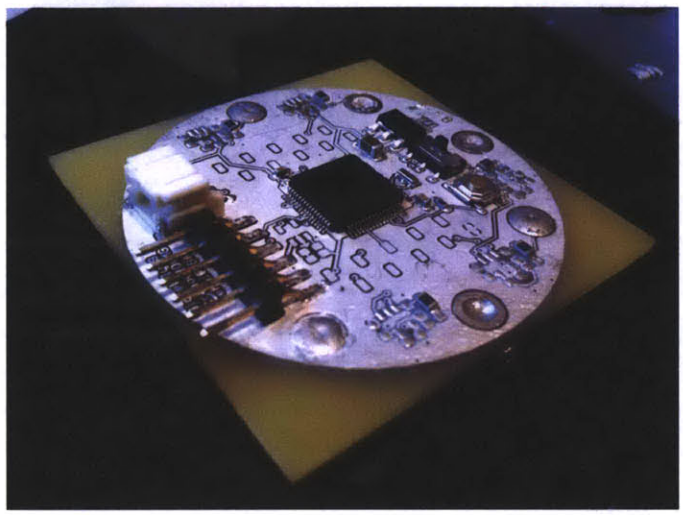


Figure 10: Control board with snap connectors

One glove (transmitter) uses the microcontroller's pulse-width modulation channels to transmit a different high frequency signal through each conductive patch. When the users perform a gesture, a different combination of patches are connected between the gloves. After conditioning the signal through an analog input stage, the other glove (receiver) counts the frequencies arriving on the pins corresponding to its pads, and a 6x6 array of current patch connections between the two gloves is recorded.

If this array matches the pre-determined "fingerprint" of a known gesture, the corresponding gesture identification number is transmitted to the host computer through a wireless serial connection.

4.3.3 *Gesture Visualization Program*

The host computer is running a program written in Processing which receives the data from the microcontroller and displays a pictogram of the gesture currently being performed by the users of the system. If the users perform a predetermined series of gestures in the correct order, an "access granted" graphic is displayed.

Figure 11: Access granted

4.4 EVALUATION AND DISCUSSION

ShakeOnIt was my first major design exploration during my course of study, and I presented it at lab open houses over the course of about one and a half years. It was used informally by around 50 people, most of whom were already culturally aware of the gesture set it employs. Nearly every user was enthralled by the system's quick detection and onscreen mirroring of the gestures, and delighted when the "access granted" sign was shown after a successful handshake was performed. Some users suggested utilizing the system to play an augmented game of "patty cake" or similar clapping games.

5

PILLOW-TALK

As an exploration into building systems of ubiquitous computing devices which mediate information between the real and digital worlds, I worked on a project entitled "Pillow-Talk[61]" in collaboration with fellow group member Edwina Portocarrero. Schematics and PCB artwork for this project can be found in Appendix C.

Figure 12: Pillow-Talk

Remembering dreams does not come easy for most people. It requires conscious effort and practice. Most of the advice for recollection suggests the use of pen and paper and a flashlight by the bed to jolt notes down. However, sitting up and writing demands an excessive physical and mental effort that is counterproductive to remembering the dreams themselves. Not only is lying still is crucial to the facilitation of recall, even the slightest movement is enough for the dream to evaporate from the mind.

Pillow-Talk invites users to realize the potential of their sleeping mind by providing a seamless interface by which to capture their dreams without distraction. It also offers a tangible and evocative visualization of the dreams themselves. Pillow-Talk provides seamless mediation between dreams, thoughts, musings and their recollection so that they can later serve the user in whatever way she might see fit: either for inspiration, self knowledge, therapeutic use or pure pleasure.

5.1 INTRODUCTION

Either physiologically as the response to neural processes, psychologically as reflections of the subconscious, or religiously as messages from the divine, dreams have been a topic of speculation and interest throughout recorded history. Dreams have been sought for divination, to determine dates for religious activities, and used as aids for healing and served as the source of artistic inspiration. Niels Bohr reported that he developed the model of the atom based on a dream of sitting on the sun with all the planets hissing around on tiny cords, while Remedios Varo and Dalí found inspiration in them for their paintings. Luis Buñuel, David Lynch and Maya Deren used dreams' spatial and temporal qualities in their films[16]. Hippocrates developed the idea that the dream was a window into illness, reflecting the body's state. This is an idea similar to the belief of the Huichol Indians from the north of Mexico who use dreams not only as insight on healing, but extend their use to political, spiritual, moral and artistic realms[6].

The digitization of information allowed by Pillow-Talk, unlike a dream diary, gives the user the potential to analyze dreams on a case by case basis as well as providing a powerful tool to evaluate dreams over time; qualifying and quantifying themes, characters and emotions. Pillow-Talk could serve as a powerful tool to bring further insight into the fears and desires of a many people as interpreted through their dreams. According to[7], "Myths are public dreams, dreams are private myths...dreams talk about permanent conditions within your own psyche as they relate to the temporal conditions of your life right now". This could be of great importance to users, for it could help relieve the sense of of alienation and create empathy by illustrating that every individual problem should be seen in reference to the human situation as a whole[38].

5.2 RELATED WORK

Persuasive technology aims to change attitudes and habits through persuasion, but it is mostly used in sales and management, politics, religion and public health[21]. Nonetheless, we find it to be a compelling field, for it exposes the individual to otherwise unrevealed knowledge about themselves. For example, Persuasive Mirror gives the user access to her own behavioral data by providing continuous feedback[15]. Omo is a relational machine, making the user conscious of the emotional and visceral aspects of breathing through imitation[18]. Francois Pachet's "Reflexive Interactions" sprouted from the idea that the creation of content technologies can enhance individual realization and establish inner dialogs through which personal content can emerge. They intend to produce an interaction in which an object has to be constructed not directly nor intentionally, but as a byproduct of an in-

teraction between the user and an image of herself, typically produced by a machine learning system. This is compelling to our research if we take the dream as an unconscious construction of an object and its recalling an interaction with one's own image[58].

There several projects that make use of the intimate qualities of a pillow as an interface. The Dreaming Pillow is a beautiful project exploring dream imagery taking the pillow as a canvas. Using capacitive sensing, it is reactive to touch: stroking the pillow enables the user to delve into the oniric landscape[43]. move.me uses pillows as an intimate input and output interface of adaptive ambient technology[53]. Pillowtalk is intended to connect remote lovers. The pillow emits a soft glow when the distant loved one has retired to bed; his heartbeat made audible in real time[51]. MusicBottles[32] is perhaps the most well-known example of jar-like objects acting as a "storage device" for digital information.

5.3 SYSTEM OVERVIEW

Pillow-Talk is a system composed of two objects:

THE PILLOW - a seamless interface which captures the users dreams and musings via embedded interaction.

THE JAR - a tangible visualization and playback device.

(a) The Pillow (b) The Jar

Figure 13: The Pillow and the Jar

5.3.1 *Interaction Design*

As stated above, it is difficult to learn from one's dreams if one can't remember them. The most common solutions for dream recollection usually require the dreamer to prepare oneself for remembering dreams before going to sleep and to keep a pen and paper by one's bed. A dream journal can encourage recall and, at the very least,

help document any fragment one does remember upon awakening. Although it has been noted that to capture detail it is best to lie still, pen and paper requires physical and mental effort which distracts the user from recalling the dream.

Thus, the component devices of Pillow-Talk have been carefully designed to integrate with the dream priming and recalling process in the most seamless way possible. The Pillow contains a recording device and a soft switch which initiates recording when the user squeezes the Pillow. This allows the user to minimize effort in storing a dream and hence optimize the chances for recall. When the audio of a dream is recorded, it is transmitted to the Jar. The Jar is designed to resemble a jar of fireflies; it contains 16 amber LEDs which twinkle in response to the users' interactions. When the user is not interaction with it, the "fireflies" that can be seen in the jar is the number of dreams contained within it, and they exhibit a calming twinkling pattern. When the user records a new dream into the Pillow, the firefly that is "coming to life" blinks rapidly as data is being transferred to the Jar. When the Jar is opened all of the fireflies fade to black except one, and a speaker in its neck plays back the recording of a random dream.

It was important to the design of the system to make its components visually evocative and have a seamless user interface that drew from the natural affordances of the objects; pillows naturally afford squeezing, and jars can be used to store things as well as opened to retrieve those things.

5.3.2 *Hardware: Pillow*

The Pillow is a normal pillow outfitted with a pillow case onto which conductive patches are sewn, and a removable control module connected via snaps to the inside of the pillowcase. A Bluetooth wireless headset paired with the host computer is also placed in the pillowcase. The control module is a neoprene pouch containing an Arduino Fio with an XBee radio as well as a Polymer Lithium Ion 1000mAh battery to power the system. The shape of the conductive patches functioning as the exposed switch were inspired by a sample user's renderings of her dream creatures.

5.3.3 *Firmware: Pillow*

The firmware of the pillow simply detects when the two conductive patches are in contact, and transmits a signal to the host computer to mark the beginning of a new recording.

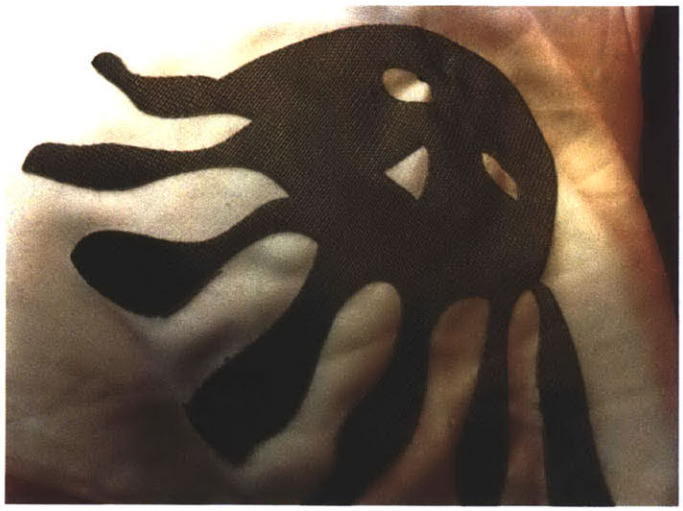


Figure 14: A dream-creature shaped soft switch

5.3.4 *Hardware: Jar*

The Jar itself is embodied as a Mason jar. The neck of the jar contains a custom PCB which integrates the functionality of an Arduino compatible microcontroller development board with an attached Arduino Wave Shield, Xbee wireless radio, and a MAX7313 16-channel LED driver. The neck of the jar also contains a speaker as well as two copper tape strips to serve as a switch that can be closed by conductive velcro on the Jar's lid when it is attached. 16 amber LEDs dangle into the Jar from the bottom of the control board. The Jar is powered with a Polymer Lithium Ion 1000mAh battery.

(a) Speaker in neck of the Jar

(b) The Jar's control board

Figure 15: Construction of the Jar

5.3.5 *Firmware: Jar*

The Jar's firmware is a control loop which accomplishes the following functions:

- Twinkle LEDs in an ambient pattern
- Check the lid switch to see if the jar has been opened. If so, play back a random sound file from the SD card.
- Check the serial port to see if the host computer is attempting to send a sound file. If so, record it and store it to the SD card.

5.3.6 *Software*

Both objects communicate through Xbee radios to a central computer which runs a Processing sketch to capture audio when the pillow is squeezed, store a sound clip, and and transmit the recordings to the jar.

5.4 EVALUATION AND DISCUSSION

We conducted a pilot study to identify the benefits of our idea and the implementation of the design. This pilot study helped identify the benefits of using Pillow-Talk over a paper based dream diary. We considered three cases: a user who normally remembered his dreams but fails at writing them down, a user who rarely remembers a dream and a user who remembers his dreams periodically. We asked each individual to be in possession of Pillow-Talk for 3 to 5 days.

In all cases, having a pillow specifically designed to record dreams served as an effective primer for retrieval. One user misplaced the pillow while sleeping and thus failed at accessing the switch and recording on multiple occasions. Another design issue mentioned was the need to turn on the device before going to sleep. While sometimes a conscious effort was made, on many occasions the need to sleep was stronger than the reminder. The Jar proved to be a delightful playback object, stimulating further use of the Pillow and adding value to the user's perceptions of their unconscious wonderings. The randomized playback was sometimes welcomed, while other times it proved frustrating when having the desire to listen to a specific dream. The design of both pillow and jar were generally praised with respect to their interfaces, and the use of the natural affordances of the jar to mediate digital information was found to be especially "natural-feeling."

6

PROTOTOUCH SYSTEM OVERVIEW

The ProtoTouch system is composed of two main parts: the touchpad and the wrist unit. During the course of the research presented in this thesis, two versions of the system were produced. A general overview of the system will be presented, and details specific to each instantiation will be discussed in the relevant subsections. Design details common to both will be repeated to aid understandability when quickly referencing one or the other. Schematics, PCB artwork, and source code can be found in appendices D and E.

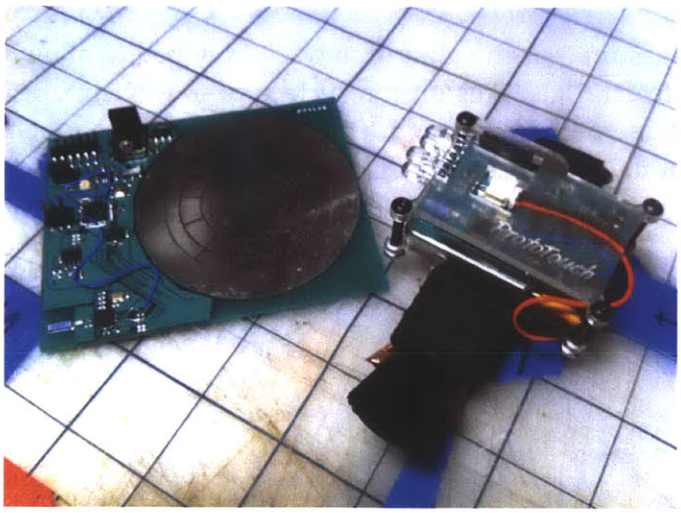


Figure 16: The ProtoTouch wristband and touchpad

6.1 THE TOUCHPAD

The touchpad consists of a multi-touch capable input surface which is capable of sending and receiving signals to and from the wrist unit, and includes broken out microcontroller GPIOs and serial port pins which can be connected to other electronic devices for control and further relay of information. This allows for interaction designs such that the user can gesture on the surface of the touchpad resulting in seamless information transfer "in the background" between the microcontroller and the wrist unit in response to the users' touch interaction.

6.2 THE WRIST UNIT

The wrist unit is, not surprisingly, worn on the user's wrist. It includes subsystems for electronic information transfer between it and the touchpad, as well as an accelerometer for sensing motion gesture and an array of infrared LEDs for transmitting information to other devices.

6.3 THE FIRMWARE

Although control programs are written specifically per application, several libraries can be used to utilize the main functions of the system.

6.3.1 *Gesture Sensing*

A naïve gesture sensing algorithm was developed to allow the touchpad to detect 6 gestures on the surface of the touchpad; up swipe, down swipe, left swipe, right swipe, pinch in, and pinch out. The design of the touchpad also affords rotational gesture sensing, but its detection is not yet implemented.

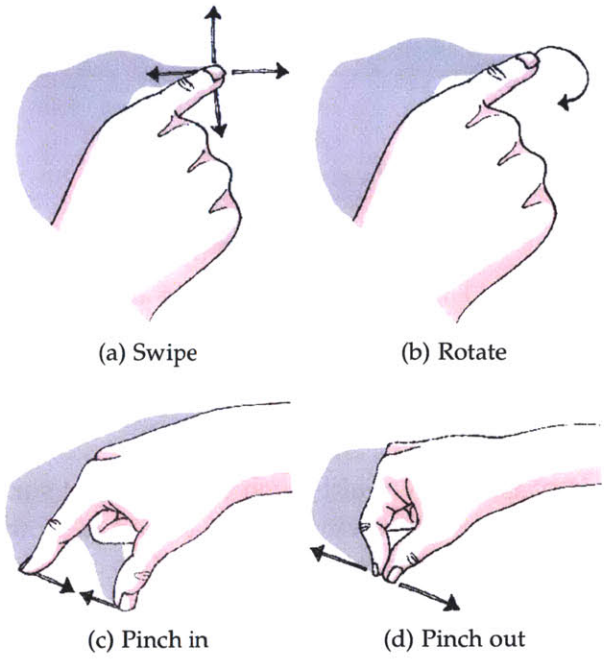


Figure 17: ProtoTouch gestures

6.3.2 *Intrabody Communication*

The SoftModem Arduino library was used to facilitate FSK communication through the body. It was modified to support FSK at 40kHz and

50kHz with a data throughput of 2450 bits per second. An averaging-based error correction algorithm was also implemented.

6.3.3 *Wireless Communication*

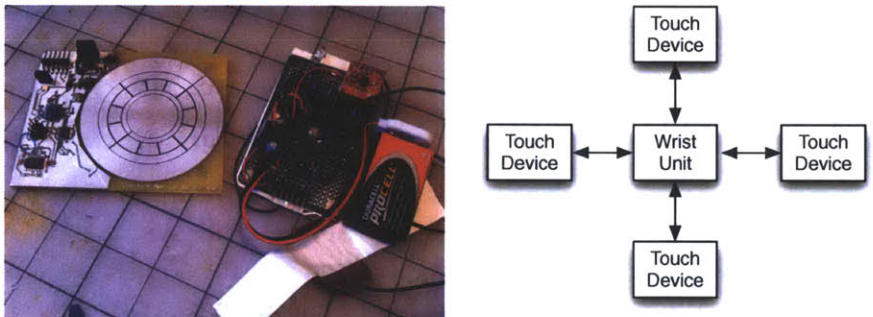
Version 2 of the system includes an 802.15.4 transceiver. In the applications described in chapter 8 of this thesis, Brian Mayton's AT86RF230 driver library was used to handle wireless communication between the touchpad and the wrist unit.

6.3.4 *Infrared Communication*

The IrRemote Arduino library was modified to support transmission of infrared information from the touchpad and wrist unit and retain compatibility with their other subsystems.

6.4 PROTOTOUCH VERSION 1

Figure 24 shows a photo of the first version of the system and the type of device networks it makes possible.



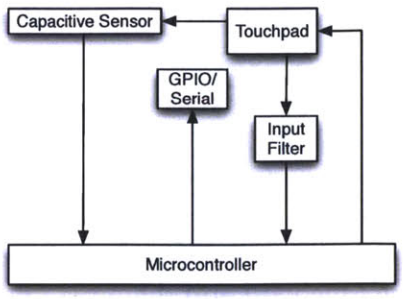
(a) Touchpad and wrist unit (b) Block diagram

Figure 18: ProtoTouch version 1

6.4.1 *Touchpad V1 Hardware Design*

Figure 19 shows a photo and the block diagram of the first version of the touchpad.

(a) The touchpad



(b) Block diagram

Figure 19: Touchpad version 1

6.4.2 *Power and Control*

The touchpad is powered either via a 9 volt "wall wart" or through its serial header. It includes two linear regulators, giving the board both 5 and 3.3 volt power rails. The touchpad is controlled by an Atmel ATMEGA328 microcontroller which is loaded with the Arduino firmware. A MAX3378 level shifter IC is employed to allow the microcontroller running at 5V communicate with the 3.3V capacitive sensing IC. A tri-color LED is included to provide visual feedback regarding system status.

6.4.3 *Capacitive Controller and Touchpad*

The capacitive sensing subsystem is made up of two components: the sensing controller IC and the touchpad itself. The sensing controller IC is an MPR121 proximity capacitive touch controller. It is capable of auto-calibrating and driving 12 channels, although the touchpad design utilized in this system only requires 7. It communicates with the microcontroller via the I^2C protocol. Because it can read the status of pads connected to it at a rate of 1000Hz, it enables multitouch sensing with compatible pad layouts.

The touchpad itself consists of 19 exposed metal pads arranged in a radial pattern to accommodate a variety of linear and rotational gestures as well as transmission and reception of signals to and from the wrist unit via the user's body.

17 of the pads are connected to inputs on the capacitive sensing IC, and two of them are used as transmit/receive surfaces for the intrabody communication subsystem. The transmit/receive pads are situated on the outer ring and the very center of the touchpad so that the user's fingers will come to rest on one of them after performing a pinch gesture, properly situating them for intrabody communication

between the touchpad and the wrist unit. The layout of the touchpad was designed in Adobe Illustrator and imported into Eagle using a python script.

Figure 20: Sensing and transceiver electrodes

6.4.4 *Intrabody Communication*

Figure 21 shows a detail of the intrabody communication receive system included on the touchpad. It amplifies the received signal to a full 5 volt swing for frequency counting by the microcontroller.

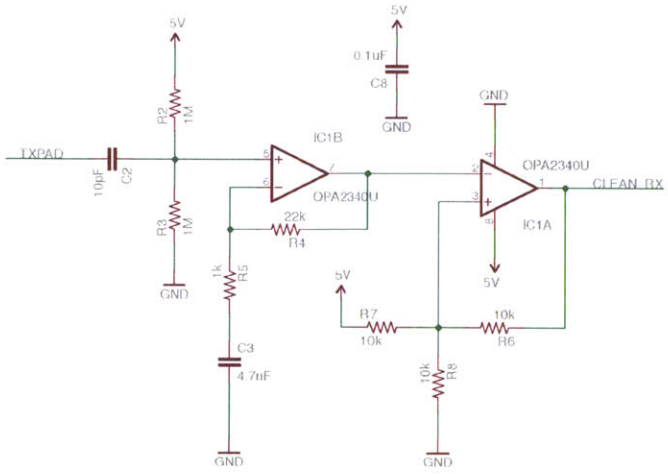


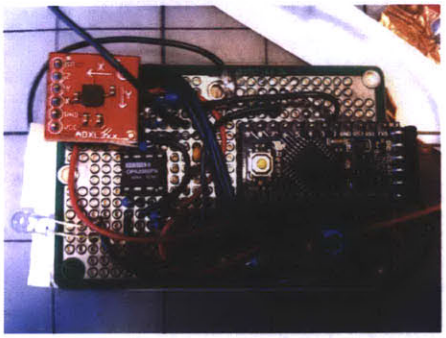
Figure 21: Intrabody communication transmit/receive section

In the above schematic, C2, R3, and R2 provide a high-pass filter to protect against environmental 60Hz noise. R3 and R2 center the received signal about 2.5V, and it is amplified via noninverting amplifier IC1B. IC1A is arranged as a Schmitt trigger with its switching band located at 2.5 ± 0.8V.

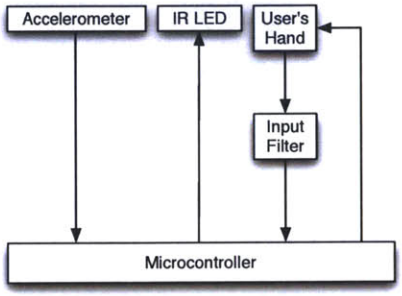
Signals are transmitted into the user by directly driving the appropriate pad directly from the microcontroller's GPIO pin.

6.4.5 *Wrist Unit V1 Hardware Design*

Figure 22 shows a photo and the block diagram of the first version of the wrist unit. The first version of the wrist unit was realized as a handheld protoboard containing the below described subsystems, a transmit pad taped to the back of the user's hand, and a long wire leading to a ground pad stuck to the user's shoe to satisfy grounding geometry constraints.



(a) The wrist unit



(b) Block diagram

Figure 22: Wrist unit version 1

6.4.6 *Power and Control*

The first version of the wrist unit is powered via a 9V battery which powers the onboard Arduino Pro Mini development board directly as well as being regulated down to 3.3V by a standard linear regulator to power the accelerometer.

6.4.7 *Accelerometer and IR LEDs*

The wrist unit includes an ADXL335 3-axis accelerometer with a sensing range of $\pm$ 3g which can be used to detect motion gesture. It also has an 850nm infrared LED to enable distance communication with other devices.

6.4.8 *Intrabody Communication*

Figure 23 shows a detail of the intrabody communication receive system included on the wrist unit. It amplifies the received signal to a full 5 volt swing for frequency counting by the microcontroller.

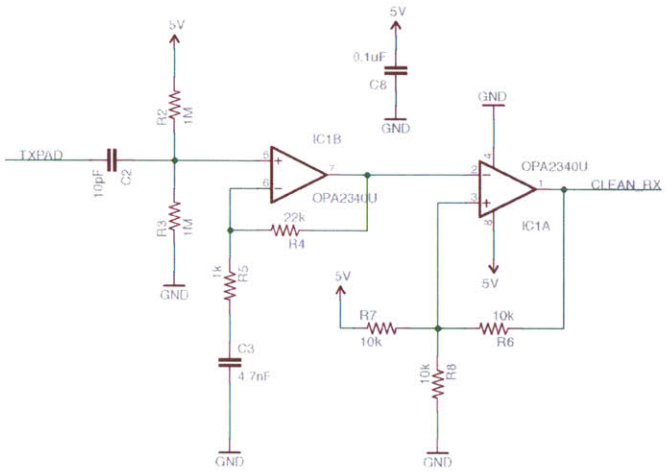


Figure 23: Intrabody communication receive section

In the above schematic, C2, R3, and R2 provide a high-pass filter to protect against 60Hz noise. R3 and R2 center the received signal about 2.5V, and it is amplified via noninverting amplifier IC1B. IC1A is arranged as a Schmitt trigger with its switching band located at 2.5 $\pm$ 0.8V.

Signals are transmitted into the user by directly driving the pad which is in contact with the user's hand directly from the microcontroller's GPIO pin.

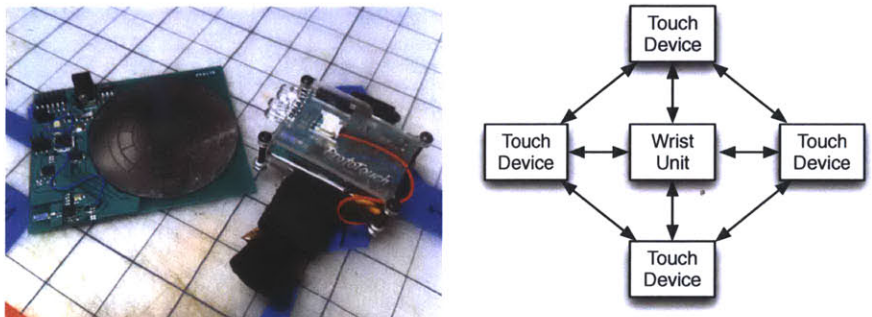
6.4.9 *Discussion*

I was able to prototype early versions of the demos described in chapter 8 using this version of the system, but the finished product left much to be desired as far as robustness and reliability were concerned. A major shortcoming of this design is that information can only be transferred when the user is making physical contact with the touchpad, ruling out the possibility of devices communicating with each other without the users' direct intervention. The data transfer back and forth between the touchpad and wrist unit requires the user to maintain a high standard of finger contact with the touchpad after they had completed a gesture, which proved to cause reliability problems when attempting to interact with the touchpad in a natural way. Additionally, the handheld nature of the first version wrist unit and its accompanying long grounding wire proved to be cumbersome

when testing interaction scenarios. There are also several general connectivity bugs which were corrected in the second version.

6.5 PROTOTOUCH VERSION 2

Figure 24 shows a photo of the second version of the system and the type of device networks it makes possible.



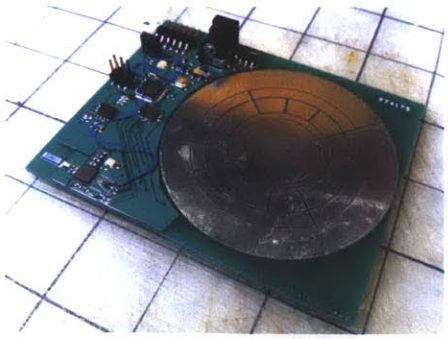
(a) Touchpad and wrist unit (b) Block diagram

Figure 24: ProtoTouch version 2

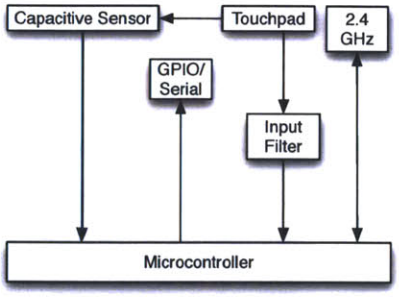
Version 2 of the system includes several significant design modifications. The first is the addition of an 802.15.4 radio subsystem to both the touchpad and the wrist unit. This allows for more robust communication between the touchpad and wrist unit, as well as between touchpads independent of intervention from the wrist unit. The second is the modification of the body transmission subsystem on both components to afford only one-way transmission from the wrist unit to the touchpad. This saves component space on the very dense wrist unit PCB, and allows it to simply continuously broadcast a "tag" through the user's hand that only needs to be successfully read once by the receiver on the touchpad, which then could carry out more robust and bandwidth-intensive communication via the radio modules. Third, the number of IR LEDs on the wrist unit has been increased to improve the robustness of optical communication from it. Fourth, a tricolor LED has been added to the wrist unit to provide visual feedback and system status. Finally, a 15V power supply is included on the wrist unit to improve the signal quality of intrabody communications to the touchpad.

6.5.1 *Touchpad V2 Hardware Design*

Figure 25 shows a photo and the block diagram of the second version of the touchpad.



(a) The touchpad



(b) Block diagram

Figure 25: Touchpad version 2

6.5.2 *Power and Control*

The touchpad is powered either via a 9 volt "wall wart" or through its serial header. It includes two linear regulators, giving the board both 5 and 3.3 volt power rails. The touchpad is controlled by an Atmel ATMEGA328 microcontroller which is loaded with the Arduino firmware. A MAX3378 level shifter IC is employed to allow the microcontroller running at 5V communicate with the 3.3V capacitive sensing IC. Inline resistors are used to enable communication between the 3.3V RF IC and the 5V microcontroller. A tri-color LED in included to provide visual feedback regarding system status.

6.5.3 *Capacitive Controller and Touchpad*

The capacitive sensing subsystem is made up of two components: the sensing controller IC and the touchpad itself. The sensing controller IC is an MPR121 proximity capacitive touch controller. It is capable of auto-calibrating and driving 12 channels, although the touchpad design utilized in this system only requires 7. It communicates with the microcontroller via the I^2C protocol. Because it can read the status of pads connected to it at a rate of 1000Hz, it enables multitouch sensing with compatible pad layouts.

The touchpad itself consists of 19 exposed metal pads arranged in a radial pattern to accommodate a variety of linear and rotational gestures as well as transmission and reception of signals to and from the wrist unit via the user's body.

17 of the pads are connected to inputs on the capacitive sensing IC, and two of them are used as receive surfaces for the intrabody communication subsystem. The transmit/receive pads are situated on the outer ring and the very center of the touchpad so that the user's fingers will come to rest on one of them after performing a

pinch gesture, properly situating them for intrabody communication between the touchpad and the wrist unit. The layout of the touchpad was designed in Adobe Illustrator and imported into Eagle using a python script.

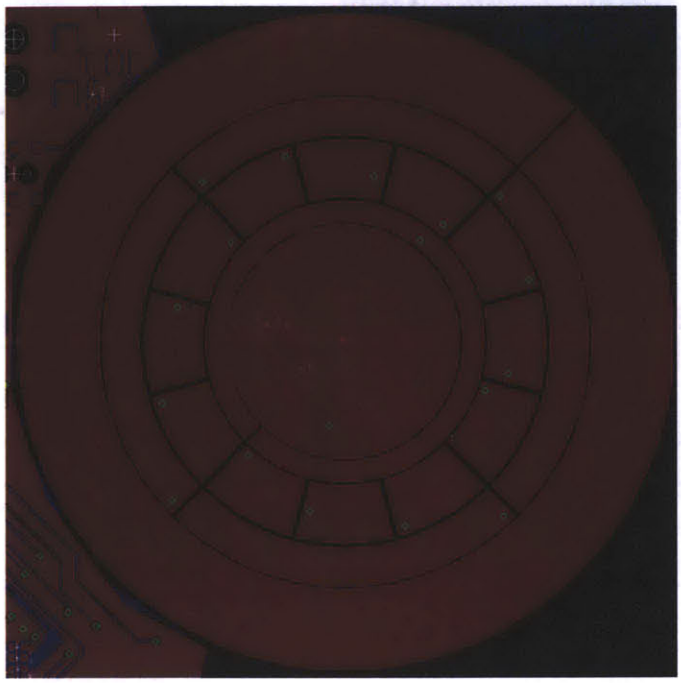


Figure 26: Sensing and transceiver electrodes

6.5.4 *Intrabody Communication*

Figure 27 shows a detail of the intrabody communication receive system included on the touchpad. It amplifies the received signal to a full 5 volt swing for frequency counting by the microcontroller.

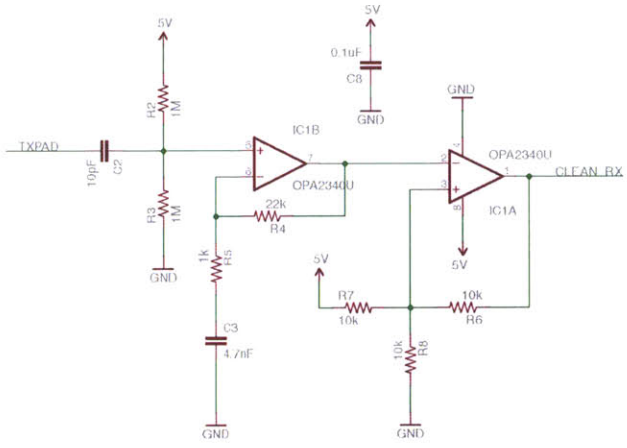


Figure 27: Intrabody communication receive section

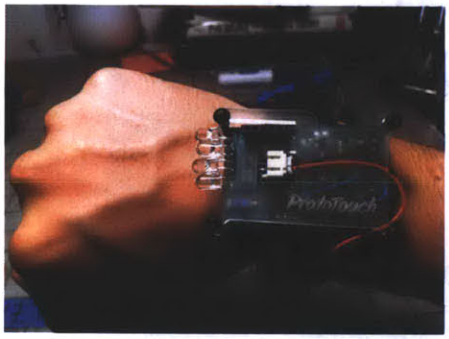
In the above schematic, C2, R3, and R2 provide a high-pass filter to protect against 60Hz noise. R3 and R2 center the received signal about 2.5V, and it is amplified via noninverting amplifier IC1B. IC1A is arranged as a Schmitt trigger with its switching band located at 2.5 ± 0.8V.

6.5.5 *RF Communication*

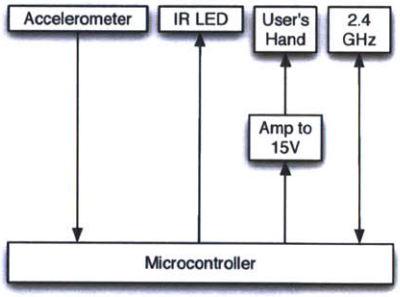
The second version of the touchpad includes an Atmel AT84RF230 2.4GHz radio transceiver. It utilizes a 2.4Ghz ceramic chip antenna, and communicates with the microcontroller via SPI.

6.5.6 *Wrist Unit V2 Hardware Design*

Figure 28 shows a photo and the block diagram of the second version of the wrist unit. It was realized as a PCB and battery sandwiched between two pieces of acrylic.



(a) The wrist unit



(b) Block diagram

Figure 28: Wrist unit version 2

6.5.7 *Power and Control*

The second version of the wrist unit is powered via a Polymer Lithium Ion 850mAh battery, which is regulated to 3.3V, 5V, and 15V by a standard 3.3V linear regulator, a TPS62100 switching regulator, and FAN5331 switching regulator, respectively. It is controlled by an Atmel ATMEGA328 microcontroller which is loaded with the Arduino firmware. Inline resistors are used to mediate communication between the 3.3V RF IC and the 5V microcontroller. A tri-color LED is included for visual feedback.

6.5.8 *Accelerometer and IR LEDs*

The wrist unit includes an ADXL335 3-axis accelerometer with a sensing range of ± 3g which can be used to detect motion gesture. It also has a bank of 4 850nm infrared LEDs to enable distance communication with other devices.

6.5.9 *Intrabody Communication*

The intrabody communication system on the wrist unit consists of a copper pad mounted underneath the control board so as to be in contact with the user's hand at all times, and a ground pad around the outside of the watchband so as to provide a good return path to the touchpad's ground plane when the user is gesturing on it. It transmits signals through the user's hand by switching the 15V power supply into the pad which is in contact with the user's wrist.

Figure 29: Wristband in close proximity to touchpad ground plane

6.5.10 *RF Communication*

The second version of the wrist unit includes an Atmel AT84RF230 2.4GHz radio transceiver. It utilizes a 2.4Ghz ceramic chip antenna, and communicates with the microcontroller via SPI.

6.5.11 *Discussion*

Version 2 of the system has proven to be much more robust and reliable than the previous version, enabling the prototyping of several interaction scenarios in touch-mediated ubiquitous computing environments, as described in chapter 8.

7

PROTOTOUCH ELECTRONIC DESIGN

ProtoTouch is designed to be a kit of parts which interaction designers can "stick on" to existing objects and devices to quickly test new touch-mediated device interactions. However, in order further integrate the sensors and transmitters into the objects themselves, it is important for interface designers to be able to "remix[25]" the hardware implementation presented in this document to suit the constraints of their own investigations. The electrical design of certain subsystems of this kit require physical considerations other than simply netlist congruence and attention to part power ratings in order to function properly. The below sections present some brief theoretical background on these topics as well as things to pay attention to when implementing them in physical hardware. In an effort to make this explanation accessible to those without a substantial electrical engineering background, emphasis will be placed on providing practical guidelines over theoretical formalism.

7.1 GROUNDING AND NOISE REDUCTION

Ground is a node in a circuit which is defined as having a steady potential of 0 volts, and is the "reference" against which voltages in the circuit are defined [37]. However, being node in a circuit, it is subject to current flow into and out of it. Because the traces used in printed circuit boards have non-zero impedance, voltage differences will occur at different points along the path of current flow. It is easy to see that if there are voltage differences in different parts of the reference potential node, problems can develop with the functionality of the overall circuit. This is of special concern to designs which incorporate delicate sensor packages. As a result, it is good practice to include a large ground plane[36] which provides a low-impedance path for return currents from different parts of the PCB.

It can be useful to put sections of a circuit especially noisy or sensitive to noise on their own ground plane and connect it to the main section via a thin and thus high-impedance trace. Because currents always follow the lowest impedance path, noise will tend to stay within its own section of ground plane because the thin trace acts as a low-pass filter.

In addition to robust ground routing, decoupling capacitors[36] are usually used to reduce noise. Decoupling capacitors essentially act as

charge storage tanks, protecting the circuit from temporary voltage changes caused by ground currents[36].

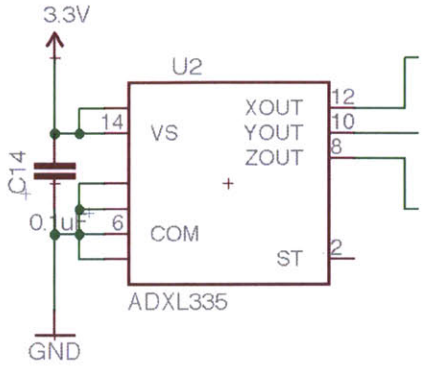


Figure 30: C14 is a decoupling capacitor

Bulk decoupling capacitors are usually fairly large(10-100uF) and placed across the main power supply rails. Smaller(0.01-10uF) decoupling capacitors are placed close to components in order to protect them from noise, by providing a high speed "bypass[1]" path between power and ground for any noise that appears near them. In designs which anticipate wider bandwidth noise in the power supply, two or more decoupling capacitors can be used in parallel (NOT combined into one equivalent capacitor) in order to maintain a low AC impedance across many decades of frequency[1].

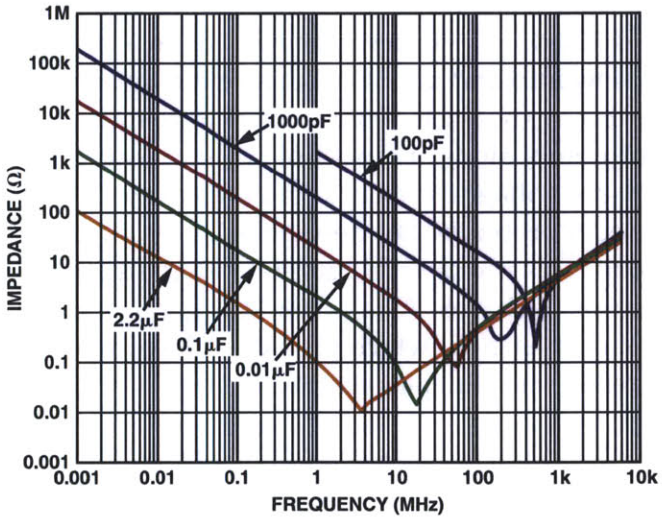


Figure 31: Capacitor impedance vs. frequency[1]

Further, it is important to pay attention to capacitive coupling between signal traces on the board. It is not good practice, for example, to run a sensitive analog signal line next to a digital signal line - the rapidly changing full-voltage swing of the digital trace can induce noise in the analog signal.[36]

7.1.1 *Design Guidelines*

- Pay attention to signal routing - heed ground return paths as well as mutual capacitance between signal lines.
- If the board has ground planes on more than one layer, place as many connecting vias between those layers as possible to further guard against potential differences.
- Keep all decoupling capacitors as close as possible to the components they are decoupling.
- When designing the layout of the RF section which serves the AT86RF230, make sure to separate the analog ground, digital ground, clock, and power planes in a star topology[36] referenced to the ground pad of the chip as described in [13].
- The chip antenna should should be surrounded by as much ground plane-free space as possible.

7.2 SWITCHING POWER SUPPLIES

The wrist unit component of V2 of the Prototouch system utilizes two DC-to-DC boost converters to provide the devices' 5V and 15V power rails from a 3.7V Polymer Lithium Ion battery. DC-to-DC boost converters provide efficient voltage level shifting by taking advantage of an inductor's tendency to resist changes in current[55]. Figure 32 shows the topology of a basic DC-to-DC boost converter.

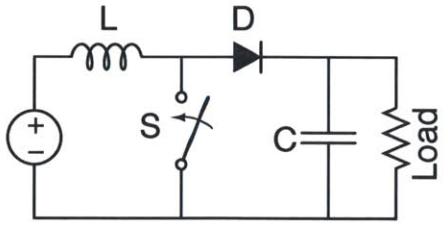
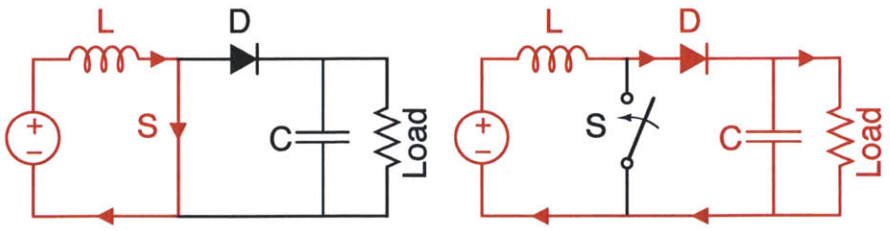


Figure 32: Topology of a basic DC-to-DC boost converter circuit

Essentially, a DC-DC-boost converter rapidly switches the current flowing through an inductor to build up charge, and thus voltage on a capacitor. A boost converter circuit exists in one of two states[55]: the "on" state when the switch S is closed and energy is being stored in the inductor L, and the "off" state when S is open and energy is being released from L, "boosting" the output voltage across the load.



(a) "On" state (b) "Off" state

Figure 33: States of a DC-to-DC boost converter circuit

When the switch S is closed, current flows through the inductor L, and it stores charge in its magnetic field[55]. When the switch is opened, the only current path out of the inductor is through the diode D, and the magnetic field around L collapses rapidly in an attempt to keep the current flowing into and out of the inductor equal when this new current path becomes available. This results in a large voltage being developed at L with respect to the original supply voltage, prompting current to flow through D and subsequently charging C. If the RC time constant of the load and the output capacitor is significantly larger than the time spent charging the inductor, the output voltage remains fairly constant[63].

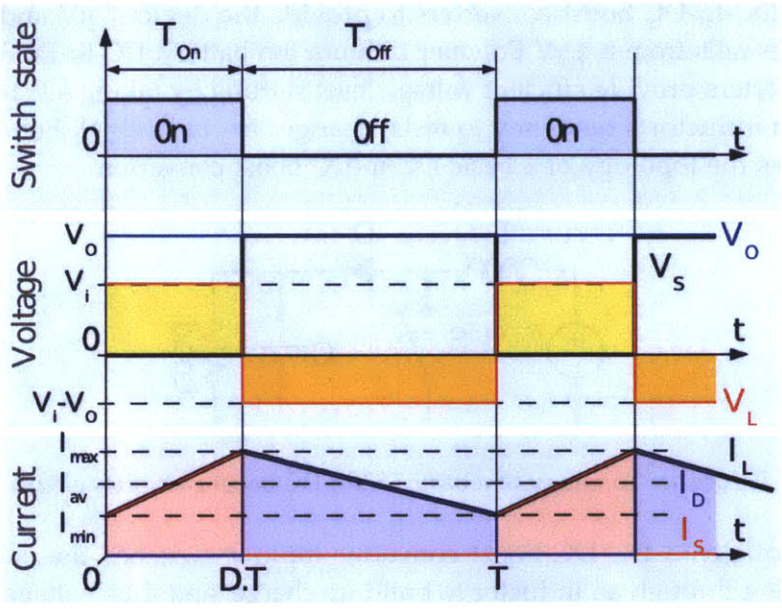


Figure 34: Current and voltage in a boost converter operating in continuous mode[74]

7.2.1 *Design Guidelines*

The large currents and high switching frequency of the boost converter necessitates attention to the physical layout of the circuit in order to

maintain output stability and low noise injection into other parts of the circuit, especially when the converter is operating near its limits. Although the supplies in the design presented in this document are chosen with a fairly high "safety factor," it is good to keep the following guidelines in mind when considering their layout:

- Separate the power and control ground nodes, and connect them at the ground terminal of the regulator IC. This minimizes ground shift problems caused by superimposition of high return currents from the power part of the circuit and the control signals[30].
- Both of the regulators in this design utilize voltage divider feedback to adjust the switching frequency of the controller. Route the feedback line away from any high current and high frequency nodes, especially those around the inductor to avoid RF coupling into the feedback signal[68].
- Place the input and and output capacitors as well as the inductor as close as possible to the control IC, and use wide traces tolerant of the high switching currents to connect them[68].

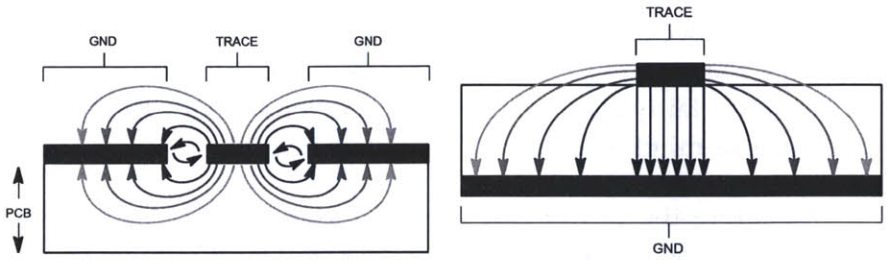
7.3 CAPACITIVE SENSOR LAYOUT

Capacitive sensing works by detecting changes in the capacitive properties of electrodes, often by measuring the change of their RC time constant. When a finger or other conductive object comes near or touches these electrodes, its capacitance increases, thus increasing its step response time[49].

7.3.1 *Design Guidelines*

The capacitive sensing chip utilized by ProtoTouch measures changes in the capacitance to ground of the electrodes to which it is connected[69]. Thus, it is important to lay out electrodes and signal lines to minimize stray capacitance to ground in the electrodes and signal lines[69] to provide maximum capacitance change when the user touches an electrode. In general, a designer should attempt to minimize trace and pad capacitance while maximizing touchable pad area[69].

- Because traces and pads can couple to ground through a PCB, ground planes should be kept away from sensor electrodes on both sides of the PCB[69].
- Traces between the sensor IC and the electrodes should be as thin and short as possible[69].
- Routing traces under capacitive sensing pads should be avoided[69].



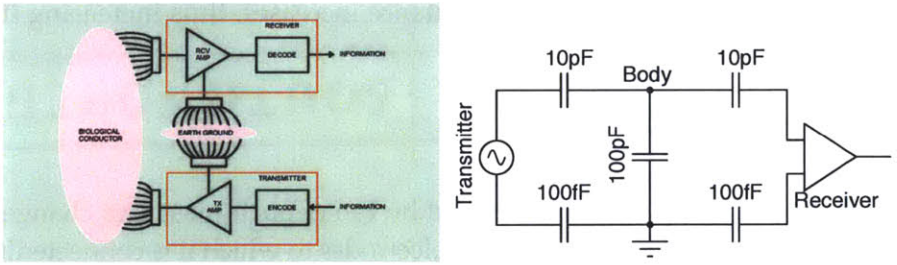
(a) Trace fringe capacitance (b) Trace ground capacitance

Figure 35: Stray capacitance[69]

- Because the electrodes are designed to be as close to "floating" with respect to ground as possible, pads can be physically as close to each other as the manufacturing process will allow[69].

7.4 INTRABODY DATA TRANSMISSION

The human body can be used as an electrical communication channel due to its low internal resistance[77]. One method of doing this is by capacitively coupling a transmitter and receiver to each other via skin-contacting electrodes[77]. Because a non-radiating signal is being transmitted, a ground return path must be provided between the receiver and transmitter in order for the circuit to function properly. Figure 36 shows a block diagram and schematic model of such a system.



(a) Physical arrangement of the system (b) System modeled as a capacitive bridge

Figure 36: Physical and schematic diagrams of the system[77?]

7.4.1 *Design Guidelines*

Given that the impedance of a capacitor is defined to be

$$Z_c = \frac{1}{j\omega C}$$

it can be seen from the above schematic that the capacitances in the signal path of the system should be maximized to minimize

impedance presented to signals flowing through the circuit. Although the contact between the body and the transmit/receive electrodes is nearly guaranteed in a system such as ProtoTouch, engineering the required ground return path to work yet not get in the way of interactions can be prove to be somewhat of a design challenge.

The second version of Prototouch utilizes a large ground plane on the surface of the touchpad and a conductive strip on the outside of the wrist unit's watchband so that they will be in close proximity while intrabody transmission of data is being carried out[1]. It is also important to note that even though the equation for the impedance of a capacitor implies maximum frequency as optimal for low-impedance communication, the body's high pass filter characteristics become unpredictable over 4MHz[9].

1 See Figure 29

8

APPLICATION IMPLEMENTATION

This chapter details several interaction design demos I made while in the process of creating ProtoTouch. Formal user studies were not performed as the purpose of creating these demos was to test and improve the robustness of the system itself.

8.1 PHYSICAL COPY-AND-PASTE OF APPLIANCE SETTINGS

This demo enables a user to set settings on an appliance, in this case, a smart LED lightbulb, and propagate those settings to other lamps outfitted with similar lightbulbs by performing touch gestures on the surface of touchpads attached to the lamps. The user can also "throw" settings to other lamps from a distance.

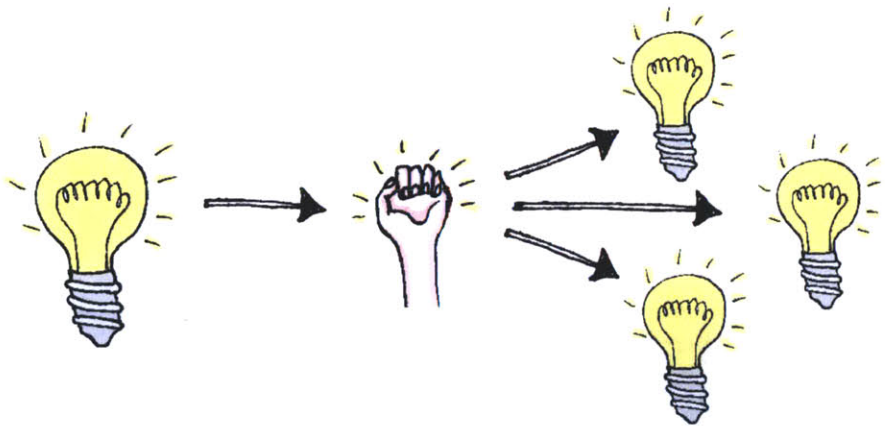


Figure 37: Propagating settings with physical copy and paste

8.1.1 *System Design*

(a) Copy setting (b) Setting in hand (c) Paste setting

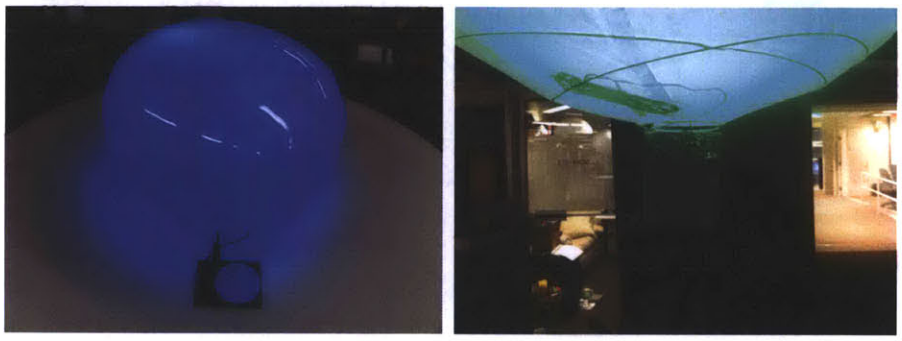
Figure 38: Copying, carrying, and pasting lamp color setting

In addition to the basic set of tools provided by ProtoTouch, this system utilized a number of "Multi-Color E27 LED Light Bulb With Remote," a brandless remote controllable LED bulb available from various sellers on Amazon.com.

Figure 39: LED light bulb and remote control

Upon receiving the bulbs and remotes, I reverse-engineered their IR transmission system and found it to utilize standard NEC protocol[8] and 850nm light. I then mapped all the codes for bulb functions and color settings available from the remote.

Next, Prototouch touchpads were fitted to LED bulb-containing lamps throughout the Object-Based Media lab space, and 850nm LEDS were connected to their GPIO outputs, enabling control of the LED bulbs from each touchpad. This system was prototyped twice; once utilizing each version of the toolkit.



(a) Table lamp (b) Hanging lamp

Figure 40: Two lamps outfitted with ProtoTouch touchpads

8.1.2 *Firmware Design*

In the first version of the system, the touchpad waits for the user to perform a gesture upon it[1]. If the user swipes left or right, the color of the light bulb is changed via the IR led. If the user pinches in, the

1 See figure 17

touchpad sends a data packet containing the current state of the lamp to the wrist unit out through the user's fingers. If the user executes a pinch out gesture, the touchpad sends a request for data to the wrist unit via the user's hand. When the wrist unit receives this request, it responds by sending the information currently held in its data buffer to the touchpad, which then actuates the color of the light accordingly. Additionally, the wrist unit is programmed such that shaking it in a "throwing" motion (detected by the onboard accelerometer) causes it to output the contents of its data buffer through its own IR LED to enable the remote application of color setting on lamps out of the immediate reach of the user.

The second version of the system utilized the same gesture detection and lamp actuation methodologies as the first version. The only major change was the utilization of the 802.15.4 radio subsystems to transmit information between the touchpad and the wrist unit. This change does not forbear the possibility of easily updating the system to support multiple users; the wrist unit's firmware could easily be modified to broadcast a packet containing its radio address to the touchpad via intrabody communication.

8.2 PHYSICAL TRANSPORTATION OF DIGITAL CONTENT

Besides "copying and pasting" of appliance settings, I experimented with enabling the user to have the appearance of physically transporting digital content. This could be useful in a situation such as changing rooms in the midst of listening to a podcast; instead of having to reload the same file and jog it to the correct timecode on a different audio playback system, the user could just "pick up" the track and carry it with them to the new listening location.

Figure 41: Physical transportation of digital content

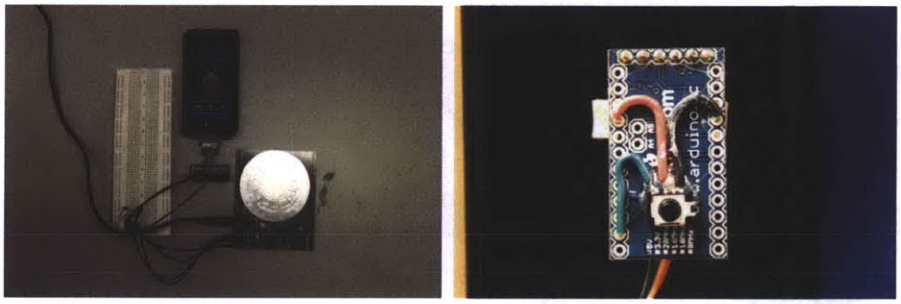
8.2.1 *Hardware Design*

In addition to the basic set of tools provided by ProtoTouch, this system utilized an iPod as well as a system for controlling an Apple TV.

(a) Grab song (b) Throw (c) To television

Figure 42: Grabbing and throwing digital content

The iPod was connected to the ProtoTouch touchpad's serial port via a PodBreakout iPod dock connector breakout board. The Apple TV was connected to a television set and to the Lab's network. A Mac Mini was also added to the network and connected to an Arduino Pro Mini outfitted with a 38kHz infrared receiver via a serial to usb converter cable. A combination of python and AppleScript read signals coming in from the IR receiver, mapped the song data to a song title in a pre-configured playlist, and commanded the Apple TV to begin playback of the appropriate song upon reception of valid data.



(a) iPod with touchpad (b) IR receiver on TV bezel

Figure 43: iPod with ProtoTouch touchpad and television with IR receiver

8.2.2 *Firmware Design*

The touchpad and was programmed to wait for a gesture to be performed on it by the user. If the user swipes left or right on the touchpad, the song currently playing in the iPod is changed. If the user pinches in, the touchpad uses the iPodSerial library to stop playback, determine the ipod's currently playing song information, and subsequently transmits this information to the wrist unit through the user's body.

Since the wrist unit fulfills the same function as a data buffer as the lamp system, the same firmware was used to send, receive, and store its data. If the user makes a throwing motion, the song information

data packet is transmitted to the Apple TV control system, causing the corresponding song to be played back on the television.

9

FUTURE WORK AND CONCLUSION

In addition to applications involving purposeful tangible manipulation of abstract digital information described in chapter 8, a very exciting interaction modality made possible by this system is the *passive* transmission of information between devices via the user. Because the system presented in this thesis can trigger digital information transfer whenever a user touches a particularly designed surface of an object, this information transfer can happen completely in the background as a user goes throughout their day interacting with objects in a normal fashion. Appropriately outfitted objects and appliances could gather information about what else the user has been interacting with, and use this information to better anticipate user goals.

For example, pairing between wireless device accessories and devices could be made much simpler. Right now, the process of accomplishing this task involves placing the devices close together, and performing a long ceremony involving patterns of button presses and double checking of PIN numbers. However, there is more than enough information present in the actual act of preparing the devices to pair that could be utilized to make the setup experience completely seamless; the user touches the accessory to place it near the device they wish to pair it with, and then touches the device's user interface. If these surfaces were outfitted with a system such as the one presented in prototouch, it would be trivial for them to find each other by uploading and downloading identification information into the user-worn information buffer. Because this information is transmitted via the user completely in the background, everything just appears to work better.

Looking even father forward, the ability to access records of every object that a person has physically interacted with and *how* they interacted with them over the course of time could be a huge benefit to many devices. For example, what if the appliances in a users' house knew what other objects they had been interacting with recently? Many user-settable devices would just need an "on" button for most interaction with them to allow identification of the user and their stored information. At a touch, the oven could predict what temperature to set itself for if it knew what food packaging and cookbook pages the user had been handling. The climate control system in the house would know to activate heating if the user has just come in from using a snow shovel, or perhaps air conditioning if they have just finished using workout equipment. The coffee machine might make stronger

coffee if the user has been using the snooze button more times than normal.

9.1 TECHNICAL IMPROVEMENTS

A number of technical improvements are possible in order to make ProtoTouch a more useful prototyping tool. The next version of the system could include a number hardware and software optimizations to allow for faster, higher bandwidth, and more reliable communication between the wrist unit and the touchpad as well as general usability improvements. These could include:

- Exploration and implementation of other information encoding and error correction schemes, such as shown in [47].
- Investigation of other connection topologies, such as one where no data is actually stored on a users' person; they could just wear a radiating tag which directs devices to communicate with one another via the cloud.
- Optimization of the currently employed FSK software to allow for faster communication. In addition to bandwidth improvement, the increased carrier frequency would relax the constraints on user/touchpad geometry by being more tolerant of lower capacitance (and thus distance between devices) in the ground return path.
- Implementation of a unified software library with a complete API.
- Implementation of a middleware protocol, such as that described in [76] to ease the development of systems with many different types of information appliances.
- A form factor redesign of the touchpad board to make it compatible with Arduino shields or other expandable microcontroller development platforms.
- Creation of a "backpack" style wrist unit (even though it wouldn't be a wrist unit any more) for metal encased cellular phones and tablet computers to enable interaction with mobile device applications.

9.2 CONCLUSION

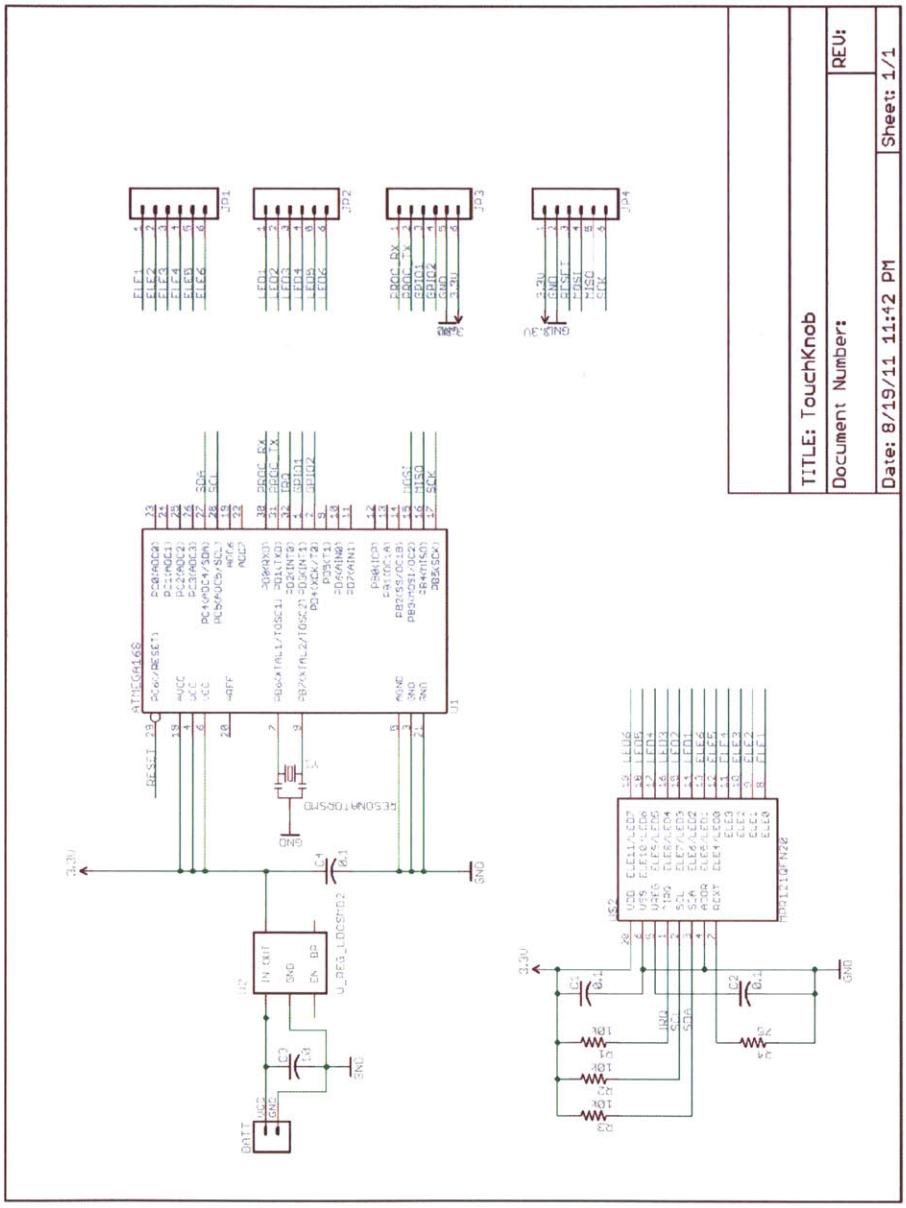
Satyanarayanan's widely cited paper on the vision and challenges of pervasive computing proposes four major research thrusts of interests when considering the practical design of ubiquitous computing

environments: *effective use of smart spaces, invisibility, localized scalability, and masking of uneven conditioning*[66]. The system presented in this thesis enables researchers to investigate the goals of creating smart environments with invisible interaction by aiding the creation of objects and interactions which leverage already-available devices and pre-established interaction modalities, in addition to prototyping the creation of new ones. Because it is the user who is mediator of information between devices created with this system, scaling is natural to whatever devices include capability to utilize data being carried by the user, and implementation of a standard middleware for such devices could allow for their natural proliferation. A user would not notice if they are interacting with unaugmented devices, since they function completely normally, and would be able to naturally discover the additional functionality from those that do include added technological benefit.

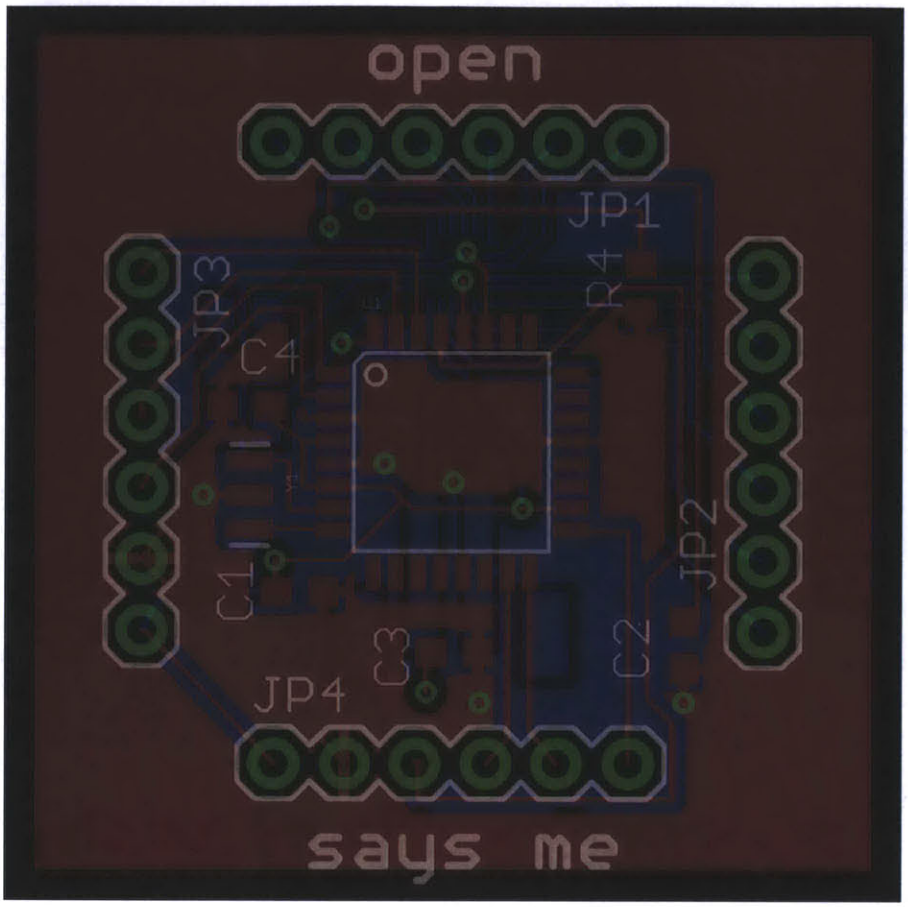
A

TOUCHKNOB DESIGN FILES

A.1 SCHEMATIC



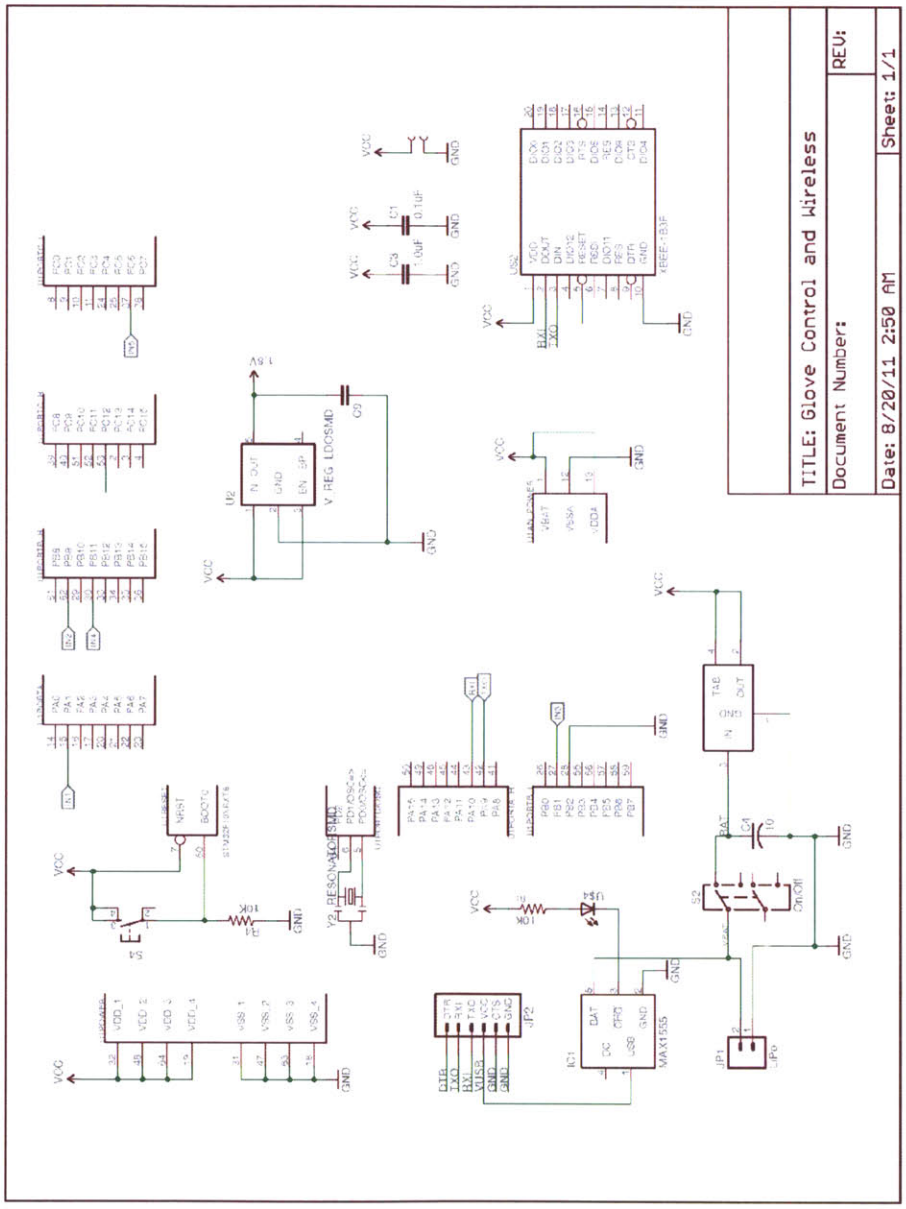
A.2 PCB ARTWORK

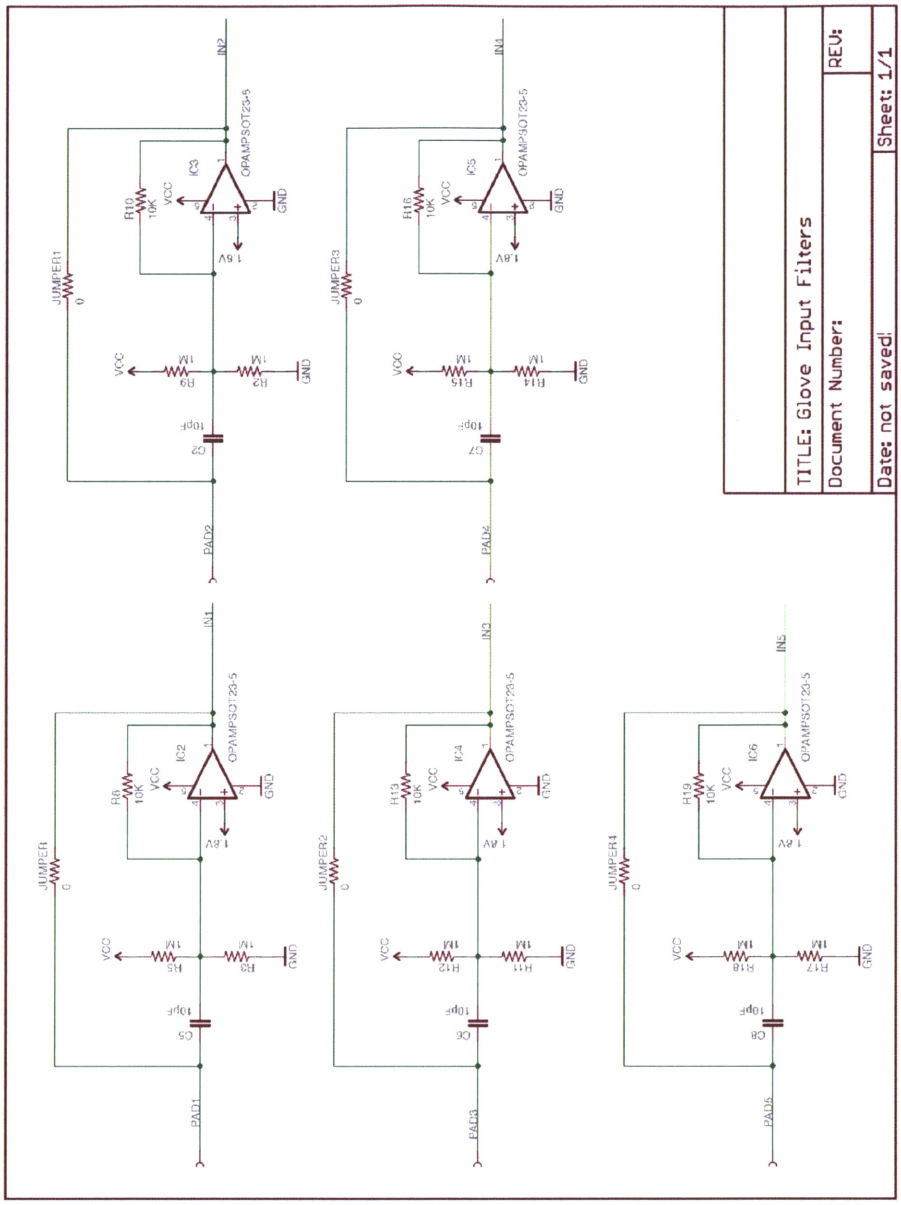


B

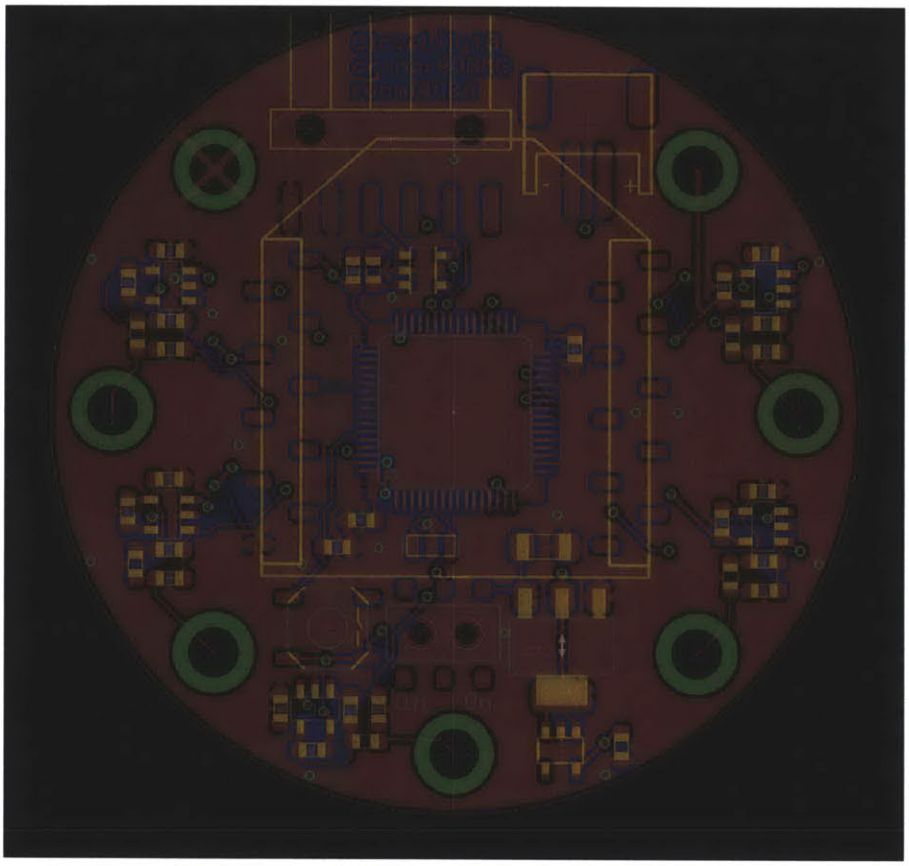
SHAKEONIT DESIGN FILES

B.1 SCHEMATIC




TITLE: Glove Input Filters
Document Number:
REV:
Date: not saved!
Sheet: 1/1
OPAMPSOT23-5
IC2
IC3
IC4
IC5
IC6
JUMPER
JUMPER1
JUMPER2
JUMPER3
JUMPER4
PAD1
PAD2
PAD3
PAD4
PAD5
IN1
IN2
IN3
IN4
IN5
VCC
GND
1.8V
10K
10pF
1M
0

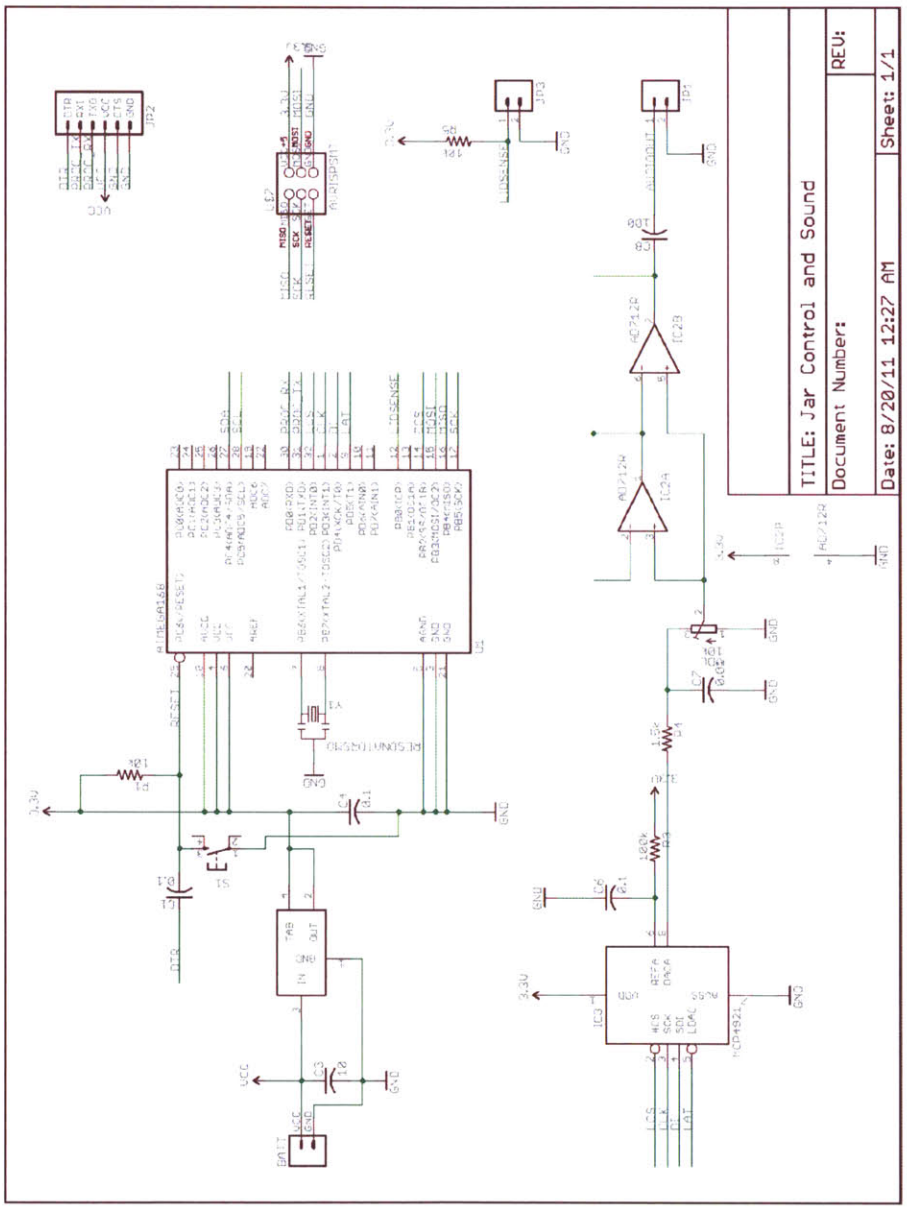
B.2 PCB ARTWORK

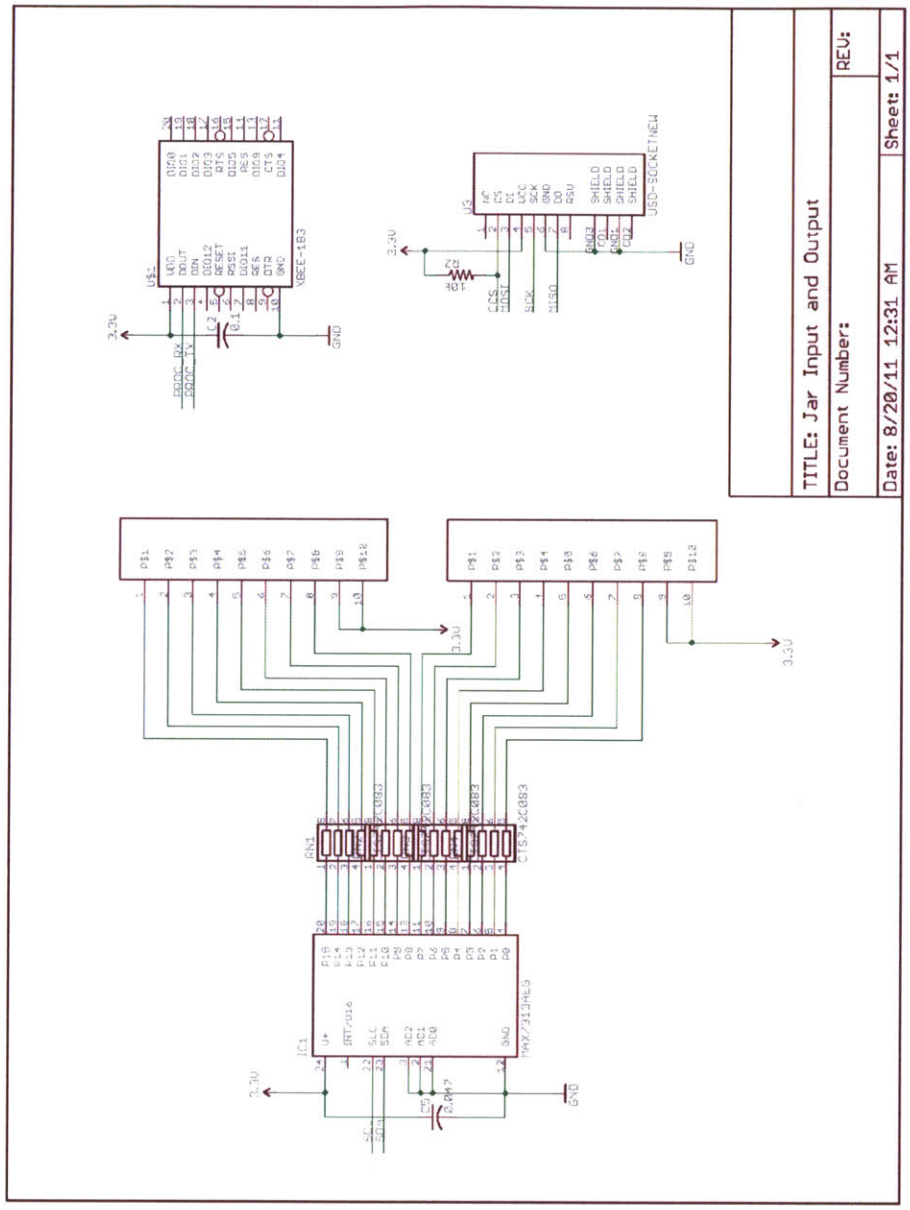


C

PILLOWTALK DESIGN FILES

C.1 SCHEMATIC

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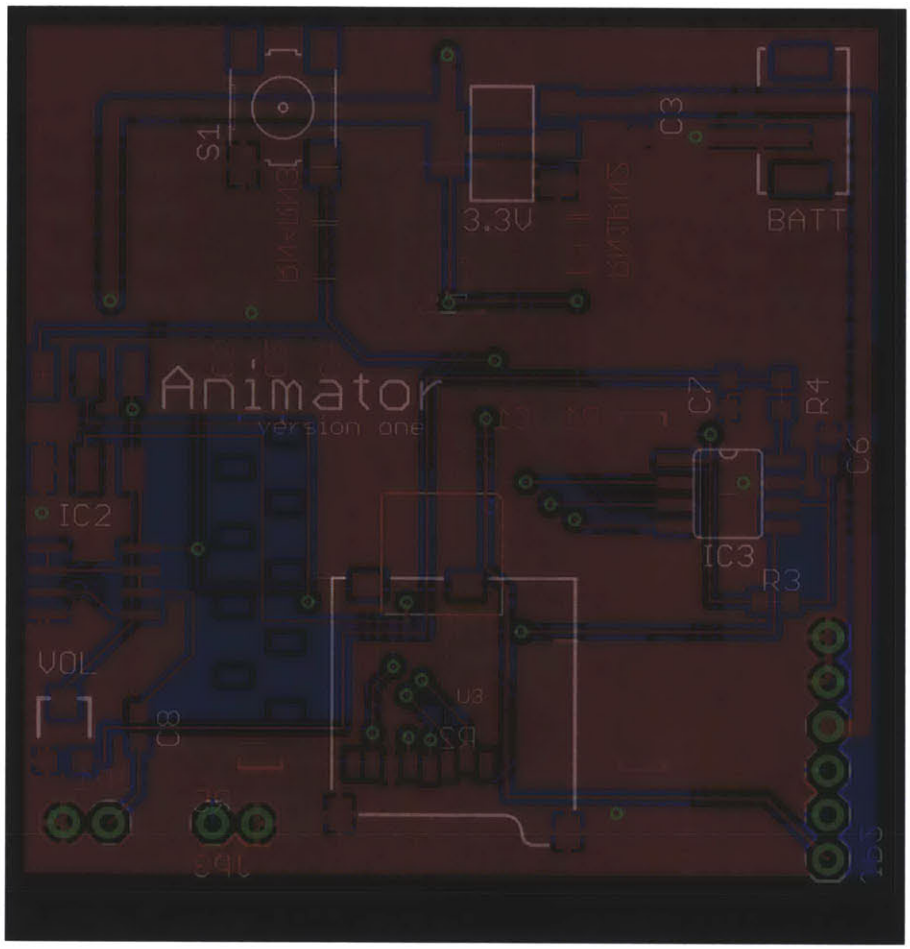
REV:
Date: 8/20/11 12:31 AM
Sheet: 1/1
XBEE-1B3
USD-SOCKETNEW
MAX7313AEG
CTS742C083
3.3V
GND

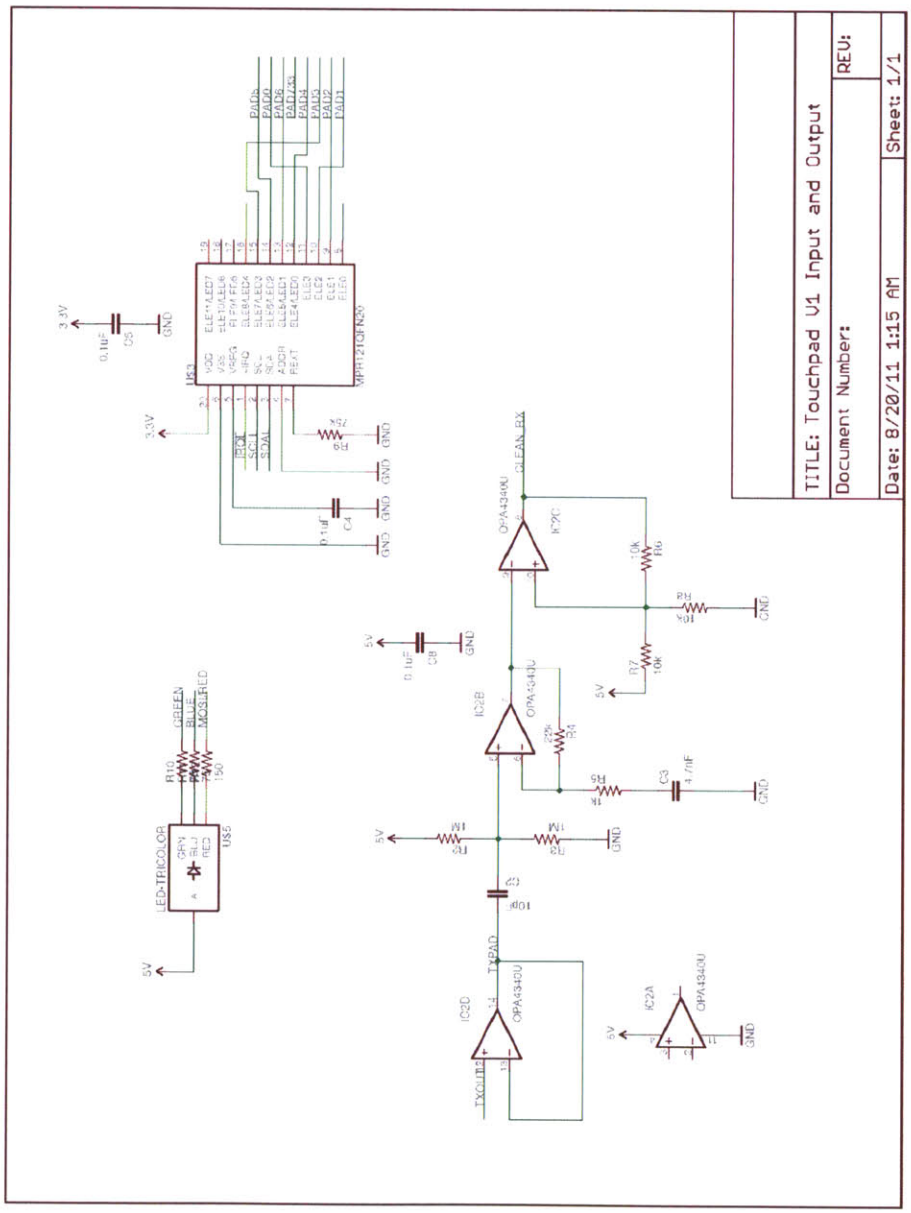
C.2 PCB ARTWORK

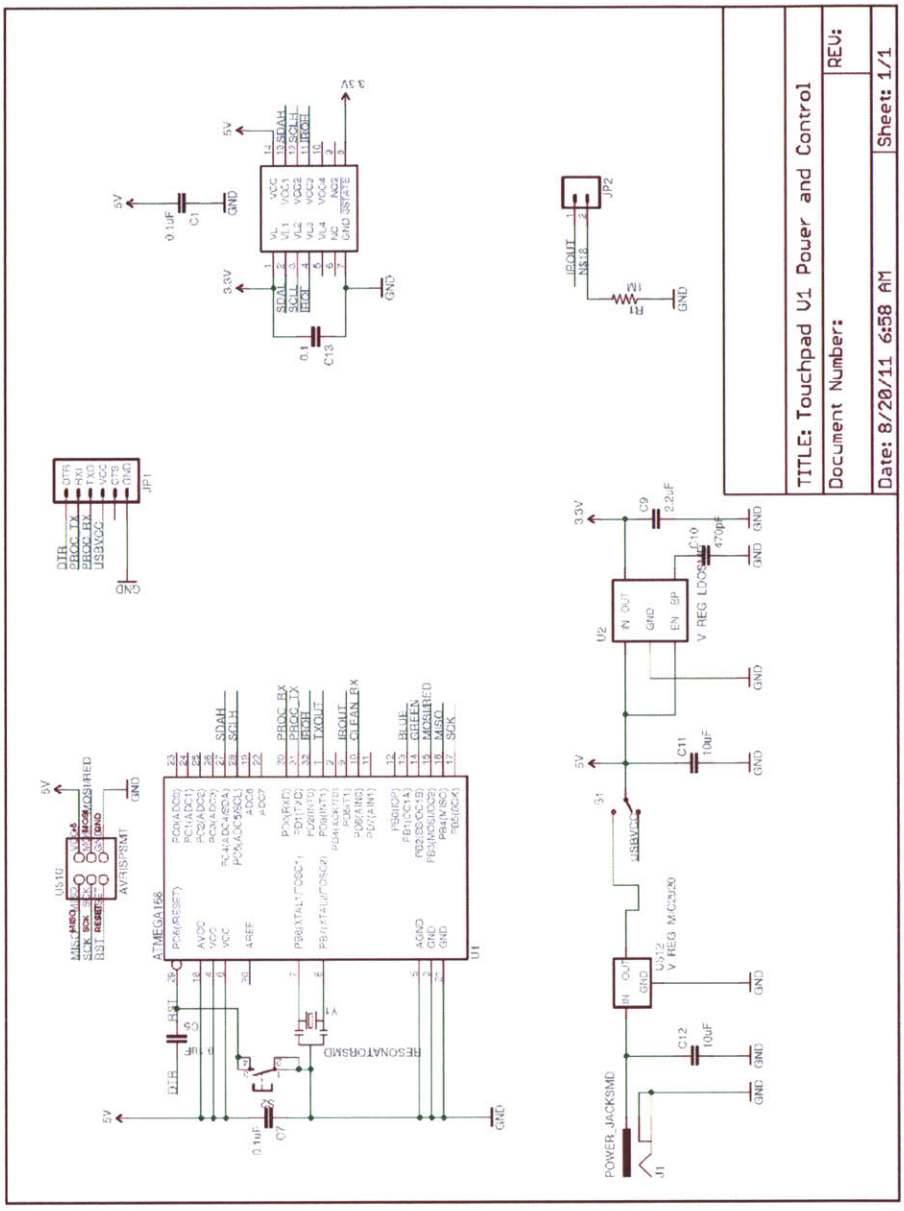


D

PROTOTOUCH V1 DESIGN FILES

D.1 TOUCHPAD V1 SCHEMATIC




TITLE: Touchpad V1 Power and Control
Document Number:
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Sheet: 1/1
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U1
U2
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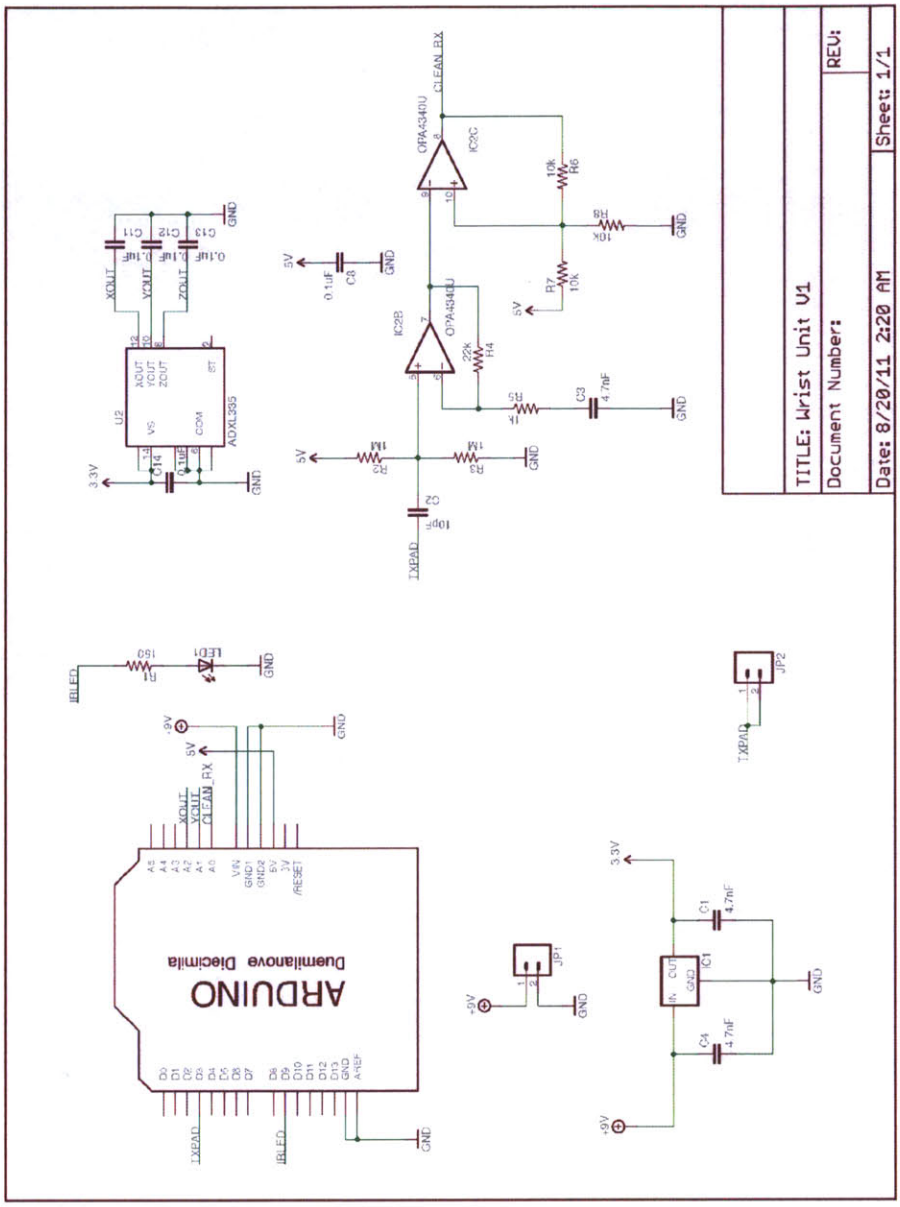
V REG MIC2520
POWER_JACKSMD
RESONATORSMD
AVRISPSMT
JP1
JP2
J1
S1
USBVCC
IROUT
NS18
R1
1M
C1
C7
C9
C10
C11
C12
C13
0.1uF
2.2uF
470pF
10uF
5V
3.3V
GND

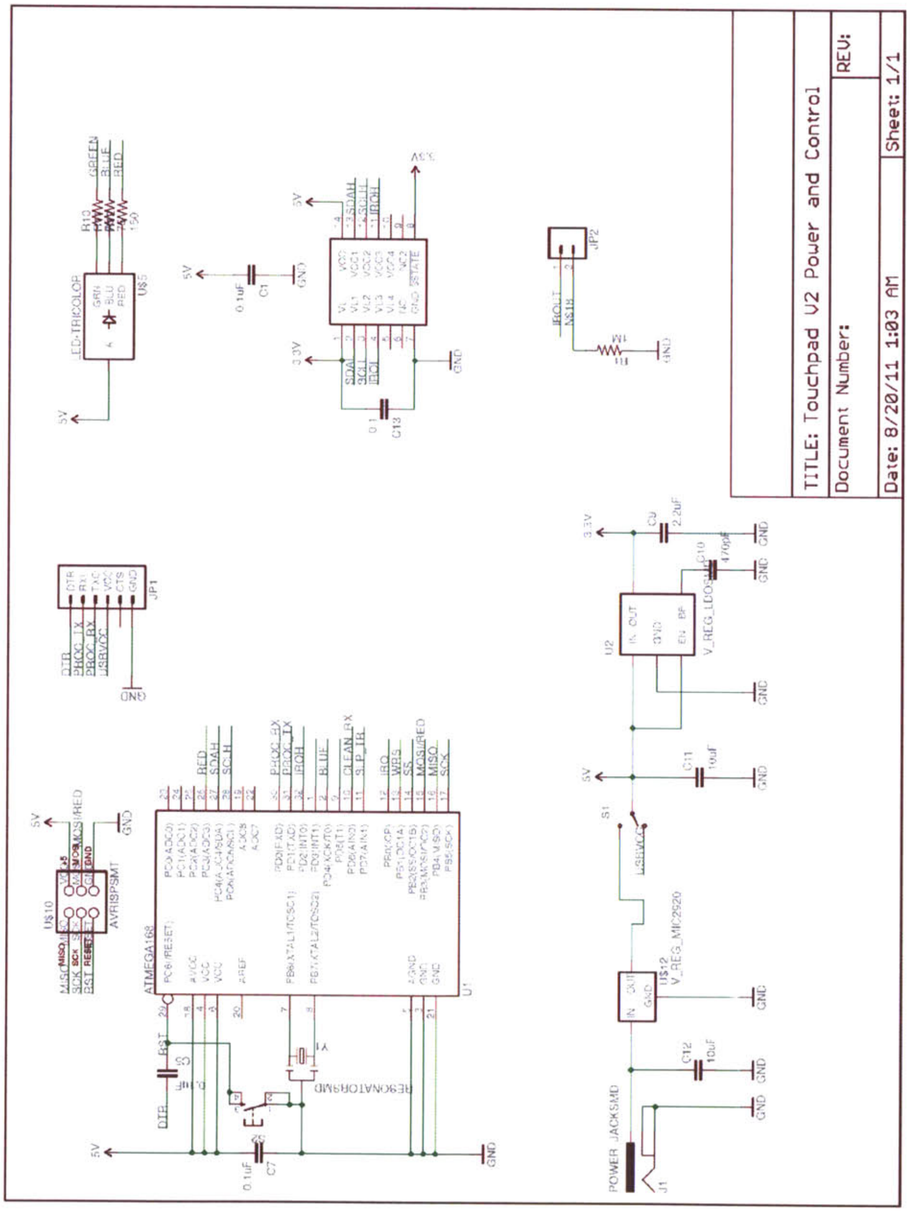
D.2 TOUCHPAD V1 PCB ARTWORK

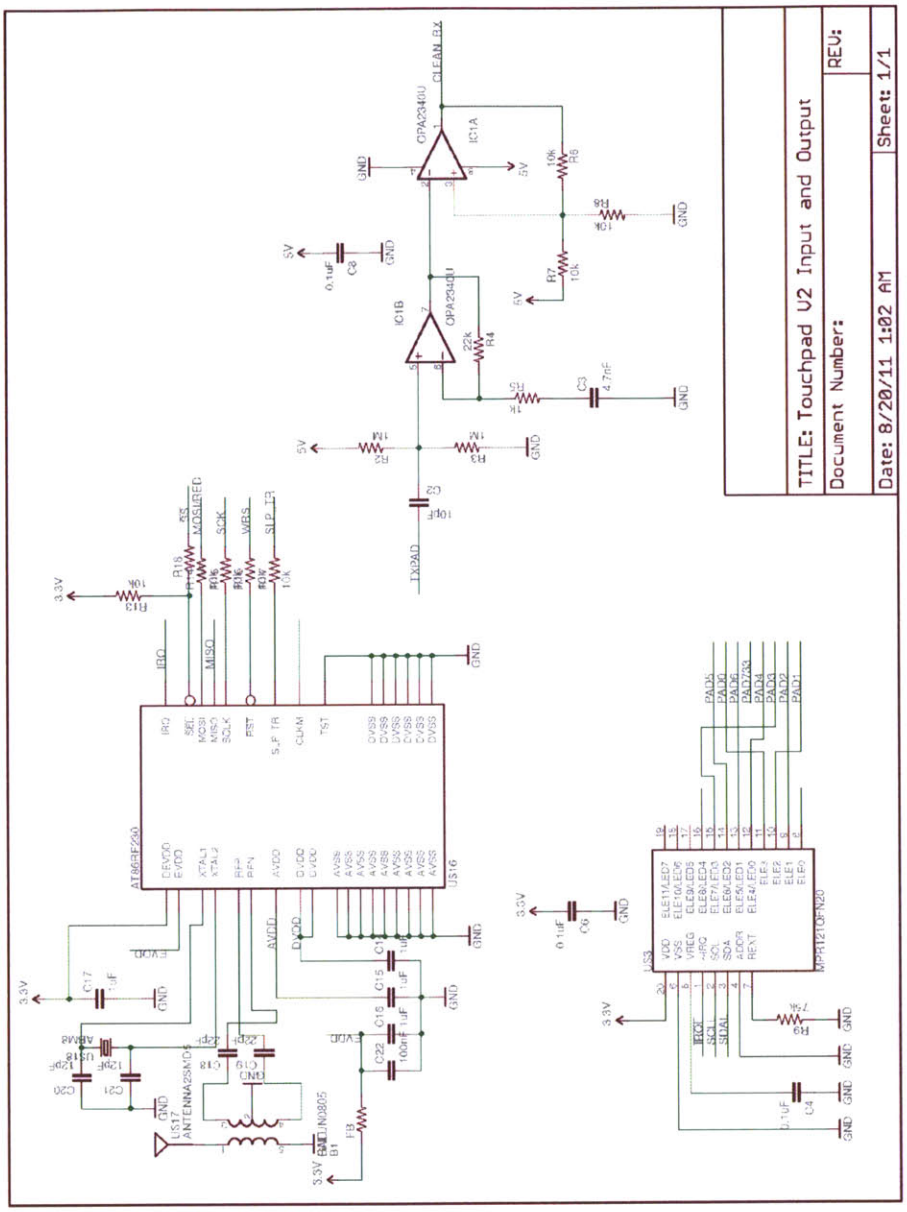
D.3 WRIST UNIT V1 SCHEMATIC



E PROTOTOUCH V2 DESIGN FILES

E.1 TOUCHPAD V2 SCHEMATIC

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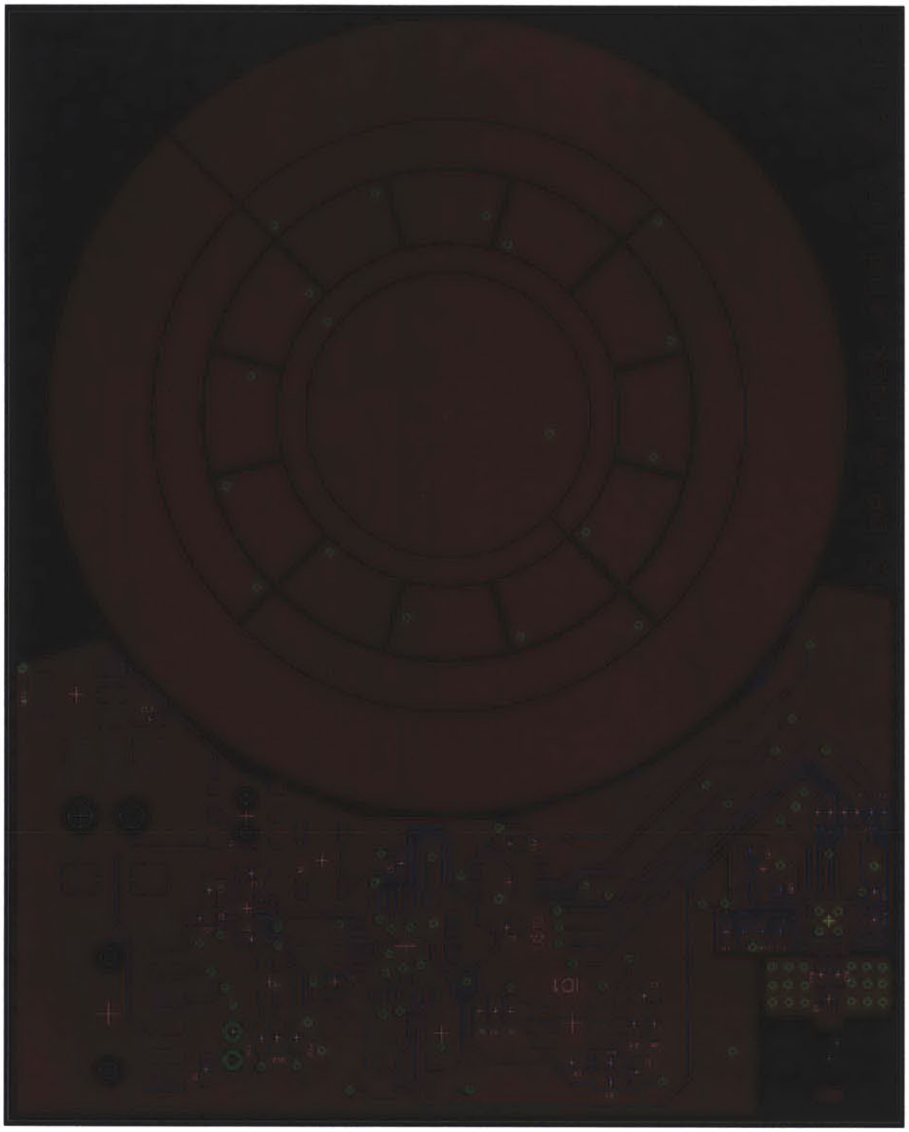
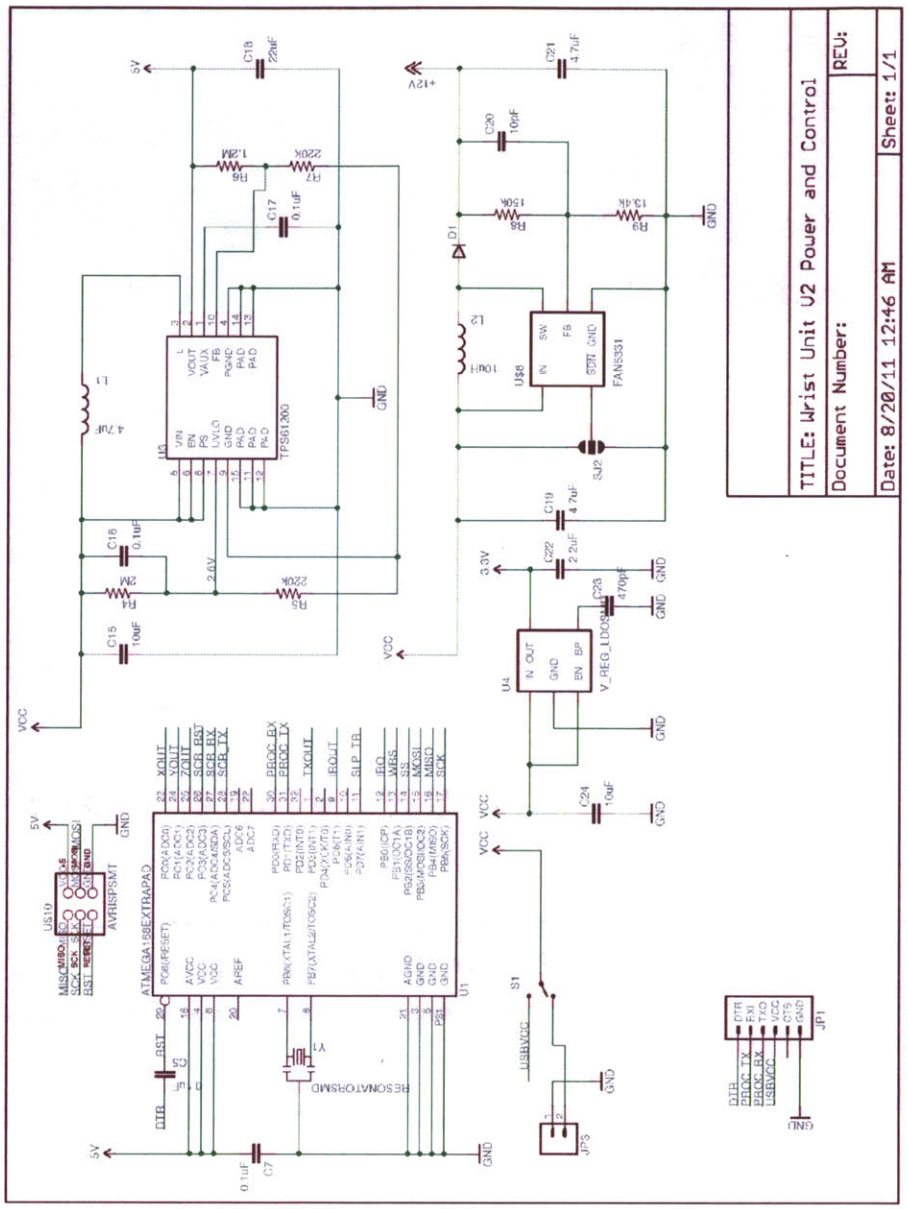
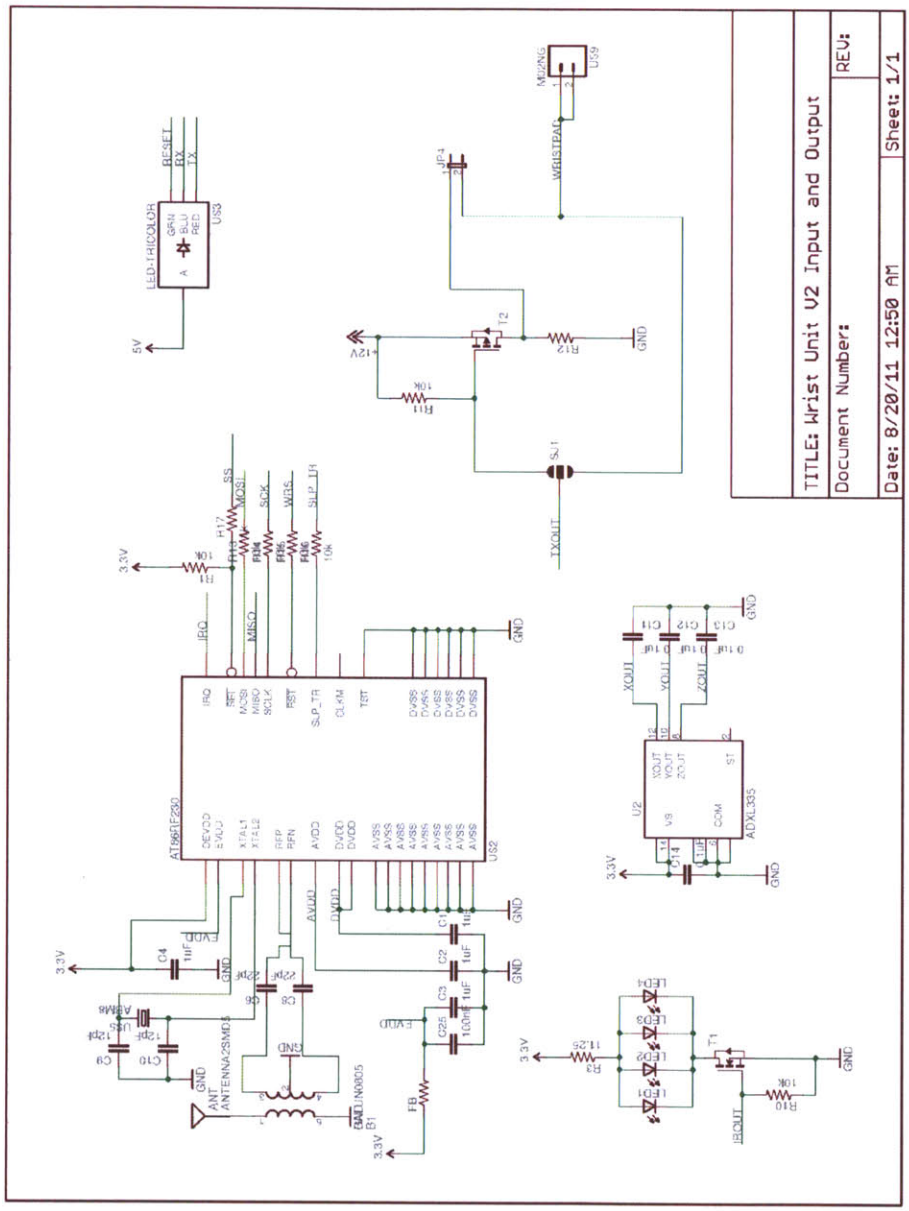
Document Number:
REV:
Date: 8/20/11 1:02 AM
Sheet: 1/1

E.2 TOUCHPAD V2 PCB ARTWORK



E.3 WRIST UNIT V2 SCHEMATIC

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Document Number:
REV:
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Sheet: 1/1

E.4 WRIST UNIT V2 PCB ARTWORK

BIBLIOGRAPHY

[1] J. Ardizzoni. A practical guide to high-speed printed-circuit-board layout, September 2005. URL http://www.analog.com/library/analogDialogue/archives/39-09/layout.html.

[2] Christina Bonnington. Analyst predicts ios and mac will fully converge by 2012. URL http://www.wired.com/gadgetlab/2011/08/ios-mac-merger/.

[3] S. Brewster and L.M. Brown. Tactons: structured tactile messages for non-visual information display. In *Proceedings of the fifth conference on Australasian user interface-Volume 28*, pages 15–23. Australian Computer Society, Inc., 2004.

[4] M. Bustillo. Retailers turn to gadgets, September 2010. URL http://online.wsj.com/article/SB10001424052748703376504575491533125103528.html.

[5] B. Buxton. Multi touch systems that I have known and loved, February 2009. URL http://www.billbuxton.com/multitouchOverview.html.

[6] S. Cambero. *El Chamanismo y las Raíces de la Terapéutica en la Medicina Tradicional de los Huicholes*. Universidad de Guadalajara, Guadalajara, 1990.

[7] J. Campbell and B. Moyers. *The Power Myth*. Doubleday, New York, July 1988.

[8] Celadon. Sample infrared code formats. Technical report.

[9] N. Cho, J. Yoo, S. J. Song, J. Lee, S. Jeon, and H. J. Yoo. The human body characteristics as a signal transmission medium for intrabody communication. *IEEE Transactions on Microwave Theory and Techniques*, 55(5):1080–1086, May 2007.

[10] E. C. Chubb, J. E. Colgate, and M. A. Peshkin. Shiverpad: A device capable of controlling shear force on a bare finger. In *EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 18–23, 2009.

[11] K. Chung, M. Shilman, C. Merrill, and H. Ishii. OnObject: gestural play with tagged everyday objects. pages 379–380, 2010.

[12] M. Coelho. Materials of interaction: responsive materials in the design of transformable interactive surfaces. Master's thesis, Massachusetts Institute of Technology, 2008.

[13] Atmel Corporation. *Design Considerations for the AT86RF230*, 2007.

[14] D. Cranor, A. Peyton, A. Persaud, R. Bahtia, S. Kim, and V. M. Bove Jr. Shakeonit: An exploration into leveraging social rituals for information access. In *Proceedings of TEI '11*. ACM, 2011.

[15] A. Del Valle and A. Opalach. The persuasive mirror: computerized persuasion for healthy living. *Accenture Technology Labs*, 2005.

[16] B. Dieterle and M. Engel, editors. *The Dream and the Enlightenment*. Honoré Champion, 2003.

[17] P. Dietz and D. Leigh. Diamondtouch: a multi-user touch technology. In *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology*, pages 219–226, 2001.

[18] K. Dobson. Omo. URL `http://web.media.mit.edu/~monster/`.

[19] A. Feldman, E.M. Tapia, S. Sadi, P. Maes, and C. Schmandt. ReachMedia: on-the-move interaction with everyday objects. In *Proceedings of the Ninth IEEE International Symposium on Wearable Computers*, pages 52–59, 2005.

[20] G. W. Fitzmaurice, H. Ishii, and W. Buxton. Bricks: laying the foundations for graspable user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 442–449, 1995.

[21] B. J. Fogg. Persuasive technology: using computers to change what we think and do. *Ubiquity*, December 2002.

[22] M. Gray. *Physical limits of intrabody signaling*. PhD thesis, Massachusetts Institute of Technology, 1997.

[23] P. S. Hall, M. Ricci, and T. W. Hee. Characterization of on-body communication channels. In *3rd International Conference on Microwave and Millimeter Wave Technology*, pages 770–772, 2003.

[24] J. Y. Han. Low-cost multi-touch sensing through frustrated total internal reflection. In *Proceedings of the 18th annual ACM Symposium on User Interface Software and Technology*, pages 115–118, 2005.

[25] B. Hartmann, S. Doorley, and S. R. Klemmer. Hacking, mashing, gluing: understanding opportunistic design. *IEEE Pervasive Computing*, 7:46–54, 2008.

[26] C. Heath and D. Heath. *Made to Stick: Why Some Ideas Survive and Others Die*. Random House, New York, 2007.

[27] K. Hinckley. Synchronous gestures for multiple persons and computers. In *Proceedings of the 16th Annual ACM Symposium on User Interface Software and Technology*, pages 149–158, 2003.

[28] L. Holmquist, J. Redström, and P. Ljungstrand. *Token-Based Access to Digital Information*. Springer, Berlin, 1999.

[29] E. L. Hutchins, J. D. Hollan, and D. A. Norman. Direct manipulation interfaces. *Human-Computer Interaction*, 1:311–338, December 1985.

[30] Texas Instruments. *TPS61200: Low Input Voltage Synchronous Boost Converter With 1.3-A Switches*, February 2008.

[31] H. Ishii and B. Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 234–241, 1997.

[32] Hiroshi Ishii, H. R. Fletcher, J. Lee, S. Choo, J. Berzowska, C. Wisneski, C. Cano, A. Hernandez, and C. Bulthaup. musicBottles. In *ACM SIGGRAPH '99 Conference Abstracts and Applications*, page 174, 1999.

[33] Robert J.K. Jacob, A. Girouard, L. M. Hirshfield, M. S. Horn, O. Shaer, E. T. Solovey, and J. Zigelbaum. Reality-based interaction: a framework for post-WIMP interfaces. In *Proceeding of the 26th Annual SIGCHI Conference on Human Factors in Computing Systems*, pages 201–210, 2008.

[34] R. G. Jahns, M. Pohl, and E. Mikalajunaite. Global smartphone application market report 2010. Technical report, research2guidance, 2010.

[35] A.K. Jain, A. Ross, and S. Prabhakar. An introduction to biometric recognition. *IEEE Transactions on Circuits and Systems for Video Technology*, 14(1):4–20, January 2004.

[36] H. Johnson. *High-Speed Digital Circuit Design*. Prentice Hall, New York, 1993.

[37] W. H. Hayt Jr., J. E. Kemmerly, and S. M. Durbin. *Engineering Circuit Analysis*. McGraw-Hill, New York, 2002.

[38] C. G. Jung and R. F. C. Hull. *Two Essays on Analytical Psychology: The Meaning of Psychology for Modern Man*. Princeton University Press, Princeton, 1979.

[39] M. Kanis, N. Winters, S. Agamanolis, A. Gavin, and C. Cullinan. Toward wearable social networking with iBand. In *CHI '05 Extended Abstracts on Human Factors In Computing Systems*, pages 1521–1524, 2005.

[40] P. Kry and D. Pai. Grasp recognition and manipulation with the tango. In *Experimental Robotics*, volume 39 of *Springer Tracts in Advanced Robotics*, pages 551–559. Springer, Berlin, 2008.

[41] Mike Kuniavsky. *Smart Things: Ubiquitous Computing User Experience Design*. Elsevier, Boston, 2010.

[42] MIT Media Lab. Media lab 25th anniversary - soul(s) of the media lab, session 2, November 2010. URL `http://www.media.mit.edu/events/movies/video.php?id=ml25-2010-10-15-6`.

[43] A. Leung and O. Oswald. The dreaming pillow (l'oreiller rêveur). In *ACM SIGGRAPH 2008 Art Gallery*, 2008.

[44] C. Liolios, C. Doukas, G. Fourlas, and I. Maglogiannis. An overview of body sensor networks in enabling pervasive healthcare and assistive environments. In *Proceedings of the 3rd International Conference on Pervasive Technologies Related to Assistive Environments*, pages 1–10, 2010.

[45] T. Lundmark. *Tales of Hi and Bye: Greeting and Parting Rituals Around the World*. Cambridge University Press, Cambridge, 2009.

[46] K. E. MacLean and J. B. Roderick. Smart tangible displays in the everyday world: a haptic door knob. In *Advanced Intelligent Mechatronics, 1999. Proceedings. 1999 IEEE/ASME International Conference on*, pages 203–208. IEEE, 2002. ISBN 0780350383.

[47] N. Matsushita, S. Tajima, Y. Ayatsuka, and J. , Rekimoto. Wearable key: Device for personalizing nearby environment. In *Fourth International Symposium on Wearable Computers*, pages 119–126, 2002.

[48] D. Merrill and P. Maes. Invisible media: Attentionsensitive informational augmentation for physical objects. *Proceedings of the Seventh International Conference on Ubiquitous Computing*, 2005.

[49] ST Microelectronics. *RC acquisition principle for touch sensing applications*, March 2009.

[50] P. Mistry, S. Nanayakkara, and P. Maes. Sparsh: passing data using the body as a medium. In *Proceedings of the ACM 2011 Conference on Computer Supported Cooperative Work*, pages 689–692, 2011.

[51] J. Montgomery. Pillow talk, October 2010. URL `http://www.joannamontgomery.com/#138095/Pillow-Talk`.

[52] M. Morris, A. Huang, A. Paepcke, and T. Winograd. Cooperative gestures: multi-user gestural interactions for co-located groupware. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1201–1210, 2006.

[53] F. Nack, T. Schiphorst, Z. Obrenovic, M. Kauwatjoe, S. de Bakker, A. P. Rosillio, and L. Aroyo. Pillows as adaptive interfaces in ambient environments. In *Proceedings of the International Workshop on Human-Centered Multimedia*, pages 3–12, 2007.

[54] T. Nara, M. Takasaki, T. Maeda, T. Higuchi, S. Ando, and S. Tachi. Surface acoustic wave tactile display. *IEEE Computer Graphics and Applications*, pages 56–63, 2001. ISSN 0272-1716.

[55] C. Nelson. *LT1070 Design Manual*, June 1986.

[56] D. A. Norman. *The Design of Everyday Things*. Basic Books, 1988.

[57] D.A. Norman. *The Invisible Computer: Why Good Products can Fail, the Personal Computer is So Complex, and Information Appliances Are the Solution*. MIT Press, Cambridge, 1999.

[58] François Pachet. The future of content is in ourselves. *Computer Entertainment*, 6:31:1–31:20, November 2008.

[59] D. G. Park, J. K. Kim, J. B. Sung, J. H. Hwang, C. H. Hyung, and S. W. Kang. TAP: touch-and-play. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 677–680, 2006.

[60] S. N. Patel, J. S. Pierce, and G. D. Abowd. A gesture-based authentication scheme for untrusted public terminals. In *Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology*, pages 157–160, 2004.

[61] E. Portocarrero, D. Cranor, and V. M. Bove Jr. Pillow-jar: seamless interface for dream priming, recalling and playback. In *Proceedings of TEI '11*. ACM, 2011.

[62] E. R. Post, M. Reynolds, M. Gray, J. Paradiso, and N. Gershenfeld. Intrabody buses for data and power. In *Digest of Papers of the First International Symposium on Wearable Computers*, pages 52–55, 2002.

[63] V. Ramaswamy. Step-up switch mode power supply: ideal boost converter. URL `http://services.eng.uts.edu.au/~venkat/pe_html/ch07s3/ch07s3p1.htm`.

[64] J. Rekimoto. Pick-and-drop: a direct manipulation technique for multiple computer environments. In *Proceedings of the 10th Annual ACM Symposium on User Interface Software and Technology*, pages 31–39, 1997.

[65] J. Rekimoto. Gesturewrist and gesturepad: unobtrusive wearable interaction devices. In *Proceedings of the Fifth International Symposium on Wearable Computers*, pages 21–27, 2002.

[66] M. Satyanarayanan. Pervasive computing: vision and challenges. *Personal Communications of the IEEE*, 8(4):10–17, August 2001.

[67] T. C. W. Schenk, N. S. Mazloum, L. Tan, and P. Rutten. Experimental characterization of the body-coupled communications channel. In *IEEE International Symposium on Wireless Communication Systems*, pages 234–239, 2008.

[68] Fairchild Semiconductor. *FAN5331: High Efficiency Serial LED Driver and OLED Supply with 20V Integrated Switch*, August 2005.

[69] Freescale Semiconductor. *Pad Layout Application Note*, September 2009.

[70] B. T. Taylor and V. M. Bove Jr. Graspables: grasp-recognition as a user interface. In *Proceedings of the 27th International Conference on Human Factors in Computing Systems*, pages 917–926, 2009.

[71] Smart Technologies. Smart board interactive whiteboards. URL `http://smarttech.com/us/Solutions/Education+Solutions/Products+for+education/Interactive+whiteboards+and+displays/SMART+Board+interactive+whiteboards`.

[72] B. Vigoda and N. Gershenfeld. TouchTags: using touch to retrieve information stored in a physical object. In *CHI'99 Extended Abstracts on Human Factors In Computing Systems*, pages 264–265, 1999.

[73] M. Weiser. The computer for the 21st century. *Scientific American*, 272(3):78–89, 1995.

[74] Wikipedia. Boost converter. URL `http://en.wikipedia.org/wiki/Boost_converter`.

[75] J. O. Wobbrock, A. D. Wilson, and Y. Li. Gestures without libraries, toolkits or training: a $1 recognizer for user interface prototypes. In *Proceedings of the 20th Annual ACM Symposium on User Interface Software and Technology*, pages 159–168, 2007.

[76] S. S. Yau and F. Karim. An adaptive middleware for context-sensitive communications for real-time applications in ubiquitous computing environments. *Real-Time Systems*, 26:29–61, 2004.

[77] T. Zimmerman. *Personal area networks (PAN): Near-field intra-body communication*. PhD thesis, Massachusetts Institute of Technology, 1995.