# HCI Gesture Tracking Using Wearable Passive Tags



by

Rachel M. Bainbridge

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Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degree of

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## Abstract

In this thesis, a wearable system is developed to track hand gestures with passive RFID sensor tags. This system was composed of an ultra-high frequency reader and small, passive, finger-worn tags powered by scavenged RFID energy equipped with a variety of sensors that could be used to detect gestures. The primary physical goals of the system were to be comfortable and wearable without interfering with other everyday activities. The computational goals of the system were to track particular hand movements, which could be used to control a wearable computer or aid in interaction with ubiquitous and other wearable devices. As a user is walking through their environments, we aim to avoid the need for pulling out an interface with keyboard, keypad, or touch screen, and also avoid bulky hand-held interfaces, allowing the user to specify input with their fingers without taking their eyes and attention off their immediate focus. This thesis first introduces our hardware, then gives some example user interface implementations, such as a mouse controlled by hand position and a click controlled by finger proximity, entering input by touching fingers, setting options when moving the hand to a particular spot of the users apparel labeled with a passive RFID tag, and otherwise mapping control onto motion of the hand, arm, and fingers. We evaluate the effectiveness of our interface via a series of user studies. The overall system was somewhat successful, but as this is an early implementation, it was still very much limited by transmit power and antenna efficiency, due to the constraints on the size of the passive tags.


Thesis Supervisor: Joseph A. Paradiso
Title: Associate Professor

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# Chapter 1

# Introduction

With the explosion of mobile (and soon wearable) computing, it will become inconvenient and impractical to employ standard human computer interfaces (HCI's). As people are walking through environments and working on tasks, holding or manipulating a familiar HCI will become increasingly impractical. Especially when interacting with a wearable display, it's going to be important to keep a user's hands and fingers as free from encumbrance as possible, yet the main user interaction will still for the foreseeable future be from finger manipulation, as our HCI bandwidth is highest there due to finger dexterity.

Accordingly, being able to track the movements of fingers and hands would be important in manipulating such distributed devices. The goal of this project is to track finger movement and contact using a small wearable and portable system of an RFID reader and tiny finger-mounted tags. We built a working prototype of this system, and present an evaluation of its utility through a series of user studies.

## 1.1 Motivation

There already exist many methods of hand gesture tracking, as summarized below. They tend to all involve constraints that make their use in a commonplace wearable system impractical.

A low power, wearable RFID tracking system would eliminate many of these problems. The ring-mounted tags could be tracked from a receiver worn at the user's wrist, eliminating the need for a camera and corresponding occlusion problems (as the human body is transparent to lower frequency RFID), and allowing the system to operate almost anywhere without requiring a line of sight. If the rings are sufficiently small, they don't significantly encumber the fingers.

## 1.2 Project Goals

The goal of this project is to create a portable system using RFID tags that would be able to track the motion of the hand and fingers and interpret it in order to manipulate something such as a system of mobile devices, a ubiquitous computing environment [24], or a wearable computer.

The user of the system will wear a small wireless tag on several or all of their fingers. The tag will need to be detected through all ranges of finger motion. Depending on whether the system is active or passive, there will either have to be a way for the system to store position information (for active tags), or there will have to be an appropriate antenna system to sufficiently couple to the reader under full finger motion (for a passive system). Note that the conventional nomenclature assumes that active tags have a battery while passive tags are externally powered. The reader must be small enough to be comfortably worn on the wrist (or better yet at the shirtsleeve), yet be fast and powerful enough to keep track of the movement and interactions of many tags in something close to real time (e.g., ideally over 30 Hz, and certainly over 10 Hz). The last element of the system will be a magnetic sensor that detects when one finger comes into proximity of another with a small magnet ring. For example, we can detect and identify finger-to-thumb gestures this way, which could be very powerful ways to express input in such a scenario.

The sensor data from the finger rings will be sent to a computer (either a wearable device, or in this case an actual PC), where the signals are further processed to extract relevant gestures.

The ultimate objective would be able to produce information from the system that could be used to enter text, select and delete items, navigate through a wearable display, and do other operations of use in mobile, wearable, and ubiquitous computing.

## 1.3 Existing Work

### 1.3.1 Finger Gesture Sensing

Several recent projects (e.g., the Meida Labs 6th Sense project [19]) involve the use machine vision to track the location of the fingers. These methods are limited by the line of sight of the camera, hence have limitations on the sensitive region. The hands need to be in front of the camera, which generally means that gesture needs to happen in the area in front of the user. This isnt always practical, e.g., when standing in a crowded train, when walking, etc. Although one could think of a sleeve-mounted camera, it would have difficulties with the fingers occluding one another. As these systems use computer vision, they can also be fragile with varying lighting conditions as well as requiring the user to nonetheless wear targets on the fingers (colored bands in the case of Sixth Sense).

Other previous projects have strove to track hand movement and gestures with other means to create novel and natural ways for users to interact with wearable technology.

Perhaps the best known products in this space are wearable and chordic keyboards such as the Twiddler (http://www.handykey.com/) and various types of datagloves [3]. Although users have achieved a high degree of fluency with the Twiddler [7], it is a relatively large object that needs to be attached to the palm with a strap, hence limits the use of the hand. Datagloves of various sorts have been used for over two decades, especially in virtual reality applications. some gloves (e.g. the Lady's Glove [20]) use a magnet on the thumb and hall sensors on the fingers to sense finger-to-thumb gesture, as we exploit in this project. As these cover the entire hand, they are difficult to wear for extended periods and in all circumstances, and although they provide ample data on finger position, they significantly encumber the fingers.

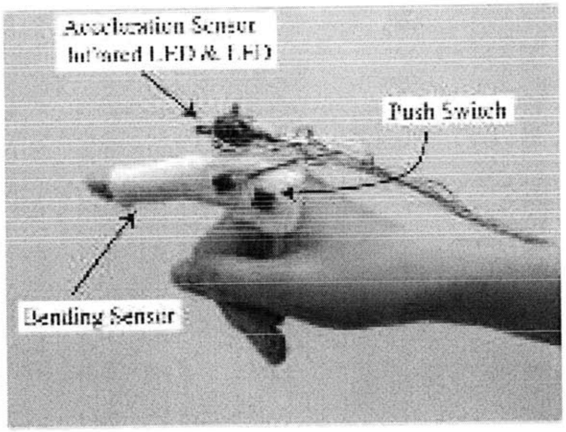


Figure 1-1: Ubi-finger prototype

In a project at the Keio University, sensors were combined to create a device that could be worn on the finger and used to control multiple electronic devices in the room with gesture, the same way a remote control might with buttons. The wearable finger device, show in Figure 1-1, included an accelerometer, a bend sensor and a push button, as well as an infrared LED to allow the device to communicate to a server that could then communicate to the appliances [13]. Our project will include some kind of motion and touch sensing, but will hopefully track multiple fingers and only cover one small section of the finger, getting as close to a ring form factor as possible.

Products have been marketed for a decade or so now that use ultrasound to track a small ring on the finger, generally mapped as a mouse controller. One recent example is the "MagicMouse" from WPI [25]. Although this product has been reinvented several times, it's never caught on because of problems related to accuracy, occlusion, lack of a clear market advantage in its targeted niche (replacement of the standard mouse), and need of wearing a fairly bulky active sonar transmitter on the finger.

Another pioneering project in this area was implemented by Masaaki Fukimoto at NTT Human Interface Laboratories [15]. Their prototype is shown in Figure 1-2. Fingertip typing is sensed by accelerometers and then transmitted capacitively using the body as part of the circuit, as in the Media Labs PAN project [26]. Although this project was groundbreaking in many ways, the fingering required batteries and

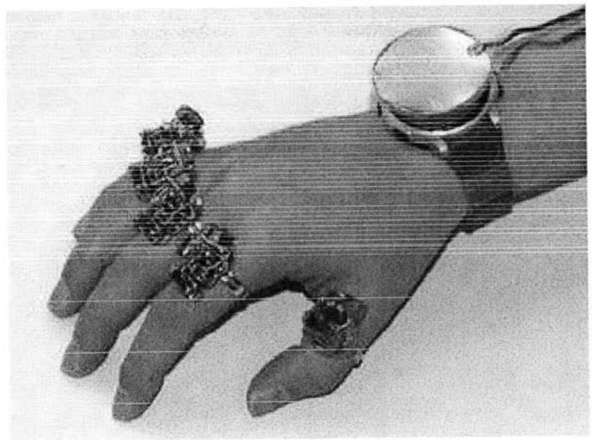

Figure 1-2: The FingeRing Prototype

the electric field communication reliability was questionable.

Several other projects have also used finger tapping for useful gesture interactions. Skinput, a project created by a graduate student at Carnegie Mellon University and Microsoft Research, has interpreted vibrations picked up on the arm to sense when different parts of the hand or arm are being touched [23]. Although this is a fascinating approach, it's still unclear how robust this system is in actual use, how difficult it is to set up, and how it varies across users.

Accordingly, we see an opportunity for a new class of wearable user interface, based around recent advances in RFID sensing, which potentially allows the passive sensors to become quite small, perhaps approaching the size of rings that could be placed inconspicuously around the upper finger joints.

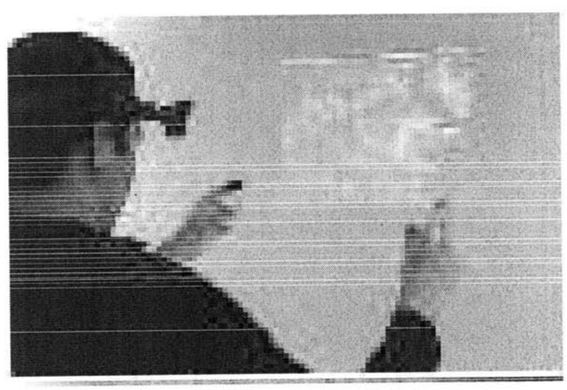

Figure 1-3: The Sixth Sense system be used with mobile projector

Another Media Lab project that is utilizing gesture to amplify interaction with the world through technology is the Sixth Sense project. Sixth Sense (Fig. 1-3) uses a computer and projector, worn either on a hat or around the neck in a "pendant" to record the user's gestures and project different interfaces for the user to interact with. Since it uses machine vision however, the user must also wear marker tabs on the finger tips. Some of the gestures the system recognizes include the "frame" gesture which allows users to capture pictures by framing their fingers around the scene they want to photograph. The user can also draw in the air to open various applications in the user interface. For instance a star will launch the weather application and an "@" will allow the user to check his or her email. [19] While some of these advanced features are out of the scope of our original project, some of the basics can be included, and more of the advanced ideas might be useful if added in later versions.

It has been shown that devices that that take free gesture beyond that of the standard keyboard and mouse/trackpad as input are both feasible and useful. Many other projects have used free gesture for interesting and natural interaction with a variety of devices, such as [5].

### 1.3.2 Object Detection With RF

Many media lab groups have already made many projects using passive RFID tags to track the location and state of objects and used them in different applications.

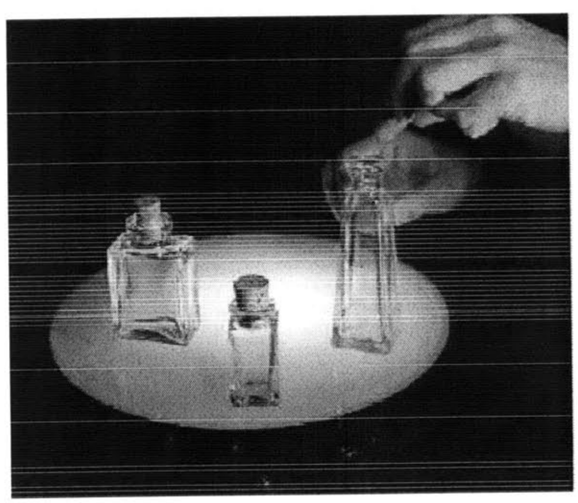

Figure 1-4: The Tangible Media Group's musical bottles

One of the best known of such projects was the musical bottles created by Hiroshi Ishii of the Tangible Media group [18]. This project consisted of three bottles on a transparent table. When the corks of the bottles were removed, different parts of a music track start to play, with each bottle corresponding to a different instrument. Whether or not a bottle is open is tracked using RFID. The cork actually contains a ferrite core that detunes the inductively-coupled resonant RFID coil located around the mouth of the bottle (an innovation proposed by Media Lab affiliate, Rich Fletcher). When the core is removed, the system can then detect this change at each individual bottle, and play the appropriate music.

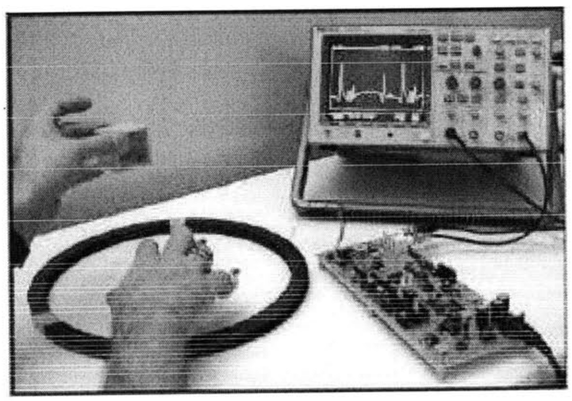

Figure 1-5: A photo of the early RF tracking projects using passive tags

An earlier project was first put together by Joseph Paradiso and Kai-Yuh Hsiao of the Responsive Environments group, in which a variety of objects were tracked via chipless resonant tags in order to control music [11]. The technology developed by Paradiso and Hsiao was also used to implement Ishii's music bottles described above. The tags used were in a low frequency range (50-300kHz). Each tag was inserted into an object, and could be sensed when it was over the reader coil, which was quite large (9.5"x11.5"). Each tag had a different resonant frequency, and the reader would sweep through the range they were in and determine if a tag was present if it drew power from the magnetic field. The interpretation of the location and state of these objects (some were also sensitive to orientation and mechanical force) could then be applied to make different kinds of music. Close to the theme of this thesis, Paradiso and Hsaio implemented tags also on rings (Fig. 1-6), producing a wireless musical keyboard, where the fingers that were being bent could be identified and their velocity inferred as they came into alignment with the magnetic field emanating from the reader.

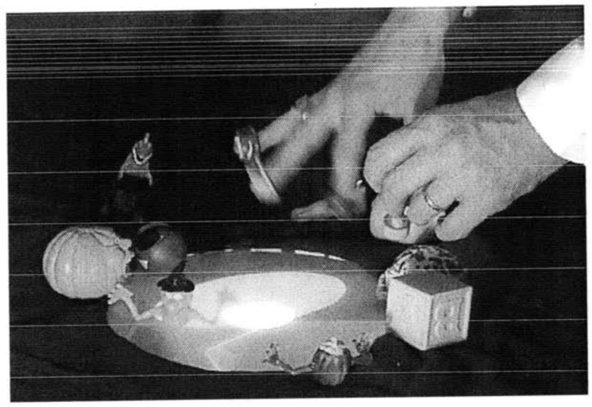

Figure 1-6: RF rings being used with musical interface

This project was later expanded by graduate student Laurel Smith, who improved the reader system and widened its musical applications [21]. A larger, lower frequency system was also created for this project, which similarly used tagged objects to manipulate music in a more complex fashion than the previous project had allowed. An orthogonal cage of reader coils was also used to determine finger position and orientation [12] (Fig. 1-7).

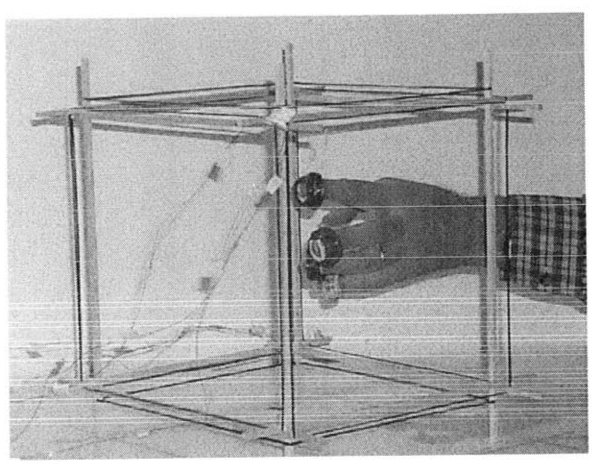

Figure 1-7: Paradiso and Hsaio's RF musical keyboard

Related research with active tagging has been performed various institutions, mostly for using wearble RFID to identify objects that users are holding [22] [2] [16].

In one project [22], wall mounted RFID readers were used to track the actions of a person cooking and their interaction with various objects. A hand-mounted RFID antenna was intended to also track the objects being picked up and used. The combination of data from the wall readers and the hand were used to determine what the person was actually doing. This research may be interesting and helpful in developing software for interpreting the tag data in our gesture tracking system.

In another project [2], a person controlled a computer by handling tagged objects while wearing an RFID reader. The tags operated at 125kHz (the low frequency range) and had a read distance of only three inches. The reader antenna coil was placed in a piece of clothing, such as a work glove, where it could read if a tagged object was being handled. Although these projects pointed to useful implementations, they generally exhibited slow update rates, and weren't aimed at identifying paticular gesture rather just identifying objects that users held and touched.

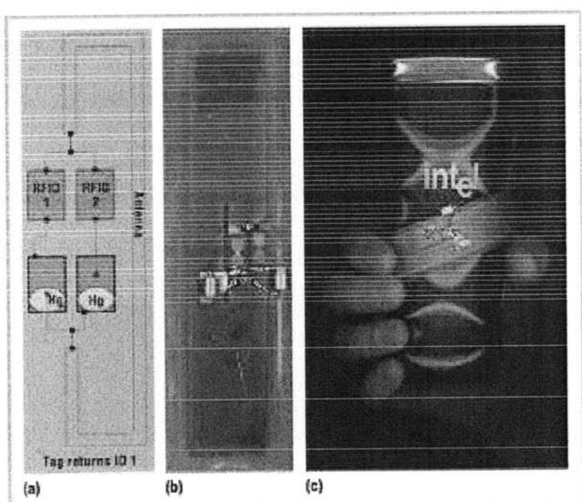


Figure 1-8: The first WISP prototype

In another project [4], called the WISP, an Intel research team experimented with putting 1-bit battery-less accelerometers on RFID tags to wirelessly detect the rough orientation of the attached object (Fig. 1-8).

This could be very useful in our application for detecting the position of the finger, but may have a negative effect on size, as multiple tags are required. In fact, a more advanced version of the WISP has more recently incorporated a 3-axis 10-bit accelerometer, together with an ultralowpower microprocessor into a passive tag [4].

Our finger tracker will use this WISP ystem, but instead of tracking the placement of objects, it will track the movement of fingers around the tracker. Although most of these earlier projects have required large homemade readers in order to achieve sufficient read range, to make the system portable, a smaller, but more powerful reader will have to be found. With the current advances in the field from the time of the original WISP publications, solutions are becoming available from industry, as described below and implemented in our studies.

# Chapter 2

# Hardware

## 2.1 Off-the-Shelf Hardware

### 2.1.1 Initial Attempts

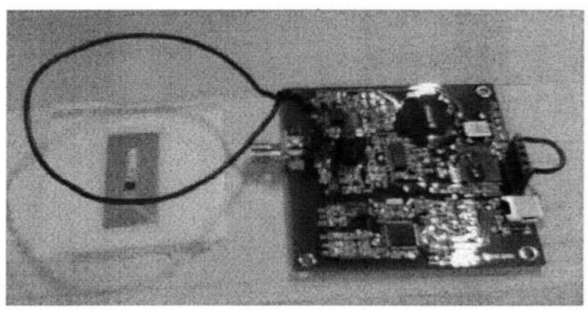

Figure 2-1: The initial TagSense reader and tag

In the beginning stages of the project, passive magnetically-coupled RFID transponders were explored, because passive transponders are extremely simple, and can to some extent indicate their distance from the reader by their signal strength. Similar systems of this type had been implemented before with success in previous work of the Responsive Environments group at the MIT Media Lab, as described in the last section (although those tags were chipless). The reader that we used was the Tag Sense LC-10 Chipless Reader (http://www.tagsense.com/), sweeping from 1 to 50 MHz. With it, various passive RFID tags could be used. Figure 2-1 shows the size of the reader and one of the possible tags that could be used with it. This system was infeasible, however, for a number of reasons.

- The signal strength of tag can also be tied to its orientation, as shown in figure 2-6
- The tags and reader were too large
- The reader was not fast enough
- The range of the reader was too limited
- It was difficult to interface between the computer and reader

While searching through possible solutions, it was found that the UHF band (860MHz to 960MHz)would allow for a reduction in tag size and also in reader size, while still penetrating the human body to a reasonable extent, avoiding major occlusion problems. Also it was found that microprocessor-equipped tags, the WISP project in particular, might also provide a viable solution to our desire to track the position of a finger - especially since the WISP already incorporated an accelerometer on the tag and required no power source except for the reader itself.

### 2.1.2 RFID reader

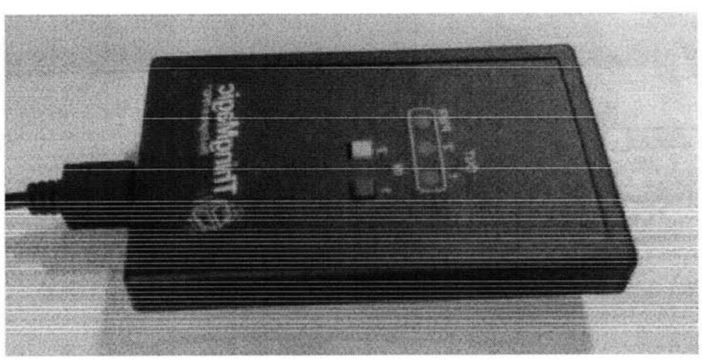

Figure 2-2: The M5e USB reader from ThingMagic

The reader used in the subject system was the compact Mercury 5e USB reader (Figure 2-2). This reader suits our purposes well, because it is in the UHF band, which means it can be used with small tags due to the smaller wavelength. The special tag we later decided to use with the system also functioned in the UHF band. It also interfaces easily with the computer through the USB port and comes with a ready-made API allowing for quick and painless development of user interfaces in many programming languages.

Later, a higher power version of this reader was used, the M5e, that allowed for considerably longer range and faster read rate. A new antenna, a monopole whip, was also used in the final system, also upping the range and read rate.

### 2.1.3 Wireless Identification and Sensing Platform

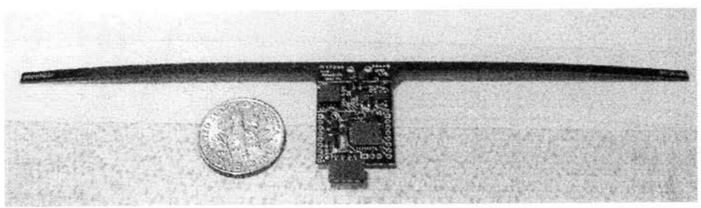

Figure 2-3: WISP Version 4.1

Figure 2-3 shows the Wireless Identification and Sensing Platform (WISP) that was developed by a collaboration of engineers from Intel Research Seattle and the University of Washington led by Media Lab alum Josh Smith [4]. It is a wireless device that utilizes a variety of different sensors and chips to gather data for many purposes, ranging from RFID encryption and security to temperature and acceleration measurement. The device is powered entirely from the RF field of the reader. The WISP fit the requirements of our system in a variety of ways.

The WISP was a smart tag, but was battery-less. It was important for our system to be portable and for the tags to be light weight. Batteries can be large and cumbersome, and need to be replaced from time to time. It was therefore ideal that our finger-worn sensors be powered entirely from the reader.

The WISP platform contains a 3-axis accelerometer. The accelerometer allows us to gather very useful information about movement and orientation that is key in gesture recognition.

The WISP is small, 1.5 cm x 2.5 cm, aside from the dipole antenna. The actual WISP platform is around an inch square (and can grow smaller with better electronics integration), so it can easily fit on the finger. The only problem was the dipole antenna, which was around 16cm in length, and was a hindrance to finger motion. However, it was within the scope of this project to reduce the size of the antenna while still maintaining the range especially since we only needed sensitivity out to a few inches or so.

## 2.2 Receiving Antenna Design

The WISP is designed to operate with a quarter wavelength dipole antenna at a frequency around 916MHz. However, even the quarter wavelength was too long for our tags to be compact and be comfortably worn on the fingers, so the antennas had to be redesigned. The antennas must be small, but they also must deliver enough power to the WISPs for them to operate at sufficient range.

### 2.2.1 Physical Goals

In order for an antenna to draw power from the RF field, it must resonate with the field at a certain frequency. Since the Mercury 5c operates in the 860MHz-960MHz range, the antenna must have a resonant frequency somewhere within those bounds so that the tag may draw power and be read. By looking at the standing wave ratio (SWR) graph via a vector analyzer, the resonant frequency and bandwidth of an antenna can be determined. By examining the antenna's Smith chart, one can determine if the antenna is properly matched to the network to achieve maximum power transfer.

In *Antennas for Wearable Devices* it is stated that: "for the body-centric network to be accepted by the public, the antennas need to be hidden and low profile" [1]. This statement was kept in mind when designing the antennas for the WISP. If possible, the ideal antenna for our system would not exceed the dimensions of the WISP itself by more than a centimeter on either side.

### 2.2.2 Effect of Body on Antenna Design

Since the WISPs and reader will be in close proximity to the hand and wrist, the effect of the body on the fields and transmissions must be taken in to account. Human tissue is a lossy medium, which can greatly alter the parameters of an antenna, which is usually characterized in free space.

One of the most notable effects the body will have on an antenna will be a deviation in wavelength, since the RF wave will travel more slowly through the human body than it would through free space. A way to minimize these effects would be to place the antenna as far from the body as possible, or to incorporate some kind of ground plane or reflector with the antenna [1].

The body will also cause far field signals to attenuate more quickly, which means dipoles and other far field antenna types will be less efficient if placed poorly in the wearable system [1].

### 2.2.3 Basic RFID Antenna Theory

There are some basic equations in antenna design theory that will allow us to take known factors about our RFID system and estimate the maximum read distance we can get from a certain tag.

The power transmitted to a tag when the reader and tag are perfectly matched can be roughly calculated as:

$$P_{tag} = \frac{P_{reader} G_{reader} G_{tag} \lambda^2}{(4\pi R)^2}$$

Where $P_{reader}$ is the power output of the reader and $G_{reader}$ and $G_{tag}$ are the gains of the reader and tag respectively [14]. Using this equation and the information given about the reader and WISP, we can find the minimum tag gain we need for a desired read distance.

$$G_{tag} = \frac{P_{tag}(4\pi R)^2}{\lambda^2 G_{reader} P_{reader}}$$

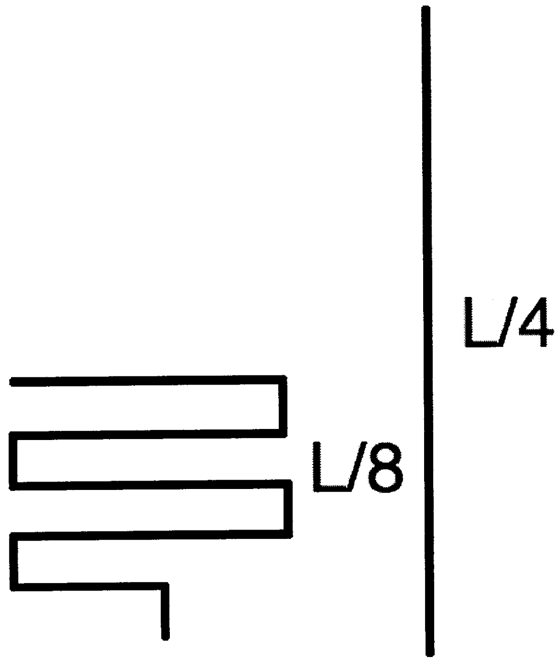


Figure 2-4: Example of what a meandered dipole would look like compared to normal dipole

### 2.2.4 Meandered Dipole Antennas

The first attempt to prototype a new antenna design was to take the old antenna and attempt to miniaturize it using the meandering technique [17]. Figure 2-4 shows an example of what a meandered dipole antenna might look like compared to a standard dipole. There are a few reasons that a meandered dipole maybe suit the project's needs.

- The standard WISP already uses a half wave-length straight line dipole
- The M5e is suited to coupling in the electric field

Size reduction and impedance matching can be achieved by simply bending the antenna and following a few principles.

- Length of wire increases overall inductance.
- Horizontal elements of the folds control radiation resistance.

- Vertical elements of the folds control energy storage and loss. [17]

This method can yield workable results, but design is dependent on a large number of parameters and therefore difficult to optimize. Some studies have shown that it is possible to reduce a dipole by half of its size without much of a reduction in gain [9].

### 2.2.5 Chip Antennas

Chip antennas are meandered line antennas that are laid out on special substrates or in special patterns to miniaturize the antenna while keeping the gain as high as possible. They can be incredibly small and come pre-designed to work at certain RF frequencies. They also tend to come pre-matched to 50 Ω so they are easy to incorporate to the existing matched system.

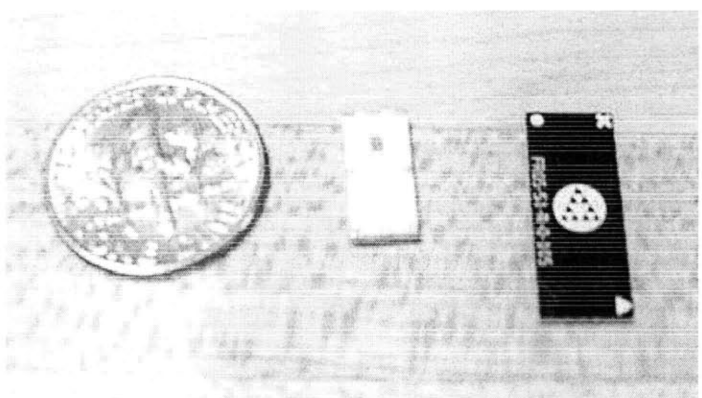

Figure 2-5: Two chip antennas

The first chip antenna tested with the system was the P/N 0920AT50A080 ceramic chip antenna from Johanson Technology pictured on the center in Figure 2-5. The antenna operated over a frequency range of 880MHz - 960MHz and had a peak gain of -0.7dBi, but it was not multi-directional. This antenna was considered mainly because of it's size. It was thought if the power from the reader could be increased, then this antenna might serve the needs of the system.

Another more omni-directional chip antenna was also tested, the Fractus FR05-S1-R-0-105 (the black antenna pictured in Figure 2-5). This antenna operated in the range of 902MHz - 928MHz and had a peak gain of over 0dBi. This antenna was much wider then the Johanson antenna, but still small enough to have minimal interference with finger motion. Since dBi is gain from an ideal source, it was expected that these would exhibit even less gain then stated on the data sheet.

### 2.2.6 Near Field Antennas

Near field antennas are usually loop style antennas that couple to the reader through the magnetic field instead of the electric field. They can also be simulated in FEKO (a German acronym for" Field Computation for Objects of Arbitrary Shape") which uses Method of Moments to calculate the predicted field shapes and strength for a given object. These antennas were also prototyped with wire. They seemed suitable to the system for a variety of reasons.

- The fingers will be within a wavelength of the reader
- The antennas can be made into small rings
- Inductive coupling leads to minimal interference from the body

However, there are also a few draw backs to the near field solution, which may be problematic:

- Loops will need to be matched to existing WISP
- Near field antennas will have to be made or bought for the M5e
- Loop antennas have a very low radiation resistance, which makes them very lossy
- Tags will only couple with the reader in one direction, as shown in Figure 2-6

### 2.2.7 Matching Networks

Since the original WISP used a dipole antenna, the output port had to be matched to the newly designed antennas. This can be done by looking the the Smith charts

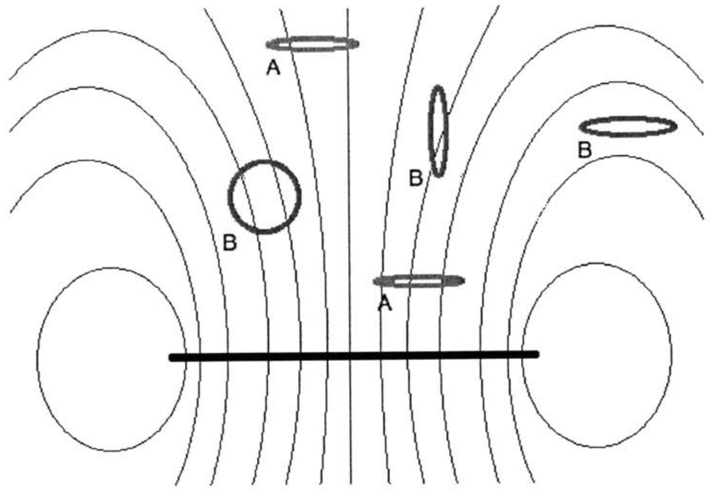


Figure 2-6: Near Field loops coupling to reader. Blue[A] is properly coupled, red[B] is not detected by the reader.

for the different designs. The Smith chart is a circle that represents the real and imaginary parts of an impedance. The line splitting the circle in half horizontally represents the absence of reactance (the imepedance looking into the wire is purely resistive). Most RF circuits are matched to 50 Ω, but our antenna port is matched to 68 Ω, the impedance of a balanced dipole. Once we design an antenna that is resonant at the proper frequency, we can move the impedance to the purely resistive line by following a few simple rules:

- If the impedance is in the top half plane, it is too inductive and a capacitor should be added in parallel (from the antenna to ground) to compensate.
- In the impedance is in the bottom half plane it is too capacitive and an inductor should be added in series to compensate.

## 2.3 Reed Switch

The reed switch was a sensor added to a WISP in order to implement a click functionality in the system. Reed switches are opened and closed based on their proximity to a strong magnetic field. Using a small magnet placed on one of the fingers (e.g., the thumb), the user can control whether the switch is opened or closed by touching

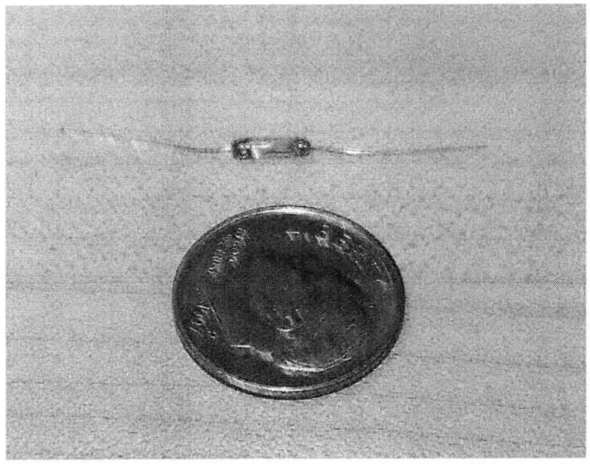

Figure 2-7: Size of reed switch compared to dime

the WISP-laden finger to the magnet-laden finger. In this way, we can have the reed switch mimic the functionality of a touch sensor. The ability to sense contact between fingers can prove very useful in gesture definition and interpretation.

The chosen reed switch used in this type of system must be small, but also operate quickly. The Meder Electronic KSK-1A08-1015, shown in Figure 2-7, was chosen, as it was only 7mm in length. It also switched on and off at a rate much faster than the reader was able to sample at, so it was sufficient to meet the system's timing needs.

# Chapter 3

# Software

## 3.1 WISP Firmware

Most of the firmware came from industry with the various pieces of hardware, but a small sections had to be added and modified in the WISP firmware to in order to support the reed switch and multiple tags.

The reader communicates to the WISP through amplitude modulation. The WISP communicates with the reader by modulating the impedance of the antenna and therefore changing the amount of energy reflected back to the reader, a method called backscatter radiation [4] .

The WISP is powered during sleep mode. A voltage supervisor watches the charge on the WISP's storage capacitor, and, once it has stored enough energy, it wakes up the microcontroller and will read the sensor and transmit the data. The WISP does not absorb power while the microcontroller is not in sleep mode [4].

The accelerometer firmware came with the WISP itself. The quick query, which was faster than the 10ms read query, was used, since power was an issue. It provided less accurate, but still useable, measurements.

The reed switch is soldered from the supply voltage to the input pin on the WISP's MSP430. When the switch is closed, the pin will be high, and when it open the pin will be low. This assures that the switch will only consume power when it has been activated with the magnet, and will not deplete the WISPs power supply otherwise.

Once the WISP has enough power, it sets the power pin high and then grabs the data on the input pin with the ADC. The shortest delay possible is taken to avoid unnecessary power consumption. The reed switch takes about .2 ms to open and settle and .15 ms to release, so the delay before the ADC grabs the data from the pin should be no longer than the latest of these delays, .2 ms.

## 3.2 Data Processing

Even in ideal circumstances MEMS accelerometers can exhibit a considerable amount of noise and also drift. In this application especially, the data had a tendency to be drifty and noisy because of the limited time the accelerometer had to settle before the data was grabbed by the ADC, which was being powered by the energy the WISP collected in sleep mode. In order to create relevant and useable data for our user interface, the raw accelerometer signals were processed in code on the PC. This allows for the micro controller, the most power hungry element on the board, to remain on for as short a time as possible, and in sleep mode, absorbing power, for as long as possible.

### 3.2.1 Tag Data Parsing

Tag data comes from the reader in the form of an EPC, or electronic product code. Our EPC contains the raw value from the ADC, plus information about the type of read that was done, the number of the tag, and the hardware version of the WISP. Our reader also sends the time separately from the EPC, so we can get an idea of how fast the WISP is reading.

Using the data in the EPC, we can figure out if we are seeing data from a particular sensor, accelerometer or reed switch, and then parse it accordingly for use in the GUI. The accelerometer sends 10 bits of data for each channel (x, y, and z), and the reed switch sends just 10 bits padded with zeros to fill the remaining space.

### 3.2.2 Accelerometer Data Filtering

It is important to filter the data from the accelerometer, especially since quick and less-accurate measurements of the accelerometer were being taken in order to conserve power. However, it is also important that the algorithms not be too complex in order to conserve time and not induce too much delay between finger movement and resultant mouse movement or other UI action. In order to create useable data for the system, two simple filters were introduced in the C # code. First, an offset filter is used to calibrate the accelerometer, then a dead zone was introduced to remove noise, finally a constant velocity filter is used to help eliminate drift.

### 3.2.3 Dead Zone Filter Implementation

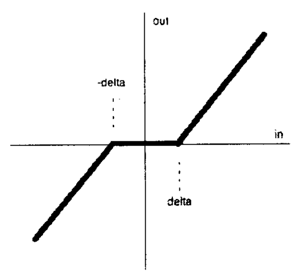


Figure 3-1: A representation of the dead zone filter

A dead zone filter is one of the simplest ways to remove noise from the output of the accelerometer. Figure 3-1 shows what a dead zone filter block. Basically, all incoming data within a certain range (in this case, *delta*) is removed and not transmitted. This has been proven effective in removing noise in other motion tracking systems based on accelerometers [6]. We know our accelerometer will be noisy, but that the at rest noise will be within a certain range of 0g acceleration. From the accelerometer data sheet, it can be determined that the accelerometer on the WISP is accurate to within ten percent of the supply voltage. Therefore it is reasonable to reject and zero any readings that are less than ten percent of the supply voltage, because it can be assumed that this is mostly noise.

### 3.2.4 Tilt Sensing

The tilt of the accelerometer is very relevant to gesture tracking, because as the finger moves, the accelerometer's tilt with reference to the ground also changes, which can give useful information about the position of the finger.

At any point with the accelerometer is static we know that $\sqrt{A_x^2 + A_y^2 + A_z^2} = 1g$ We can use trigonometry to extract the pitch (the angle of the x-axis relative to the ground) the roll (the angle of the y-axis relative to ground) and theta (the angle of the z-axis relative to ground). We find

$\rho = \arctan \frac{A_x}{\sqrt{A_y^2+A_z^2}}$
$\phi = \arctan \frac{A_y}{\sqrt{A_x^2+A_z^2}}$
$\theta = \arctan \frac{\sqrt{A_x^2+A_y^2}}{A_z}$

Note that was cannot determine $\phi$ (the angle about the ground vector) without more information, such as would be provided, for example, by a magnetometer, which draws far too much power for WISP implementation.

### 3.2.5 Position Tracking Algorithm Experimentation

It is nearly impossible to track the tag's position without adding another sensor, such as a gyroscope, to track the attitude of the accelerometer and compensate for ground. Some experiments were run to test the feasibility of using the accelerometer to track the position. By holding the WISP in the same orientation relative to the ground throughout the test, the attitude will be a constant and so all that will be apparent will be acceleration due to change in position.

In similar inertial navigation systems that have been used to track human movement, it has been found a person will almost never move at a constant velocity. Therefore it can be assumed that any prolonged constant velocity may be due to integrated offset error or noise. In order to filter out this error, velocity is tracked and if it remains constant for a certain amount of time, it is set back to zero [6]. This becomes a bit like a high pass filter, since it removes any long-standing values from the system.

## 3.3 User Interface

The user interface was created in C #, runs on a Windows platform, and makes use of the Mercury API created by ThingMagic. Our application allows the wearer of the system to manipulate the mouse with finger orientation and perform selection operations in various ways. Care was taken to keep the application lightweight and uncomplicated to allow for easier adoption.

### 3.3.1 Motivation and Objectives

The goal of the user interface is to provide smooth and comfortable interaction between the user and the computer (or in the future, possibly another wearable device). It should incorporate a number of gestures that can be found in everyday life and that are used in manipulating devices.

The actual finger interface should stay away from the wired and glove type devices that have been used in the past, and remain small and wireless. The reader should also remain small and comfortable to wear.

Other systems have used gestures to interact with a similar wearable, environment such as the "Ubi-finger" [13] and Sixth Sense [19]. This system will include some of the gestures that have been successful in these projects.

### 3.3.2 Physical System

The tags are worn on the part of the finger closest to the hand, the proximal phalanx, which allows the system to do tilt and vibration sensing. Gesture can still be detected well with the tags close in to the palm of the hand, because tilt requires only a small movement for detection.

This also allows for the reader to be as close to the tags as possible and still be worn on the wrist. The reader is worn on the wrist and the antenna is worn farther up the hand, closer to the tags, to help minimize the influence of the body.

With an improved reader, we hope that it can be moved out to the vicinity of the wrist and perhaps built into the wearer's cuff or a bracelet. Likewise, the tags can be moved to the upper knuckle, where easier and more expressive gesture may be made.

## 3.4 Gesture Recognition

As summarized above, there has been ample previous research into using gesture to interact with devices such as lights, computers, and phones. Interfaces have ranged from wristbands to wired finger devices.

Our interface contains three modes: An off mode (where no gesture is parsed), a keypad mode (in which the user uses a combination of the tilt of their hand and touching of the fingers to enter words, much like texting with a keypad), and another mode which allows the user to scroll and click with the mouse. The ability to dynamically switch between these modes mean that the number of unexpected inputs will be reduced [13].

### 3.4.1 Finger Vibrations

In several previous studies, it has been shown that accelerometers placed on the fingers can allow for detection of finger tapping, and even discern between which part of the finger is being tapped. [15] Different levels of vibration and acceleration on the x and z axis indicate if a tap has occurred and what kind of tap it is.

This type of gesture recognition can very useful, since a taping motion with the finger could correspond to a button press, and eventually help lead to some kind of keyboard-less typing. Since the WISP already incorporated an accelerometer which was used for other gesture recognition, integrating in finger tap recognition in the gesture mode seemed both useful and plausible.

Our system will analyze acceleration data and determine if the user has tapped something, such as the table, or the user's leg.

### 3.4.2 Finger Thumb-Finger Clicking

Two of the user interface modes make use of thumb to finger touching. The system will be able to recognize if a finger is being touched, which finger it is, or if it is both fingers at once. The WISP samples the output of the read switch. Once it is closed and the value drops below a certain threshold, the program will register that the switch has been pressed. Similarly it can recognize when it has been closed, because the value will rise again.

In keypad mode, tilt will select the row of the keypad, and the finger or chord will select the key. The user can then scroll the letters with multiple clicks. Then bending the hand forward will select the letter to enter.

In mouse mode, the tilt will control mouse movement, and the thumb to finger touching will enable/disable this movement. The second finger will create a mouse click.

### 3.4.3 Sensing tags on other parts of the body

As mentioned above, the system will include a "mode-change" feature to limit gesture confusion. This will be implemented by placing a tag elsewhere on the body that can also be read by the reader, but at a greater distance. When the user wants to change modes, he or she only needs to bring the hand close to the tag, and it will activate a mode-change. This tag can be worn in the belt area to provide enough distance from the reader.

### 3.4.4 Device Manipulation

In the Ubi-button and Sixth sense projects, recognizable finger and hand motions were used to wirelessly accomplish certain tasks. One of the gestures that seemed most interesting was recognizing a turn of the wrist to the right or left [13].

Recognizing a wrist turn is easily realized using the tilt sensing capability of the the accelerometers. Once the wrist passes a certain angle, the system recognizes it as the wrist being turned either left or right. In typing mode, the system will calculate the angle of the WISP and once it passes a certain threshold, recognize that the wrist has been titled. In mouse mode, it will use the analog angle multiplied by some constant to determine the speed of the mouse. This allows the user to finely control the speed at which the mouse moves.

Our system recognizes whether the hand is straight up and down or turned to the right or left. This could be used in the system, to manipulate a mouse or some other functionality in a computer.

# Chapter 4

# Results

## 4.1 Basic Results

### 4.1.1 Physical System and Portability

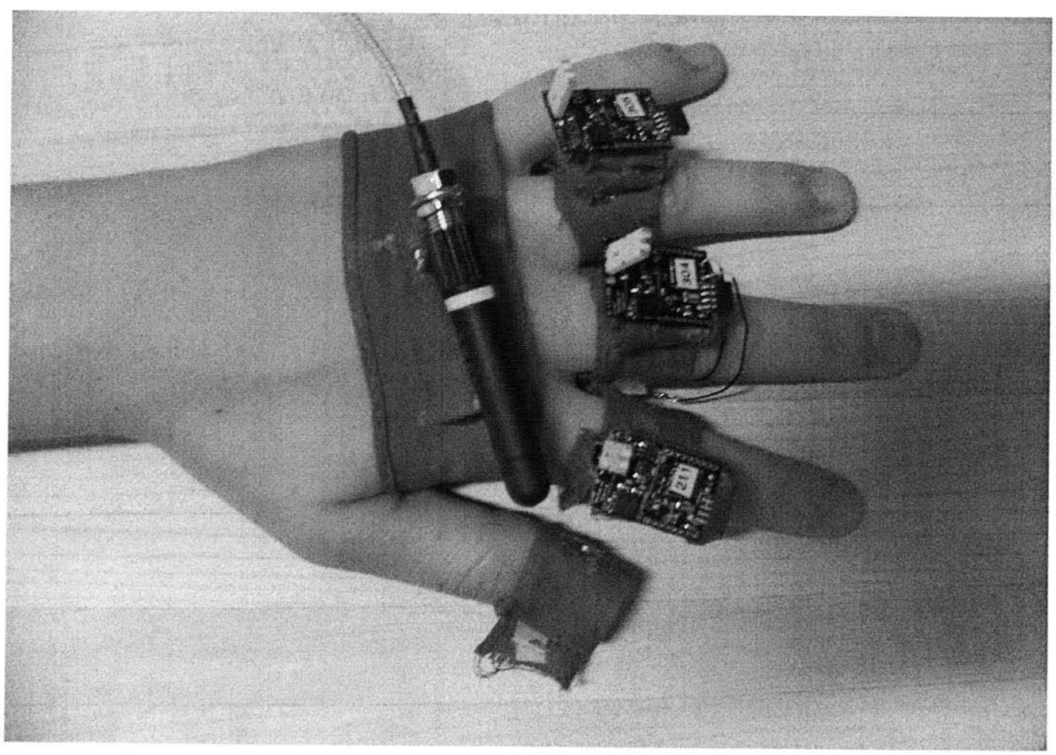

Figure 4-1: User Interface - A subject wearing tags and antenna

The resulting system had to be both comfortable and easy to put on and take

| Read rate in free space | | | |
|---|---|---|---|
| | Dipole | Meandered Dipole | Chip |
| 0 " | 38.56 read/s | 37.73 read/s | 37 read/s |
| 1 " | 37.24 read/s | 37.9 read/s | 17.73 read/s |
| 2 " | 35.56 read/s | 36.7 read/s | 10.9 read/s |
| 3 " | 35.56 read/s | 32.6 read/s | 9.78 reads/s |
| 4 " | 33 read/s | 18.5 read/s | 7.08 reads/s |

Table 4.1: Free space read rate vs. distance from reader

| Read rate in presence of hand | | | |
|---|---|---|---|
| | Dipole | Meandered Dipole | Chip |
| 0 " | 35.56 read/s | 37.04 read/s | 17.71 read/s |
| 1 " | 35.56 read/s | 37.5 read/s | 11.5 read/s |
| 2 " | 32 read/s | 35.5 read/s | .07 read/s |
| 3 " | 30.1 read/s | 27.91 read/s | 0 reads/s |

Table 4.2: Read rate in proximity to body vs. distance from reader

off. The WISPs were attached to soft rings that could easily be taken on and off, but would not slip around or inhibit movement while they were being worn. Velcro was added to the rings and antenna attachment, which allowed the system to fit people with many different hand sizes, and allowed for easy donning and removal. A experienced user, the author, could put on the system in about 30 seconds. Figure 4-1 shows the prototype being worn on the hand.

### 4.1.2 Speed and Range

The performance of the tags varied greatly with their size and proximity to the body. Tables 4.1.2 and 4.1.2 show the reads per second for three kinds of antennas when they were being worn and when they were in freespace. The tables show the read rate and range for the final reader, the M5e. The inches indicate how far the tag was from the reader during the test. The read rate for the dipole, was by far the best and least affected by the presence of the body. The meandered dipole was less than one third the size of the original antenna, and still maintained a decent read rate, even in the presence of the body. The chip antennas suffered greatly, because they had less gain to begin with, and were not suited to use in the presence of the body.

The system left much to be desired in terms of read range. Since the tags and antennas had to be kept small, their gain suffered. The proximity to the body also lowered the efficiency of the system and decreased the read rate at the desired range. The WISP PCBs were also not designed for the off-the-shelf chip antennas, so it was difficult to include the necessary ground plane and tuning parameters for the chip, and it was also not reliably tunable in the presence of the body.

## 4.2 Antennas

### 4.2.1 Meandered Dipole Antenna

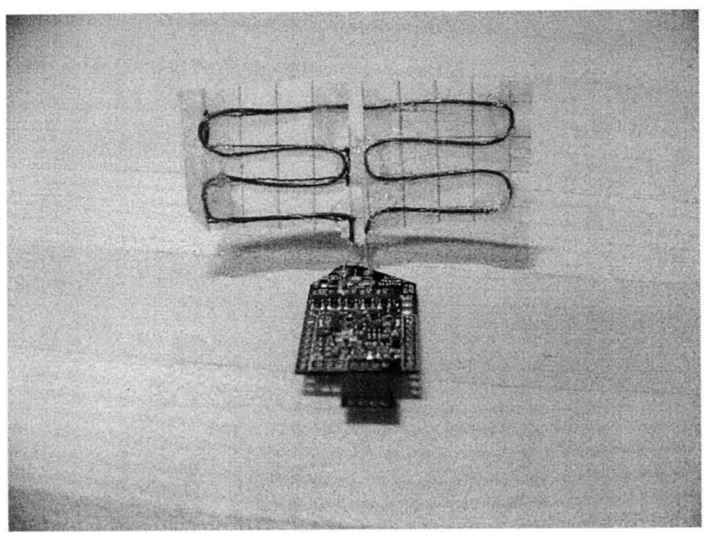

Figure 4-2: The meandered dipole prototype on the WISP

At first, the meandered dipole designs were simulated in FEKO to determine if they would have radiation patterns similar to dipoles at the 916 MHz. Figure 4-3 shows the results of a simulation on the dipole design. One can see that these radiation patterns are very similar to that of a dipole, which indicates the antenna should have acceptable gain and therefore range at the frequency of interest.

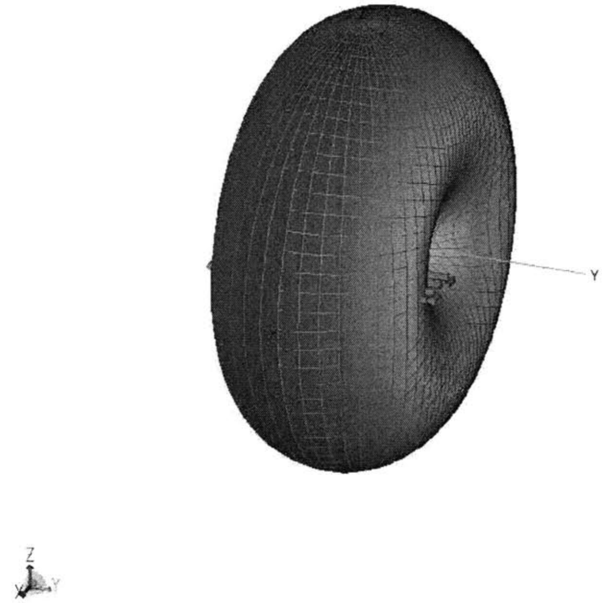


Figure 4-3: Simulated far fields for meandered dipole

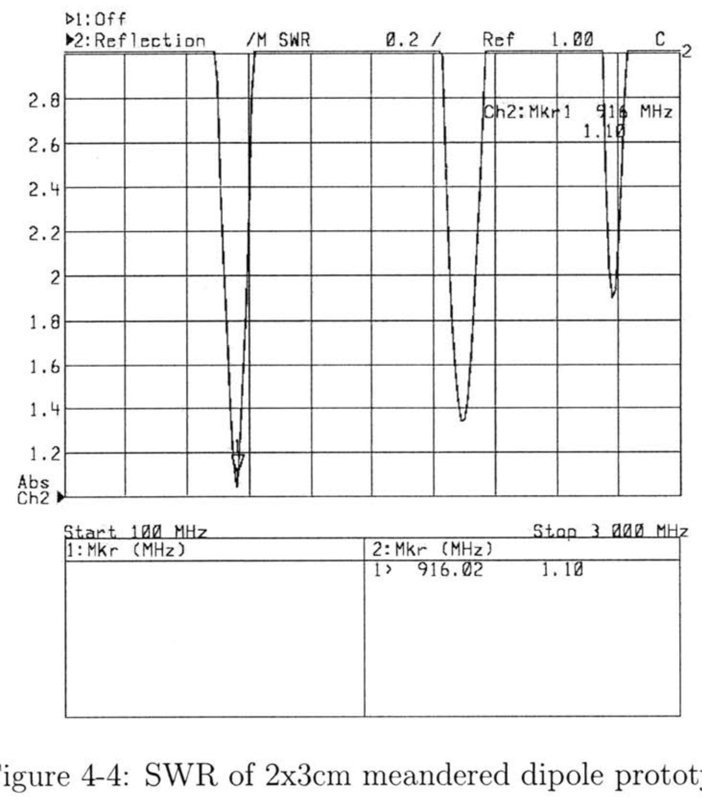


Figure 4-4: SWR of 2x3cm meandered dipole prototype

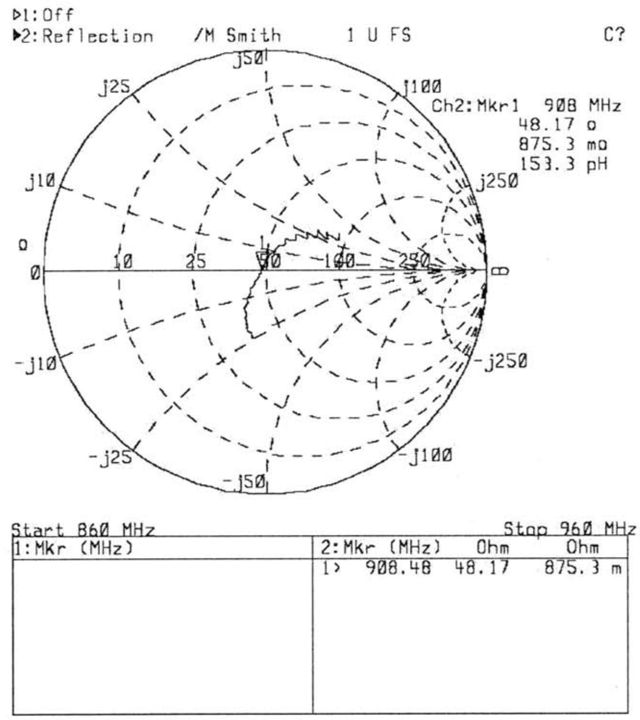


Figure 4-5: Smith Chart of 2x3cm meandered dipole prototype

The first few prototypes were made of wire, and sometimes would lose their shape and detune during testing. Final prototypes were glued down to paper at exact dimensions, however, the paper also interfered with communication. Figure 4-2 shows the meandered dipole prototype that was tested in one configuration of the system. The resulting antennas had a little less gain and bandwidth, but still a reasonable read distance. Figure 4-4 shows the VSWR of one of the dipole prototypes. One can see that at the desired frequency, 916 MHz, the VSWR is almost 1:1, which indicates maximum power transfer. One can also see the higher frequency harmonics of the dipole, at which it would also resonate, but draw less power. The bandwidth, however, is much narrower than a dipole. Figure 4-4 shows the impedance of the same dipole prototype, over the frequency range of the reader, 860 MHz - 960 MHz. The impedance was almost perfectly matched to $50\Omega$ at 916 MHz, which indicates that the dipole doesn't need any extra matching network before it is attached to the WISP.

The dipoles that were designed by hand had gain comparable to the chip antennas.

Meandered dipoles are simple, but difficult for one person to perfect in a matter of a few months, which was the situation for the project. The meandered dipole antennas were tested in the final system. With the internal antenna, their performance was comparable to that of the chip antennas. Once the reader was converted to the monopole whip however, their performance became notably better. Therefore these antennas were used in the early prototypes of the design.

### 4.2.2 Near Field Antenna

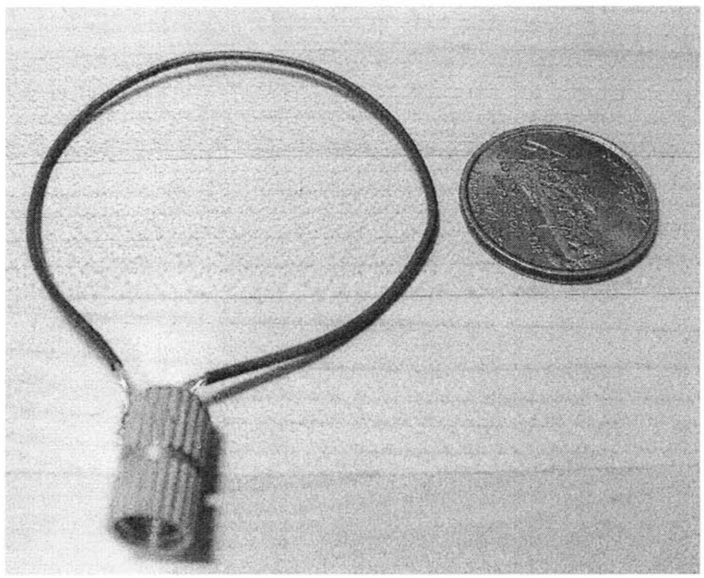

Figure 4-6: A prototype of a near field loop antenna

To help with the design of the near field magnetically inductive antennas, an EM field simulation tool, FEKO (http://www.feko.info/), was used. This program helps visualize the strength of the fields created by the antenna and how the currents are flowing through the wire. Figure 4-7 shows the magnetic fields around a simple half wavelength loop antenna and Figure 4-8 shows the fields around a half wavelength antenna that has been looped twice.

As expected, the doubly looped antenna shows a stronger magnetic field. Figure 4-9 shows the near fields around a simple square antenna, which are by far the weakest performers. This is probably due to reflections inside the antenna due to the corners and phase shift in the current distortion that can lead to some cancellation in the

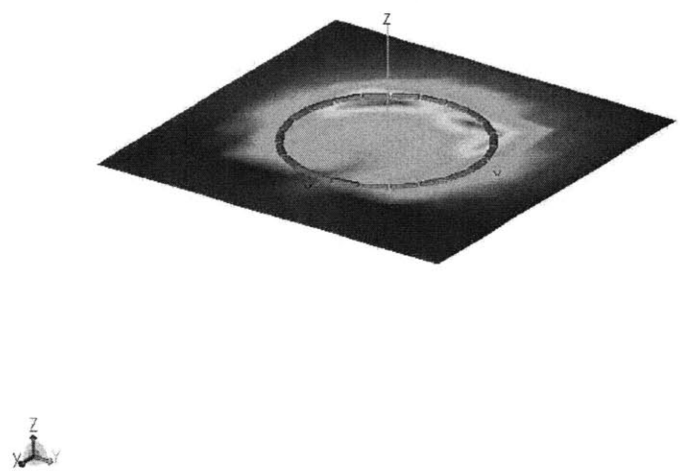

Figure 4-7: Near field patterns of a simulated circular loop

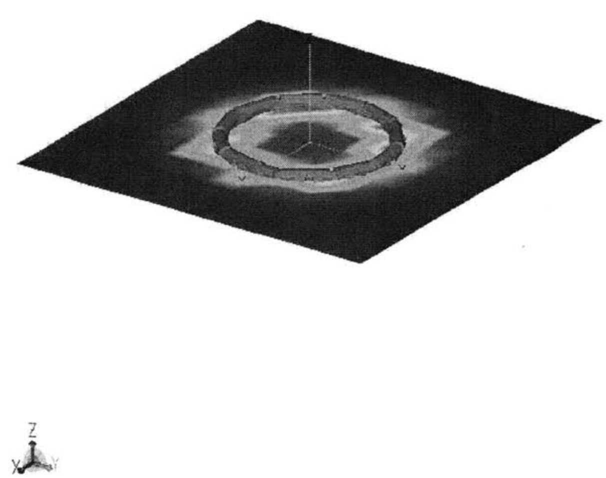

Figure 4-8: Near field patterns of a simulated double loop

field. Using these simulations we can get an idea of how a certain antenna shape should function in the real world.

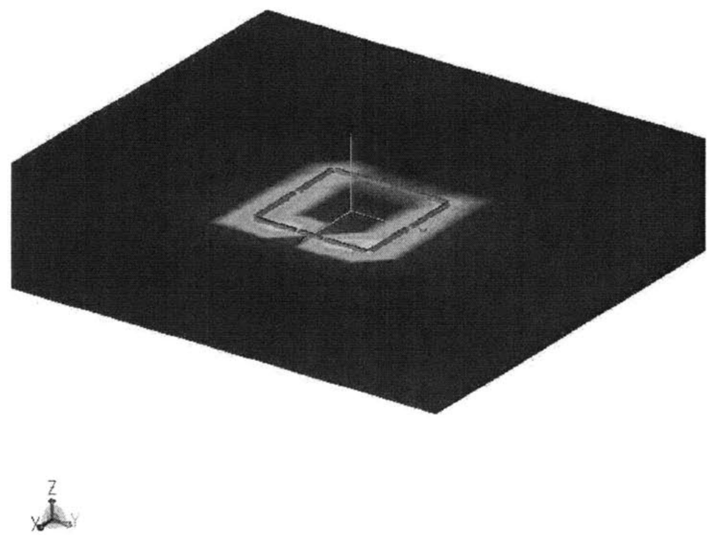

Figure 4-9: Near field patterns of a simulated square loop

The near field antennas were also prototyped with wire before they were tested on the the WISPs. Figure 4-6 shows the near field antenna that was made for the reader when testing near field prototypes, since the chip antennas and dipoles would not couple in the near field, and most commercially available near field antennas are 3-4 times the size of our reader.

Figure 4-10 shows the SWR of a half-wave loop antenna. The wire was looped twice and then matched with a 10 pF capacitor to 50 Ω. The bandwidth, which ranged between 900 MHz and 930 MHz, was smaller than the dipole. The center frequency was around 920 MHz only a few MHz off from what was desired. Figure 4-11 shows the Smith chart of the same loop antenna, showing that it is matched to 50 Ω at the desired frequency.

The near field antennas worked well in close to the read antenna, but the read range was less than an inch. Moreover, they also only coupled to the antenna in a

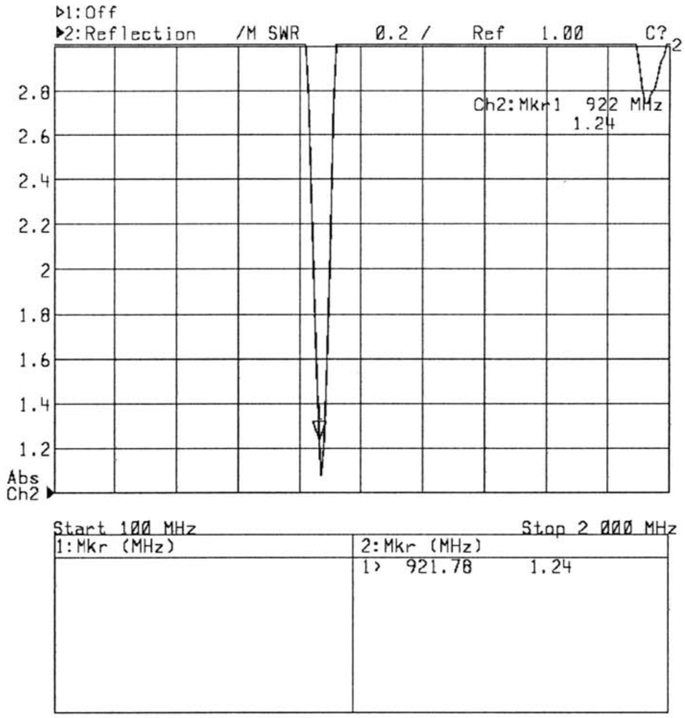


Figure 4-10: SWR of a double loop antenna

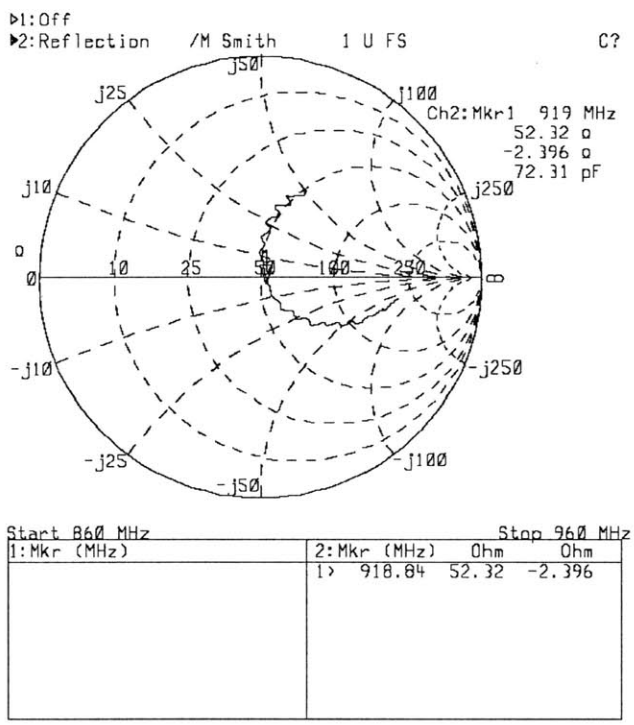


Figure 4-11: Smith chart of a double loop antenna

very specific orientation and position. Even just a slight tilt to the loop could prevent the WISP from coupling with the reader, so the near field tags were not used in the final system.

### 4.2.3 Chip Antennas

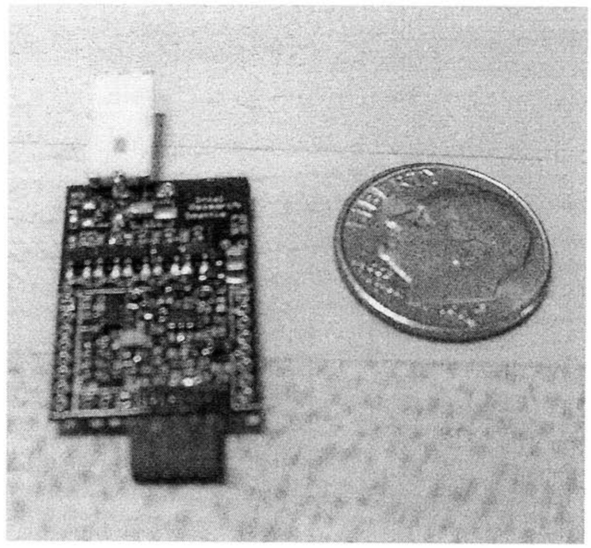

Figure 4-12: WISP with Johanson Chip Antenna

The chip antennas were small, but the read distance was shorter than one inch. The biggest problem with chip antennas is that they are made for unbalanced monopole RF systems, while the WISP is outfitted for the balanced dipole. This makes matching, tuning, and positioning difficult. Monopoles are usually meant to work with large, low impedance ground planes, that make a monopole appear like a dipole system, by creating a reflection of the monopole antenna.

Various methods were attempted to achieve maximum gain from the chip antennas. Since the application was vastly different from what the antenna was intended for, it was difficult to determine the optimum configuration without some tests. We do know that the orientation of the chip antenna with respect to the reader is important, in order to keep phase loss at a minimum. The optimal position ended up being with the chip antenna over the top edge of the WISP, and the ground contact left floating, as shown in Figures 4-13 and 4-12. The Johanson chip antenna can also be placed at a right angle to the board with similar results. The optimal situation for these antennas would be to redesign the RF front end on the PCB, so that it would be well suited to the antennas as specified on the data sheet. Since we did not have time to design and make our own WISP PCBs, a balun was used to change the WISP from a balanced to unbalanced load and also match the impedances. However, the balun also leads to insertion and return loss, which decreases the performance of the antenna.

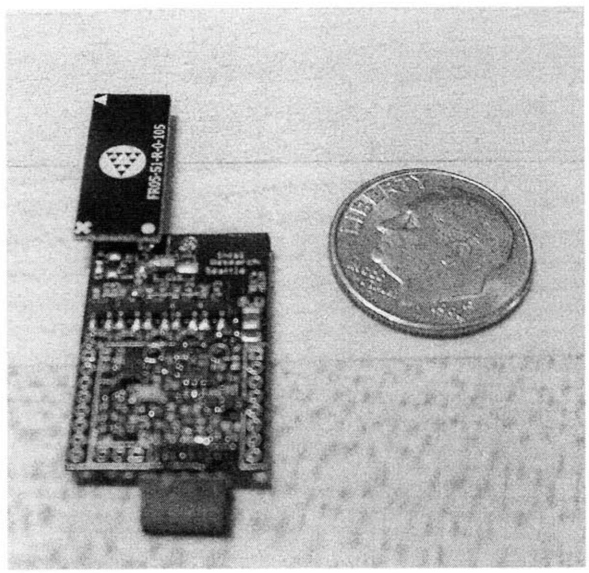

Figure 4-13: WISP with Fractus Chip Antenna

The chip antennas offered the smallest form factor, best directionality with a moderate read range, which made them more desirable than the other types of antennas tested. The only problem faced with the chip antennas interference from the body. To circumvent this problem, the tags were oriented in such a way that the antennas were as far away from the body as possible. This technique helped stop the read range from disappearing completely, but still saw a reduction in read rate of about 3-5 times less than without the body present. Experiments were done with shielding, but the shields interfered too much with the communication between the tag and reader to make them useful.

Accordingly, chip antennas could not be used with the USB reader, but were used in the final prototype with the high power reader module.

### 4.2.4 Reader Alteration Results

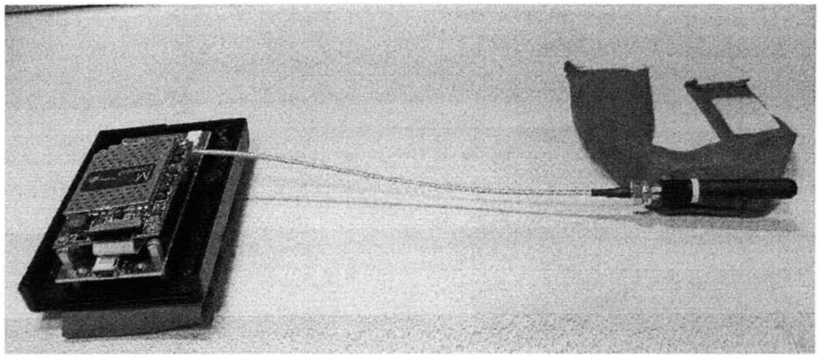

Figure 4-14: USB reader with new antenna

The M5e Compact has an MMCX output port which is matched to 50 Ω. The USB reader comes with an internal chip antenna which is matched and hooked to the output of the reader. However, this chip antenna is exactly the Johanson chip antenna used in the chip antenna experiments above, and has a very low peak and average gain. In order to introduce more gain from the reader, the internal antenna was switched for a larger external one.

The new antenna was a 1/4 wavelength monopole whip, which was matched to 50 Ω and broadcast at 916 MHz. Its maximum gain is 2dBi, much higher than the -0.7 dBi of the internal chip antenna. It was attached to the reader through 7" of RG-178 coaxial cable, which offered around 96 % efficiency, assuring little loss due to the cable itself. The reader and new antenna setup are shown in Figure 4-14 The change of the antenna gave almost twice the number of reads for the standard dipole antenna and increased the read rate and range for the chip antennas, which were also far field type antennas.

The added length of the wire also allowed us to place the antenna further up the hand, while leaving the cumbersome reader further up on the wrist or arm.

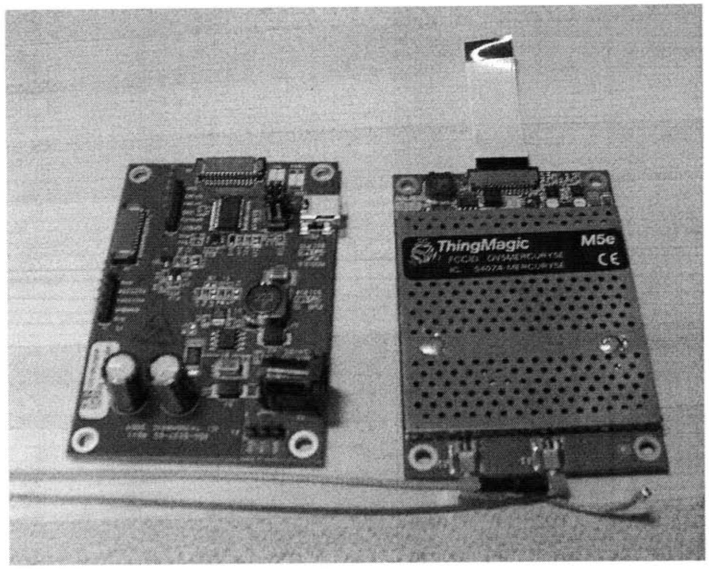


Figure 4-15: M5e Modules and Power/Interface Board

| Read rate in freespace | | | | |
|---|---|---|---|---|
| | USB Reader | | M5e | |
| | Meandered Dipole | Chip | Meandered Dipole | Chip |
| 0 " | 12.56 read/s | 25.3 read/s | 37.73 read/s | 37 read/s |
| 1 " | 11.5 read/s | .04 read/s | 37.9 read/s | 17.73 read/s |
| 2 " | 11.38 read/s | 0 read/s | 36.7 read/s | 10.9 read/s |

Table 4.3: Read rate vs. range for USB Reader vs. M5e

The second and most notable improvement came when the reader was exchanged for a higher power module, the M5e also from ThingMagic, shown with the power/interface board in Figure 4-15. The newer module required a wall outlet for a power supply instead of just a USB connection, (although a wearable power supply can be designed), but the improvements in range and read rate were worth the trade-off. The USB reader used the M5e-Compact, had a max power output of 23dBm, but the larger

| Read rate near hand | | | | |
|---|---|---|---|---|
| | USB Reader | | M5e | |
| | Meandered Dipole | Chip | Meandered Dipole | Chip |
| 0 " | 17.2 read/s | 1 read/s | 39.04 read/s | 17.71 read/s |
| 1 " | 6.27 read/s | .02 read/s | 38.5 read/s | 11.5 read/s |
| 2 " | .66 read/s | 0 read/s | 35.5 read/s | .07 read/s |

Table 4.4: Read rate vs. range for USB Read vs. M5e near body

module, the M5e, was able to supply 30 dBm, a huge improvement. However, the M5e also drew a max of 12.5W of power vs. the 2.9W for the USB reader. The improvement of read rate in free space and near the body is shown in Tables 4.2.4 and 4.2.4. The M5e was also much larger, but since it could be worn on the arm, it wasn't too much more cumbersome. The new reader made the chip antennas feasible for use in the final system, shrinking the wearable tags considerably.

### 4.2.5 Reed Switch

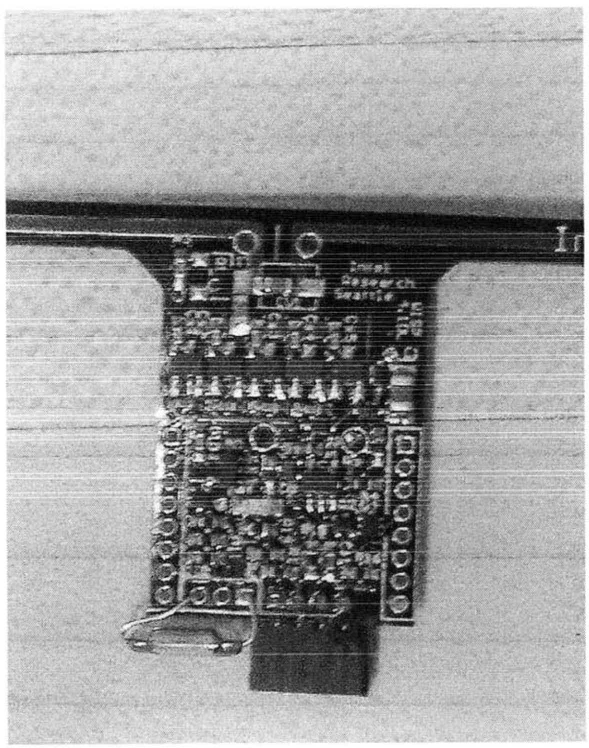

Figure 4-16: The WISP with reed switch attached

The reed switch functioned very well when it received enough power. Experiments were done to show that the tags read at the same rate regardless of whether the switch was pressed. The problem biggest problem was seen when the fingers were touched to the thumb, causing the antennas to rotate and come out of the correct polarization with the antenna. This led to a slower read rate, since the antennas absorb less power.

## 4.3 Gesture Interface

The gesture interface was tested with a variety of accelerometer filters and gestures appropriated for HCI. First a variety of filters were tested on the accelerometer data, to make sure that values being used for gesture sensing were as accurate as possible.

There were three WISPs worn on the middle, ring and index fingers, only one WISP had an accelerometer. The accelerometer was used in tilt sensing and was put on the index finger, since it is most natural to point with this finger. The two reed switched were placed on the middle and ring fingers, as these were the two remaining fingers closest to the thumb. The thumb contained two magnets, both small, but powerful enough to activate the switches. Two small magnets ensured that the switches could be activated either one at a time, or both at the same time, for a chord. If a larger magnet was used, there was danger of opening both switches a significant distance form the thumb, when this was not the intention of the user.

In the end, the most successful gestures were chosen for testing in usability studies. These gestures tested included tilt sensing, position sensing for an un-tilted WISP, tapping on hard and soft surfaces, and thumb-to-finger touching. While position and tapping were not accurate enough (or required extra sensors) to be tested in the final system, tilt and thumb-to-finger interaction were combined and used in the final system that went on to be tested by users. In general, the users found the idea of a tilt mouse to be very intuitive.

The power limits of the WISP made the accelerometer data more difficult to work with. The quick sampling option had to be used in order to keep power usage down. Less power also led to a slower sampling rate and slower and less smooth updating of the user interface.

No machine learning was used in the tests - simple detection thresholds were manually set by inspection, all to data generated by the author using the system.

### 4.3.1 Accelerometer Accuracy

The accelerometer data sheet states that it is 10 % accurate, but the WISP quick sampling does not allow enough time for it to settle entirely, so the accuracy can be even lower. Figure 4-17 shows the noise on an unmoving accelerometer. The accelerometer output can range between -3g and 3g. These factors help us determine what values will be useful for our dead zone filter.

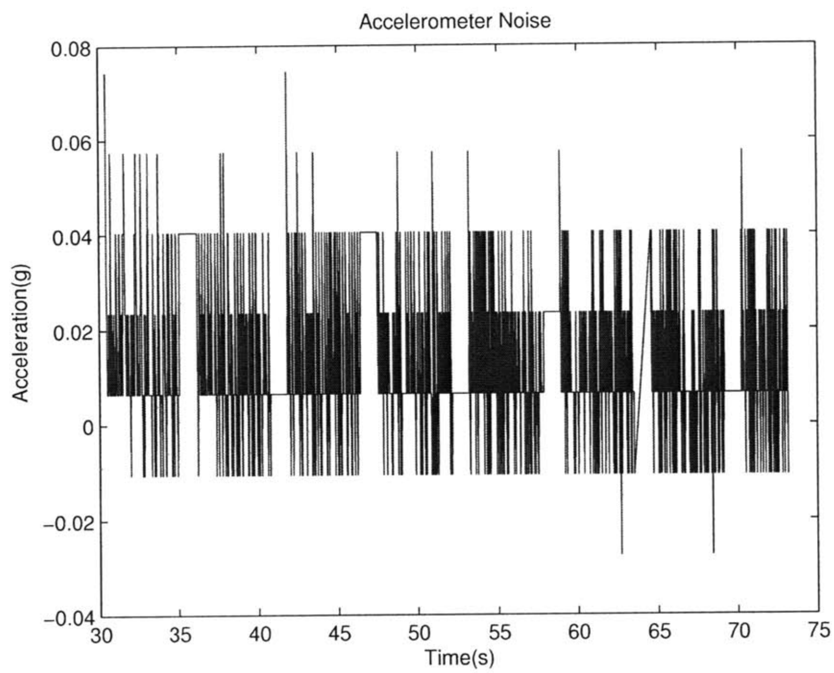


Figure 4-17: Noise on unmoving WISP

### 4.3.2 Filtering

Figure 4-18 shows the outcome of the offset filter. With the average removed the output of the accelerometer is now centered around zero, so when the data is used, there won't be problems from integrated offset.

The noise filter was implemented by removing any accelerometer data that fell below a certain value, *delta*. This leads to an obvious trade off between noise and sensitivity. If *delta* is too high, then the system will not be as responsive to movement. If *delta* is too low, then the system will exhibit jitter due to noise. Figure 4-19 shows

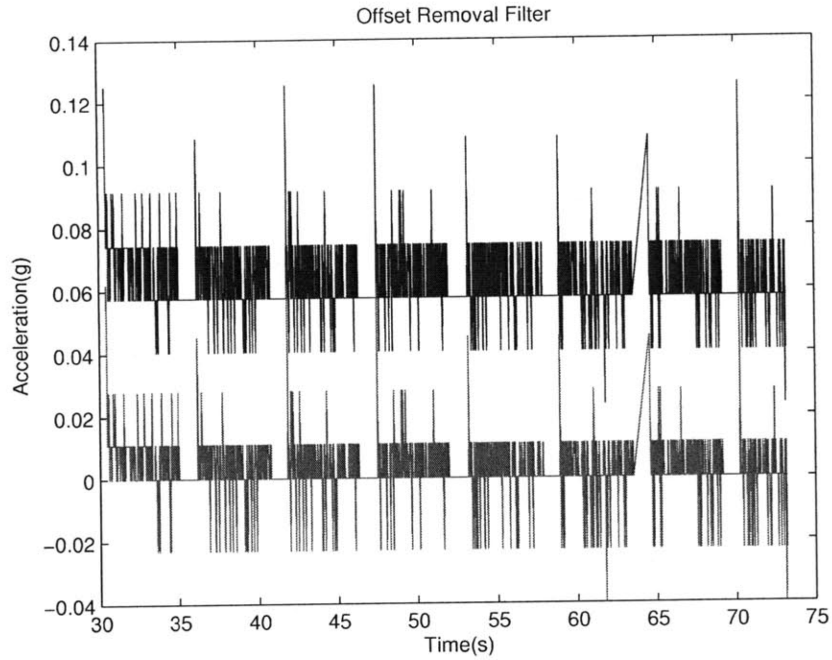


Figure 4-18: Offset removal filter on stationary WISP

how the noise on a unmoving WISP is affected for three different values of *delta*. There should be no apparent acceleration, but noise is still observable until *delta* has been made up to 10 % of the maximum output value.

### 4.3.3 Position Experiments

The results of the "high pass" velocity filter are shown in Figure 4-20 for different filter constants. Figure 4-21 shows recorded position, velocity, and acceleration without the high pass filter. The "f" parameter denotes how many reads the velocity (integrated acceleration) is allowed to remain constant before it is reset to zero. The WISP was moved up and down above the reader for 30 seconds. From the graph, it is apparent that the lower cut-offs filter out too much of the movement, but the higher ones allow for too much divergence. It makes sense to pick the filter constant based on the read rate you expect. If the readers takes ten samples a second, then it would make sense to stop after 30 or 40 samples, because it is unlikely that someone will be moving at a constant velocity for ten seconds. This filter is hard to apply well without

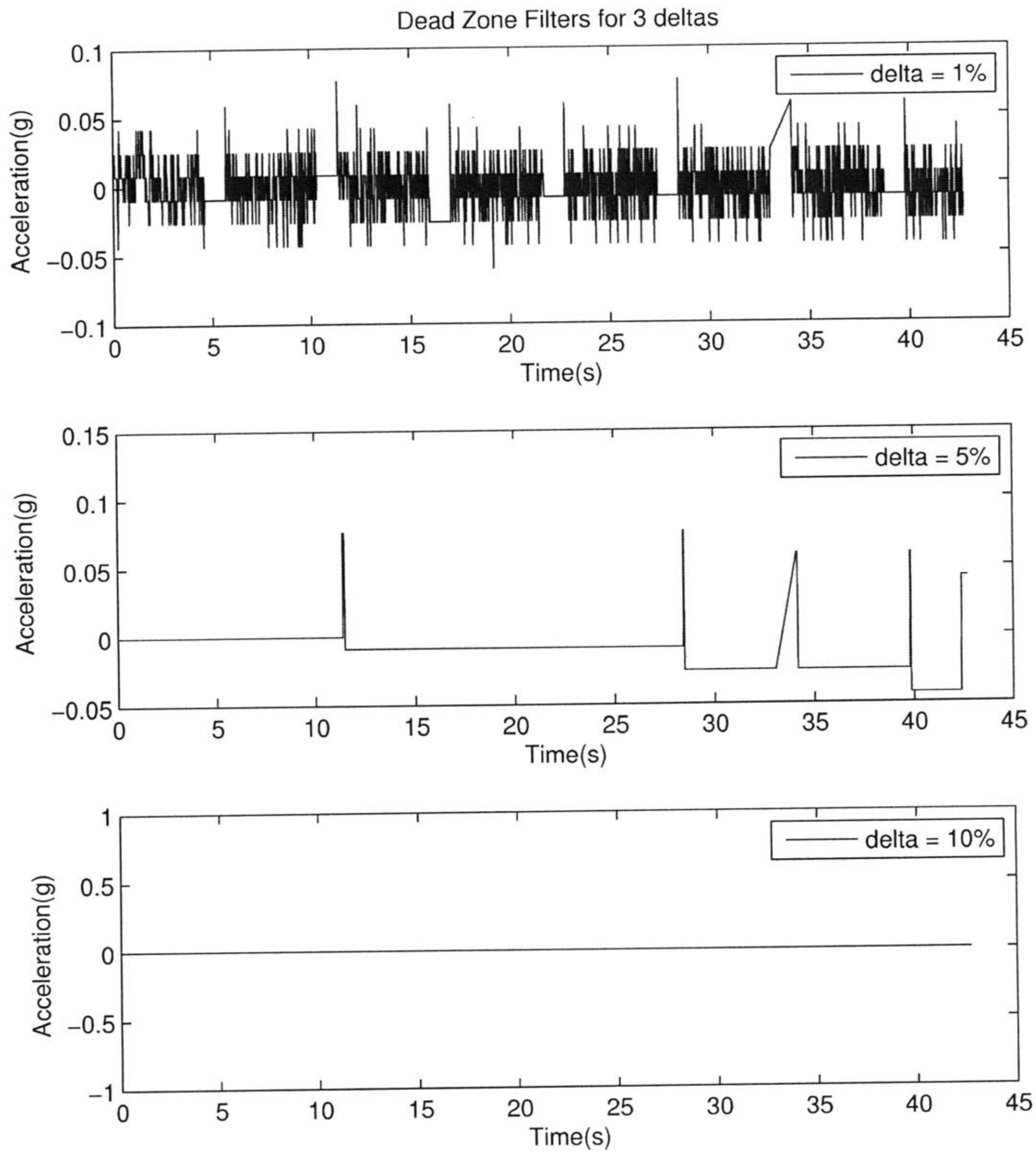


Figure 4-19: Deadzone Filter for stationary WISP

a gyroscope that can tells us the angle of the WISP and therefore the acceleration due to gravity, but gyroscopes are still too power-hungry for passive implementation.

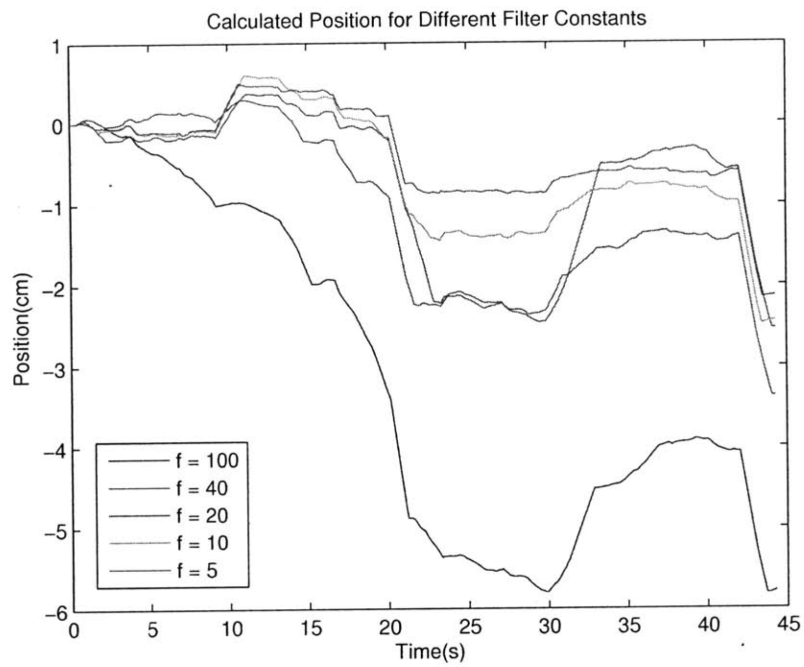


Figure 4-20: Constant Velocity Removal Filter for tag moving cyclically up and down

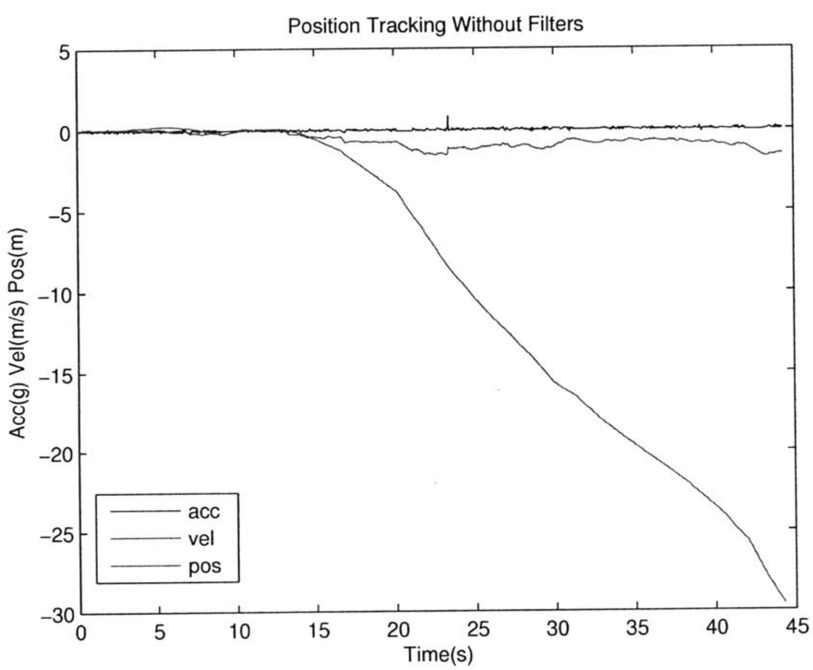


Figure 4-21: Unfiltered output of accelerometer under integration for tag cycling up and down

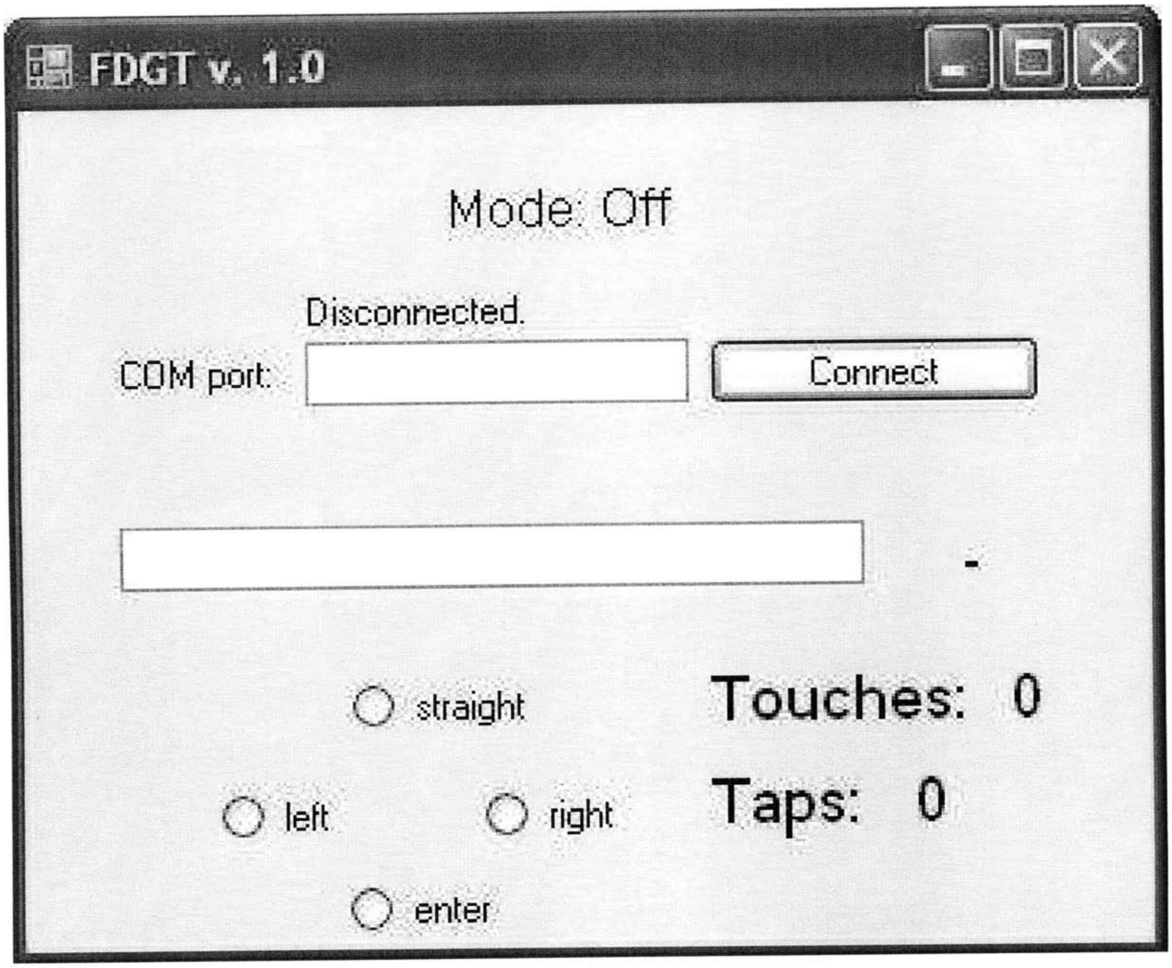


Figure 4-22: GUI Display

### 4.3.4 Graphical User Interface (GUI)

The goal of our vision was to keep the user interface simple and self explanatory. Fig. 4-23 shows what the GUI looks like when it is being used to manipulate the mouse on the screen. The user is free to navigate away from the system control dialog box and interact with other windows and icons. Figure 4-24 shows a user interacting with the computer through the user interface, which is includes the tags, reader, and GUI.

The GUI itself contained a number of features. A a small text box is present for going through the set up process for the reader and calibrating the accelerometer tag. It is in the middle of the display shown in Figure 4-22. The status bar, above the box for entering the com port, also lets the user know whether they are connected and if the tags are being read. The program only needs to know to which com port

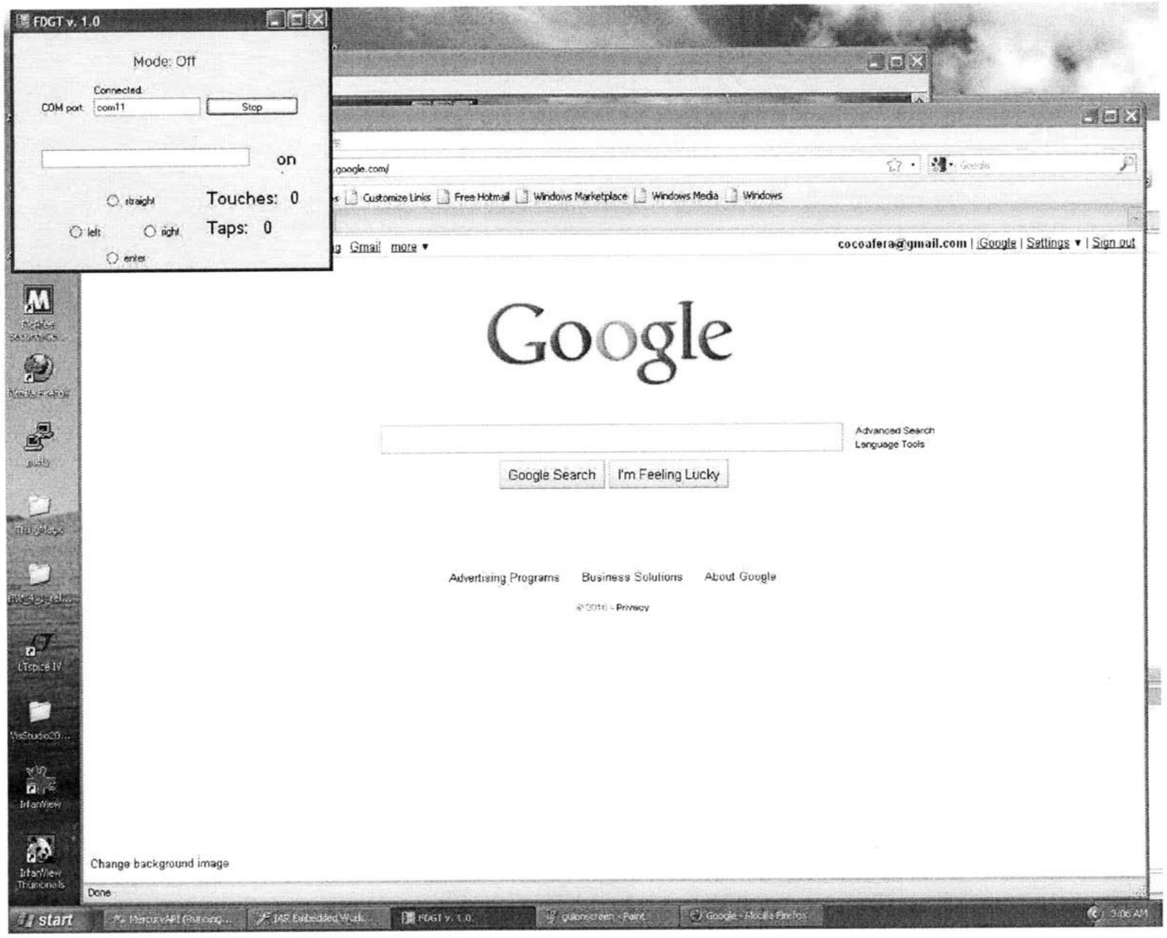


Figure 4-23: Screenshot of tag interface used to control a PC

the reader is connected in order to communicate with the system.

The GUI also indicates which mode the program is operating in. The mode indicator can be seen at the top of the display in Figure 4-22. In the end, the user interface included three modes that were controlled by an active tag that could be placed far from the user's wrist – Figure 4-25 shows this mode changing tag. This tag is a standard active tag that comes with the M5e system that stores an EPC and is read more quickly and from a much farther distance than the WISP. It was also small and flexible, and therefore easily hidden anywhere useful on the body.

The idea behind this tag is that moving the hand with the reader near a part of the body where this tag is worn constitutes a definite and easily-discerned gesture that can be used, for example, as an explicit "mode change". In our case, we toggle cyclically between a set of modes when the hand is near this tag. In practice, tags

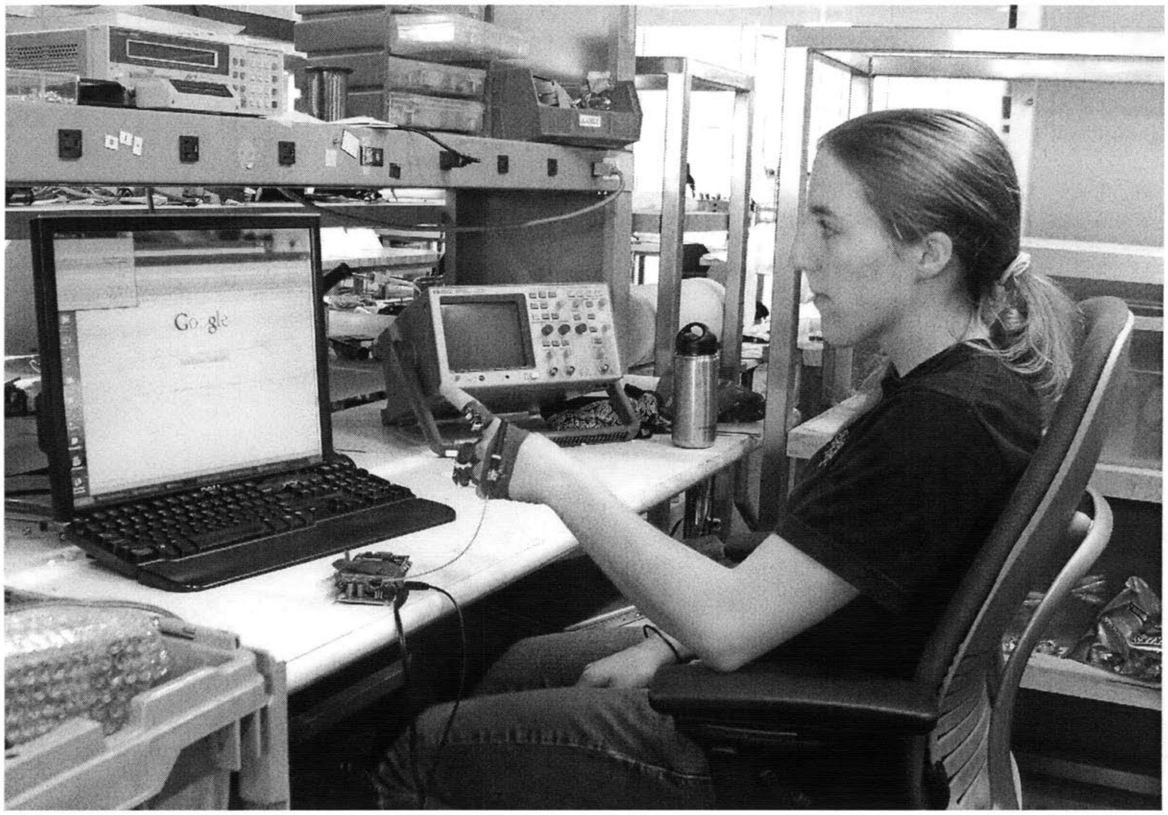

Figure 4-24: User interacting with the computer through the complete user interface

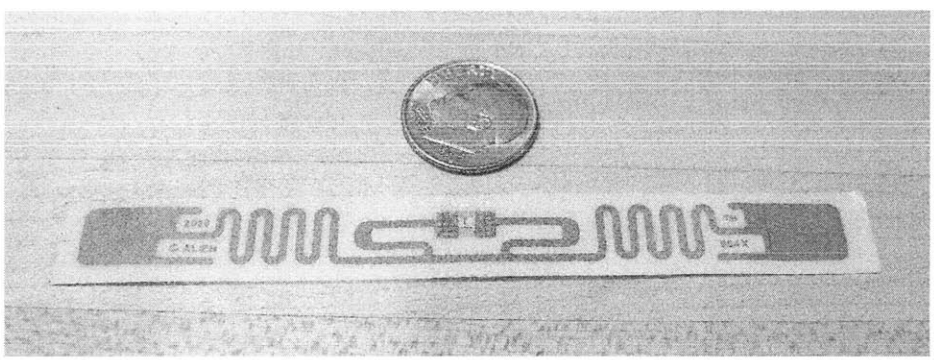

Figure 4-25: Mode changing tag

could also be put at a few reference places on the body, allowing for spatially explicit mode selections (similar to the way parts of the body were virtually tagged in Body Mnemonics [5]). Since the tag is read so rapidly, care had to be taken that the modes would not be toggled so quickly that the user would not be able to stop at the desired mode. In order to assure a certain delay in mode switching, the software records the time when the tag is read. If the tag is read again within a preset number of seconds,

| | | Actual | | | |
|---|---|---|---|---|---|
| | | Left | Straight | Right | Enter |
| Expected | Left | 20 | 0 | 2 | 0 |
| | Straight | 2 | 20 | 1 | 1 |
| | Right | 0 | 1 | 20 | 0 |
| | Enter | 0 | 1 | 0 | 20 |

Table 4.5: Confusion Matrix for Binary Hand Tilt

then the mode will not be changed. This allows ample time for the user to bring his or her hand in range of the mode switching tag, and then remove it beyond the read distance before the mode is switched away from the user's goal.

Keypad mode allows the user to visualize the gestures the system is recording on the the screen and enter text through a T9-like system. It utilizes radio buttons to indicate the orientation of the hand and has a counter that indicates the number of thumb to finger touches. It takes the orientation of the hand that it sees and uses that to select the keypad row, and takes the finger being touched to select the key. Thus the first finger would select "a,b,c" in the straight position, "j,k,l" in the left position, etc. The current selected letter is displayed next to the text box. If the hand is dipped forward, then the selected letter will be entered into the text box.

Mouse mode allows the user to scroll with tilt of the hand, and click with the mouse. Touching one finger to the thumb enables mouse scrolling. Touching the second finger creates a mouse click. Mouse scrolling and clicking works across the entire PC screen, not just the GUI command box, hence users can already operate a PC with our interface.

### 4.3.5 Gesture Tracking

Hand orientation was done with the tilt sensing method. It took the filtered acceleration and used the equations presented in Chapter 2 to calculate the angles of the different axes relative to the ground. The end results was very reliable as long as the arm was stationary and only changing its orientation. Table 4.3.5 shows the confusion matrix binary tilt for a single experienced user (the author). Tilt detection for this system was very accurate. It was used for mouse scrolling and text entry in the user interface.

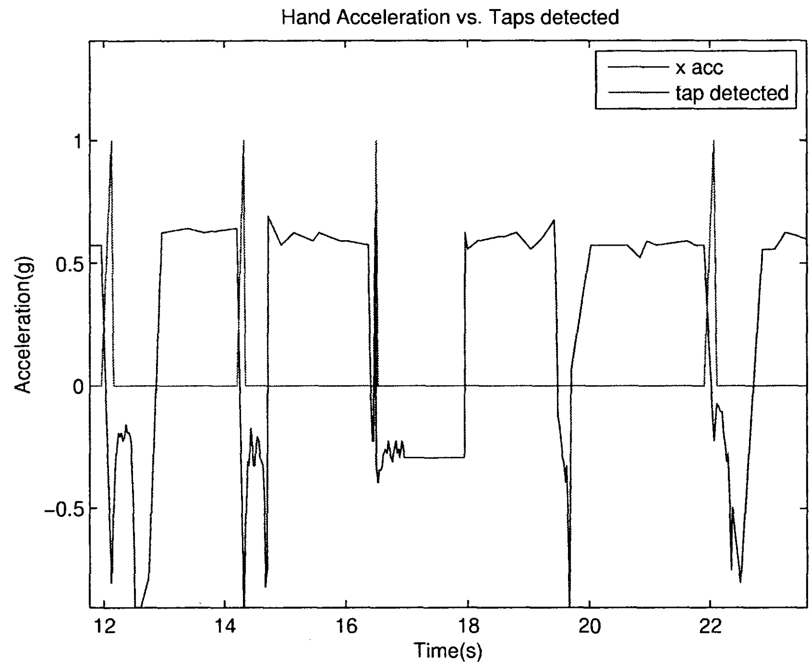


Figure 4-26: Finger tap on hard surface

Tap detection (tapping fingers against various surfaces) was done by sensing data above a fixed threshold. By observing data collected in previous projects, it was determined that the acceleration due to a tap of the finger looks like a sine wave that quickly rings back to zero, on both the x and z axes.

Figure 4-26 shows the accelerometer data along the x axis from finger tapping on a hard surface such as a table for a sample of time during one of the tests. The green line indicates when the system registers a tap, and Figure 4-27 shows the acceleration along the same axis for tapping on a soft surface, such as a leg, during a sample time in another test. The blue line is the acceleration, and the green indicates whether a tap was detected. A spike in the green line indicates a detected tap.

Our system updates too slowly to record the full ringdown, and instead we see two peaks, one positive and one negative, in rapid succession. This happens not because of the vibration, but is caused by the motion the finger goes through in the

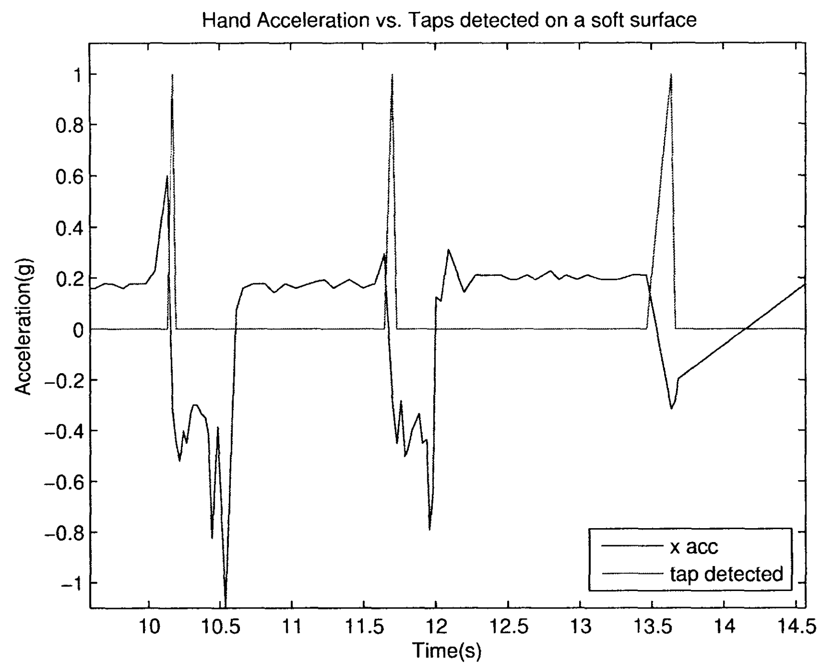


Figure 4-27: Finger tap on soft surface

process of the tap. By searching for this pattern, we can identify if the user has tapped their finger. However, detecting the peaks of finger motion up and down are not always reliable, as similar acceleration patterns can be achieved through other gesture motions. The thresholds for the detecting a tap also vary between the types of surfaces touched. Tapping on a soft surface results in a smaller deceleration, and is therefore harder to detect. The resulting tap counting algorithm will occasionally miss a tap or record an extra one, resulting in an average error rate of about 15%. An extra-counted tap is less of a problem, because it can easily be filtered out in software, if the time between the taps is so small to make the tap physically impossible. Missed taps can are more troublesome however, since a missed stroke in typing can lead to annoying errors. Better results, however, could be expected if a more sophisticated detection framework is used that exploits or is trained on several features in the data, rather than the simple ad-hoc algorithm used here.

The finger to thumb touching provided interesting information about the position

| | | Actual | | | |
|---|---|---|---|---|---|
| | | Finger 1 | Finger 2 | Chord | None |
| Expected | Finger 1 | 25 | 0 | 0 | 5 |
| | Finger 2 | 2 | 22 | 0 | 6 |
| | Chord | 5 | 6 | 19 | 0 |
| | None | 2 | 1 | 0 | – |

Table 4.6: Confusion Matrix for Finger-Thumb Touches

of the hand. The most troublesome problem encountered in the thumb-finger touches came from changing the orientation of the hand and reducing the power transferred to the WISP. Table 4.3.5 shows the confusion matrix for the finger to thumb touching and chording for two fingers by a single experienced user (the author). Touching one finger at a time was very reliable, although it was not always picked up by the reader. Chording was less reliable, since it required both reed switches being pressed at the same time. If one switch was not activated properly, then the program would register just one of the fingers be touched, and not the chord. The touch gesture was used in both mouse control and clicking, and touch typing in the user interface.

### 4.3.6 Usability

The system was tested by six different users. All of the users were students at MIT with a background in computers and engineering. They were instructed on how to put on the tags and reader, connect to and calibrate the system, and operate the system in different modes. On average they used the system for twenty minutes to a half hour. Once they were wearing the system, they were given an explanation of how the gestures were recognized for the mode they were operating in, and given a few minutes to practice with the system before being asked to try to complete a task, such as type a word or click a button. The system was not specially calibrated to them, aside from the beginning calibration for gravity and initial hand tilt.

The physical system received mixed reviews from testers. On average they rated the system a 7 out of 10 in comfortableness (Fig. 4-28), which means they felt it was pretty comfortable, however the testers did not like how long it took to put on all of the rings and the antenna, which could be as long as a minute. In fact 28.5

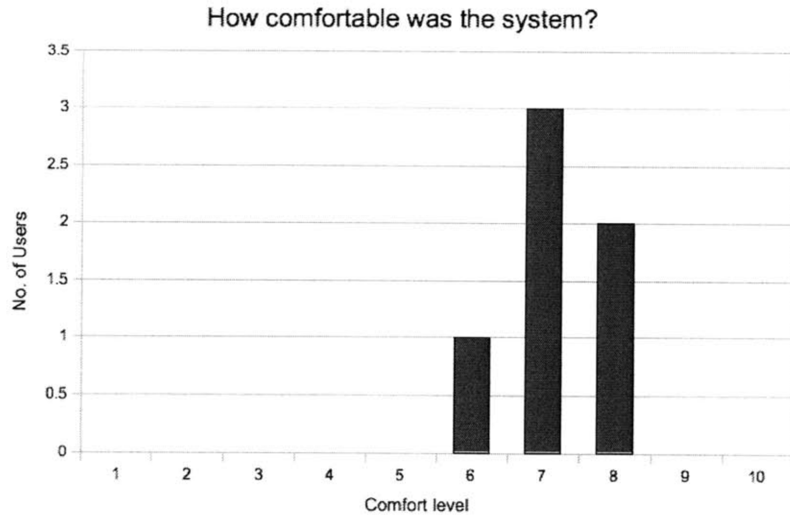


Figure 4-28: Comfort of system as rated by users (1 being the least comfortable, 10 being most comfortable)

% of testers said they wouldn't want to own something that took that long to put on. Most of the testers said they could see themselves completing other tasks while wearing the system, and all of them were able to type on a standard keyboard while wearing it.

The testers had no problem connecting with the system, however many had trouble with the calibration of the tilt sensor. They still rated the difficulty of the task at 2 out of 10, which meant they found it quite simple.

The typing mode ended up being very difficult. The testers usually rated it an 8 out of 10 on the difficulty scale (Fig. 4-29). When asked to type the word "cob," the testers took an average of 40 seconds to complete the task. This is much longer than most methods of typing, but it has been shown in the Twiddler studies that ability to type with a certain system will increase with the usage [7]. In fact the author, who spent a couple hours using the system during testing, was able to much more easily complete these tasks. The "typing" input could also be improved with better rule definition and gesture processing.

The mouse mode was the most popular among the users. They rated the difficulty of use at an average of 6 out of 10 (Fig. 4-30). Most of the problems arose from either a poor calibration, which led to poor sensitivity. When asked to navigate the

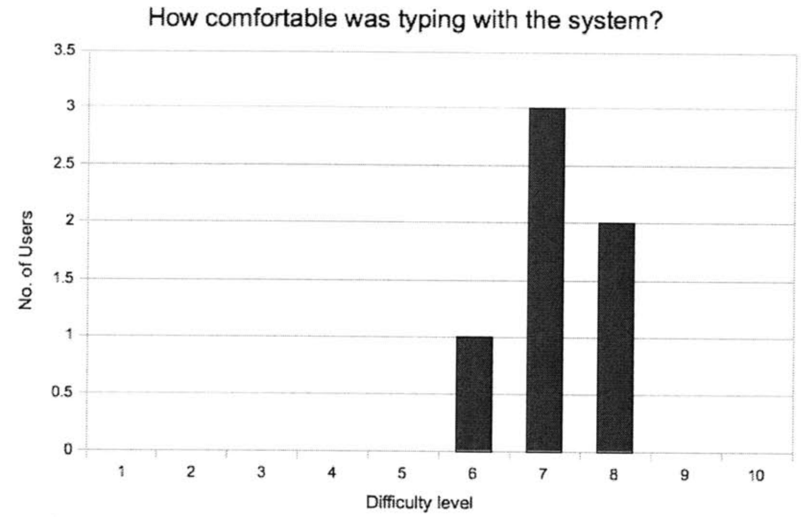


Figure 4-29: Difficulty of typing with system as rated by users (1 being the least difficult, 10 being most difficult)

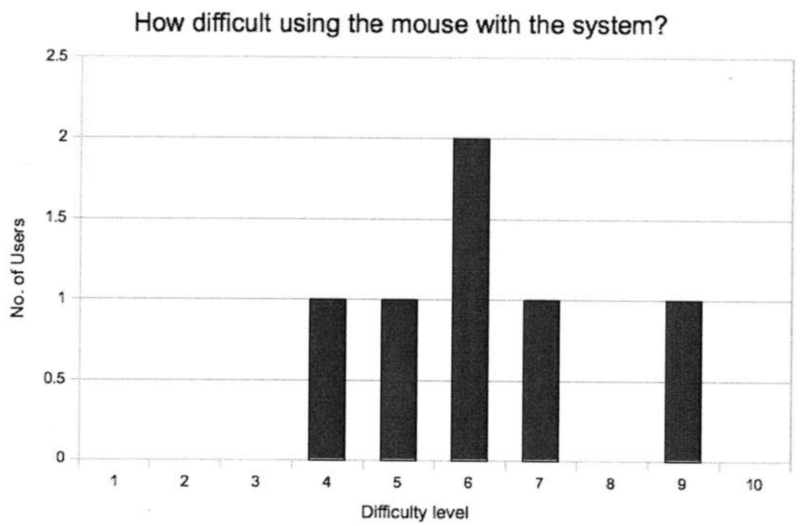


Figure 4-30: Difficulty of using mouse with system as rated by users (1 being the least difficult, 10 being most difficult)

mouse and click a button, the testers took anywhere between 30 seconds and over a minute. This part of the system would benefit the most from an ability to adjust the sensitivity of the mouse.

Overall the users found the system to be intuitive, especially for mouse manipulation. Most testers could see the system being used with a wearable interface.

# Chapter 5

# Conclusion and Future Work

A proof of concept system was completed, that reached its goal of demonstrating that useful HCI gestures could be tracked with passive RFID tags on the fingers. The gestures tracked included hand tilt, thumb-to-finger contact and fingers tapping against various surfaces. The system was small enough to be comfortable, and felt intuitive to most of the testers. However, improvements can and should certainly be made before such a system becomes truly useful.

## 5.1 Hardware Extensions

### 5.1.1 WISP

The WISP was a very useful addition to the system, and provided a great deal of information that was used to interpret a few basic gestures and implement some mouse pointing control.

A few improvements to the WISP could help our system in many ways. First, the WISP is now being made into a system on a chip. If the accelerometer could be integrated with the system, then the finger rings could be made much smaller and more comfortable. There's also the possibility that smaller antennae could be printed on the PCB with the reader, which would improve the physical integrity of the finger tags. Another group that works with the WISP has very recently started trying to integrate an planar inverted F antenna, or PIFA, on the board with the WISP. With more time to design the antenna and fabricate their own version of the WISP, this experiment should yield interesting results that will be very relevant to this project. An ASIC for this project could also take less power than the MSP430. Accelerometers are also beginning to take less power (e.g. analog conditioned passive accelerometers can take a few $\mu$A [8] and capacitor MEMS accelerometers are beginning to to approach a draw of circa 10$\mu$A or so).

If enough power can be put into the system, then the addition of a gyroscope to the WISP would greatly improve the ability to do inertial navigation. With an added gyroscope, one could now sense both the angle and acceleration of the tag, therefore allowing for the ability to better extract the position and attitude of the fingers and hand. Knowing better position could be very useful in interpreting a multitude of gestures. An extra sensor would, however, slow down the system and require more power.

### 5.1.2 Reader Antenna and Power

Since even the final system suffered from insufficient power, one could experiment with higher gain antennas on the reader. A brief search was done for higher gain antennas that would fit with the size of the system, but nothing suitable was found to be commercially available. It may be possible to include a specially-designed antenna, perhaps a dipole array, that could have a gain higher than the 2dBi of the monopole whip but not take up significantly more space.

The current reader now takes 12.5W max, which would yield operation times of 15 minutes with a cellphone battery, 2 hours and 12 minutes on a cam-corder battery, and a little less than 4 hours on a standard laptop battery.

The reader could also be integrated into the sleeve to make it more wearable. It might also be possible to drop the operation frequency to 800MHz in order to make the body more transparent to the RF waves.

If more power or body transparency could be achieved, then it may be possible to wear the tags on the upper knuckle. With an ASIC, the tags could also be made smaller.

An active tag could also be integrated. This involves a battery, but waking up on RF query and the short transmit distance from the fingers could minimize battery size, making this more an issue or convenient recharging when the system is inactive or stowed away. This would tremendously minimize the power used by the reader, making it trivially wearable.

## 5.2 Software Extensions

If the hardware adjustments were made, especially adding the gyroscopes, perhaps the tested position tracking algorithm could be applied with more accuracy, and allow for actual finger tracking. Clever software, perhaps with machine learning, may enable simple sensors on the WISP to comfortably parse a variety of gestures. One could also attempt to use a Kalman filter [10] on the output, to help eliminate noise and other error.

The user interface output's useful information about gestures, and allowed for mouse control. However, the current implementation of a PC GUI isn't the best suited application of such a wearable system. It maybe possible, for example, to take this gesture recognition and use it to control appliances or robots, as in previous similar works. It might also be feasible to extend the vibration sensing to create some kind of freeform wireless keyboard as seen with the body coupled system [15]. The taping coupled with better position sensing of the WISP with additional sensors could lead to a mobile wireless keyboard, wherever the user chose to put his or her hands. It will also be relevant in some other kind of simpler selection scheme that doesn't need full typing.

## 5.3 Possible Additions

### 5.3.1 Addition Tags and Sensors

This project only made use of two to three WISP tags at a time, so the actual interpretation of movement was rather limited. While there were some useful gestures that could be defined with our limited resources, improvements in the hardware could lead to some very interesting additions to the gesture interface.

The project was severely limited by the availability of some of the hardware. Some interesting additions could be made if either more WISPs or another reader became available. With the addition of more tags (with possibly more sensors), one could track the movement of the hand more precisely.

With the addition of tags, however, comes a reduction in speed, and an increased risk of collision or bad reads due to the large number of RF devices transmitting in one area. There was already some issue with this, with just three tags. A scheme could be developed in which tags were turned off for a certain amount of time after they were read, or otherwise synchronized, so as not to send signals that would interfere with another tag's read. This would also assure that the tag was gathering power during the period it was not being read instead of trying to transmit without being heard.

### 5.3.2 Portable Visualization

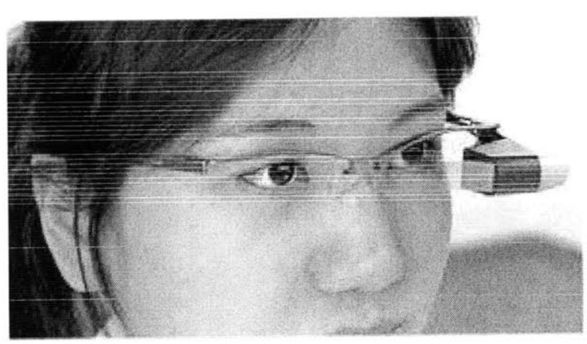

Figure 5-1: A mobile eyeglass display

Figure 5-2: An LCD eyeglass display

Fig. 5-1 shows an example of a wearable display under develoment by Brother Corporation (a prototype retinal projection device). Several eyeglass displays are presently available from companies such as MicroOptical, Microvision, and even low cost LCD eyeglasses from companies like Sony (e.g., the Glasstron). Such a display, the Vuzix iWear from Inition, is shown in Figure 5-2. When our tag system is interfaced with such wearable displays, an immersive computing paradigm is realized, where the user is continuously interacting with a dynamic information environment.

## 5.4 Summary

This project was concerned with developing a system that used active RFID tags to track the motion of fingers and hand gestures. Overall the system was functional and was able to register a few simple gestures based on movement of fingers and the wrist. It was very unfortunate the system was so limited by power, but many of these problems could be solved by better designing for the application. The nature of UHF RF necessitates that everything be matched perfectly for the best performance, which is difficult to accomplished when trying to piece together sections of hardware meant for many different applications.

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