4-2008

Ultra-Wideband Frequency Surgical Navigation Probe

Stuart J. Deaderick
University of Tennessee - Knoxville

Follow this and additional works at: https://trace.tennessee.edu/utk_chanhonoproj

Part of the Biomedical Engineering and Bioengineering Commons

Recommended Citation

This is brought to you for free and open access by the University of Tennessee Honors Program at Trace: Tennessee Research and Creative Exchange. It has been accepted for inclusion in University of Tennessee Honors Thesis Projects by an authorized administrator of Trace: Tennessee Research and Creative Exchange. For more information, please contact trace@utk.edu.
Ultra-Wideband Frequency Surgical Navigation Probe

Spring 2008 Final Written Report

BME 469

Submission: April 25, 2008

Team:

Stuart Deaderick
Lucas Groves
Ryan Hammonds
Paul VanGilder
Daniel Wells
Abstract

The goal of this project is to deliver a functioning handheld radio frequency probe to be used in surgical navigation. The probe will utilize ultra-wideband frequencies to provide accurate positioning measurements that can be used to provide better surgical outcomes. The design process will also incorporate the entire surgical navigation system including base stations and computer interface. There are four main components to the project: electrical, spatial arrangement, materials, and ergonomics. By focusing on these four main design factors and relating them all together, the design team hopes to be able to efficiently research and design the ultra-wideband radio frequency probe.
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>4</td>
</tr>
<tr>
<td>Background</td>
<td>6</td>
</tr>
<tr>
<td>Literature Survey</td>
<td>8</td>
</tr>
<tr>
<td>Patent Search</td>
<td>9</td>
</tr>
<tr>
<td>Contacts</td>
<td>10</td>
</tr>
<tr>
<td>FDA Regulations</td>
<td>13</td>
</tr>
<tr>
<td>Design Methodology</td>
<td>14</td>
</tr>
<tr>
<td>Design Alternatives</td>
<td>16</td>
</tr>
<tr>
<td>Electrical</td>
<td>16</td>
</tr>
<tr>
<td>Spatial Arrangement</td>
<td>24</td>
</tr>
<tr>
<td>Materials</td>
<td>28</td>
</tr>
<tr>
<td>Ergonomics</td>
<td>28</td>
</tr>
<tr>
<td>Description of Final Design</td>
<td>31</td>
</tr>
<tr>
<td>Electrical</td>
<td>31</td>
</tr>
<tr>
<td>Spatial Arrangement</td>
<td>35</td>
</tr>
<tr>
<td>Materials</td>
<td>39</td>
</tr>
<tr>
<td>Ergonomics</td>
<td>48</td>
</tr>
<tr>
<td>Testing and Results</td>
<td>66</td>
</tr>
<tr>
<td>Conclusions and Discussion</td>
<td>72</td>
</tr>
<tr>
<td>References</td>
<td>73</td>
</tr>
<tr>
<td>Appendix 1: Figures</td>
<td>75</td>
</tr>
<tr>
<td>Appendix 2: Tables</td>
<td>95</td>
</tr>
<tr>
<td>Appendix 3: Contact Information</td>
<td>100</td>
</tr>
<tr>
<td>Appendix 4: FDA 510(k) Application</td>
<td>Attached</td>
</tr>
</tbody>
</table>
Introduction

Surgical navigation is an emerging technology in the medical field. Medtronic, a leader in medical technology, defines surgical navigation as “a tool by which surgeons can track instruments in relation to a patient’s anatomy, track the anatomy itself, and quantify soft-tissue balancing during a surgical procedure.” Medtronic also points out the similarity between surgical navigation and global satellite positioning [1]. Prior to surgical navigation doctors had to use their best judgment when positioning instruments and other medical devices in surgery. Surgical navigation systems now offer surgeons accurate measurements that can be used during a surgical procedure to provide a better surgical outcome. The outcome of the team’s design project will provide an even more accurate tool for surgeons to use allowing greater control and confidence in surgery.

The design team’s system uses Radio Frequency to communicate between the instrument being tracked and the stations receiving the signal for computation. According to Huzaifa Al Nahas and Jitender S. Deogun of the University of Nebraska, Radio Frequency Identification uses a microchip for computation and an antenna for communication. This configuration is referred to as a tag. A signal is generated, processed, and transmitted through the antenna to be received [2].

The navigation system being designed uses ultra wideband radio frequencies for tracking instruments. Ultra wideband radio frequencies operate over a large range of frequencies. By using such a large bandwidth, ultra wideband is able to provide extremely short signal pulses which allow for very high resolution [3]. Since the signal pulses allow for such high resolution and are used for tracking instruments, the navigation system is capable of very high accuracy in determining the position of the surgical instrument.
To compute the position of the tags in the operating room, an algorithm called the Time Difference of Arrival is used [4]. This algorithm is based on the synchronization of the stations receiving the signal and the difference between the time the signal arrives at each station. This algorithm is used then the signal is processed to compute the position of the instrument in the operating room. The system uses this algorithm with the short signal pulses from the ultra wideband frequency to provide highly accurate tracking of instruments.
Background

Surgical navigation systems are already being used in the operating room in a broad range of surgical procedures including hip and knee replacements, spine procedures, neurosurgery, trauma, and various other minimally invasive procedures [5]. Current systems use infrared camera tracking to determine the position of instruments [4]. The biggest problem with these systems is the issue of line of sight; there must be a clear path between the instrument and the camera tracking equipment to provide an accurate position measurement [6]. The system being designed would eliminate the issue of line of sight by using ultra-wideband frequencies to track instruments. Not only would the surgeons be allowed more freedom in the operating room, ultra-wideband frequencies would provide a more accurate position measurement. Functioning much the same way as a Global Positioning System, the surgical navigation system would utilize base stations to calculate the position of the markers attached to the handheld probe [4]. Because of the properties of the ultra-wideband frequency used in the system, a highly accurate reading could be determined for the position and measurements made by the probe.

The design team is not developing any new technologies. The focus of the project is on developing the actual probe, while the signal generation and processing is being developed by the customers (Graduate students Mike Kuhn and Brandon Merkl).

Another focus in the design was testing how the ultra wideband tags would interact with each other to provide the most accurate readings. Using HFSS software, the radiation patterns of the antennas were simulated. This allowed the signal transmittance to be analyzed in respect to the interaction between the antennas and the material. The program was also used to test for coupling among the antennas. A Matlab program was created to determine the accuracy of the probe. This program was based on a constrained version of Arun’s method, as suggested by
Brandon Merkl. This algorithm uses the location of each antenna and the orientation of all of the antennas to pinpoint the actual probe tip location.

As discussed in further detail throughout the paper, the team has decided to use a specific thermoplastic to construct the desired medical device. Thermoplastics offer excellent resistance to heat. Additionally, high temperature thermoplastic compounds at increased temperatures offer significant retention of physical properties and dimensional stability than do normal polymer compounds. Many types of thermoplastics exist and each may be modified for flame retardance, wear resistance, conductivity, structural reinforcement, and color, to name a few. Specifically, the team has chosen to use a class of thermoplastics known as Polyketones. Polyketones are a family of high-performance thermoplastic polymers. The highly polar ketone groups in the polymer backbone of these materials gives rise to a strong attraction between polymer chains, which increases the material's melting point by up to 225 degrees Celsius [7].

Surgical navigation is already established in the medical field and is a growing technology [1]. Because the system being designed would allow more accurate measurements and better surgical outcomes, the ultra-wideband surgical navigation system would be in high demand and has enough market potential to continue further research and development.
Literature Survey

A large part of the literature survey was done on the web looking at journal articles as well as medical device companies' websites to become familiar with the topic. For example, the Stryker Surgical Navigation webpage was surveyed to obtain a basic understanding of how the system works and some of its possible applications. The website also provided the team with some insight into what a handheld probe already used in surgical navigation looks like.

The survey was very useful in providing background on how ultra wideband frequency can be applied to a system such as surgical navigation. In essence, ultra wideband contains a large bandwidth and is thus capable of generate very short signal pulses [3]. This short pulse allows for a high level of accuracy when tracking the position of the antennas.

The survey also returned information on radio frequency (RF). RF is used in many applications where the RF identifies the signal generator to the receiver. This will be used in the probe to let the base stations know which tag the signal is coming from.

The survey also returned information on materials. The properties of thermoplastics were researched to determine the factors that would contribute to choosing the appropriate material to construct the probe. The team gained a better understanding of the difference between thermoplastics and polymers which led to the decision to use a polyketone in the production of the probe [8,9].
**Patent Search**

United States Patent 5041943: Hermetically sealed printed circuit board

This patent was for a system to seal circuit boards. The patent claims to hermetically seal in the components on a printed circuit board. This would be useful for when the probe must be autoclaved.

United States Patent 6756766: Autoclavable Battery Pack

This patent was referenced for its information on batteries that are able to be run through an autoclave. Because the probe must be sterilized between uses, the power supply must also be able to withstand the conditions of an autoclave. The patent states that any battery type including the lithium ion batteries in the probe design can be used.

United States Patent 6827723: Surgical navigation systems and processes for unicompartmental knee arthroplasty

This patent gave information on how instruments are tracked in the operating room and gave insight into the computer support system that will function in accord with the probe. This patent was written in reference to a surgical navigation system to be used in a Unicompartmental Knee Arthroplasty which is an application that would be appropriate for the probe being designed.
Contacts

Appendix 3 contains full contact information. Company name and address are listed below.

Mike Kuhn, Brandon Merkl and Dr. Mohammed Mahfouz
University of Tennessee
Mechanical, Aerospace, and Biomedical Engineering Department

These graduate students and professor were consulted throughout the course of the design process.

Materials:

BMJ Mold & Engineering Co.
P.O. Box 2676
Kokomo, IN 46904-2676

This company was contacted in order to confirm that PEEK, the plastic being used to construct the probe capsule, could be shaped using a pre-designed casting mold.

Boedeker Plastics, Inc.
904 West 6th Street
Shiner, Texas 77984 USA

This company was contacted in order to receive a price quote for the team’s finished prototype.

Advanced Industrial
11020 Bailey Rd.
Cornelius, NC 28031

This company was contacted in order to receive a price quote for the team’s finished prototype.

Röchling Sustaplast LP
216 Philips Road
Exton, PA 19341

This company was contacted in order to receive a price quote for the team’s finished prototype.
Solvay Advanced Polymers, L.L.C.
4500 McGinnis Ferry Road
Alpharetta, GA 30005-3914 USA

This company was contacted in order to receive a price quote for the team’s finished prototype.

Oxford Polymers
221 South Street
New Britain, CT 06051

This company was contacted in order to begin the process of constructing a working prototype. The team was referred to a different corporation.

Oxford Performance Materials
120 Post Rd.
Enfield, CT 06082 USA

This company was contacted in order to complete the process of constructing a working prototype. Company knows the team’s goals and is ready to continue on with project once contact has been reestablished.

Tools for Working Wood
32 33rd Street 5th Floor
Brooklyn, NY 11232

This company was contacted in order to purchase a stainless steel trammel point that will be used for the medical device’s probe tip.

Cotronics Corporation
131 47th Street
Brooklyn, NY 11232 USA

This company was contacted in order purchase epoxy needed for the adhesion of the team’s antennas.

Electronics:

Micro Power Electronics, Inc.
13955 SW Millikan Way
Beaverton, OR 97005
This company was contacted regarding the use of their batteries that can be autoclaved.

No response was received.

Tronser, Inc.
3066 John Trush Jr. Blvd.
Cazenovia, NY 13035

Tronser was contacted about fabricating the electronics housing. They said they could fabricate the housing.

Memtron Input Components, Buttons
530 North Franklin
Frankenmuth, MI 48734

This company was contacted about making the button system for the probe. They told the team that they could make a button system for the probe.

Pasternack Enterprises
purchasing@pasternack.com

The team ordered the SMA connectors for the antennas from this company.
**FDA Regulations**

After conducting searches of 510(k) documents for surgical navigation it was determined that surgical navigation systems are class II medical devices. Devices from Stryker Corporation, Pathfinder therapeutics, Inc, BrainLAB USA, Inc., and Medtronic Surgical Navigation technologies were surveyed to determine not only characteristics that could be applicable to the probe, but what is needed in a 510(k) application for a surgical navigation probe. There are several FDA regulations that apply to the probe. Title 21, Chapter I, Subchapter H of the Code of Federal Regulations applies to medical devices. Section 880 on general hospital devices, section 882 on Neurological devices, and section 888 on orthopedic devices were among the sections referenced in filling out the 510(k). Medical devices such as the probe must be able to be sanitized. The probe will be autoclaved to allow proper sanitation. Another consideration for the FDA is biocompatibility. The only portion of the probe to come in contact with the patient is the stainless steel probe tip which is substantially equivalent to previously approved devices. Another applicable section of the code was on electromagnetic compatibility and electrical safety. The probe is within all of the limitations set forth by the FCC as discussed in the IEEE Ultra Wideband Tutorial [3].

A 510(k) application was filled out to get the ultra wideband probe approved by the FDA. The guidance document for industry and FDA staff titled “Format for Traditional and Abbreviated 510(k)s” was followed to ensure all applicable sections of a traditional 510(k) application were included. This guidance document is available on the FDA website. The 510(k) application for the ultra wideband probe is attached as appendix 1.
Design Methodology

The approach to designing the handheld probe can best be described as a team effort. The team consists of five members each with a specific role that integrates into the project as a whole. Each of the four main design areas is led by a “specialist” on the topic. Competency and knowledge in the field was not a prerequisite for leading a certain design area, but a thorough understanding of the topic is being acquired as the project progresses. The final team member acts as a team leader and coordinator between the design areas. The team leader is not only in charge of scheduling and conducting meetings, but also providing background and keeping the overall design goals in perspective.

The most important part of this team is communication between all the members. While each member has a specialty area, they are not confined to simply working in that area. There is a large amount of overlap between the design areas which is addressed by team members communicating and working together on certain aspects of the project. This team effort ensures that all steps of design are fully thought through.

The team used the quality function deployment plan (QFD) in Table 1 to prioritize customer needs with engineering constraints.

<table>
<thead>
<tr>
<th></th>
<th>Transmit Signal</th>
<th>Battery Location</th>
<th>Sterilization Capability</th>
<th>RF Tag Location</th>
<th>Compatible Bone Tag vs. Probe</th>
<th>Ambidextrous</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Ease of Use</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Ergonomics</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Durability</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Autoclaving</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Battery Charge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Quality Function Deployment
This provided the team with a basic guideline for designing the probe by allowing certain design features priority over others as well as showing which customer need affected each engineering constraint. The QFD forced each team member to consider how the design area they are in charge would factor into the final design as well as how it would affect other design areas. The most important consideration in designing the probe was accuracy. The customers specified this consideration to be their main interest. Therefore, the highest priority was given to accuracy and certain other aspects of the design were sacrificed to ensure the greatest accuracy.

The team met fairly regularly once the project began. Progress in each design area was discussed and future plans were laid out. It was always stressed that interaction between design areas was a must and the team actively fulfilled this obligation. Meetings were conducted in an informal but structured manner allowing all team members to easily express their ideas and concerns about all aspects of the design process. The team also met often with the graduate students overseeing the project. This resource provided the team with some much needed direction throughout the design process and was also a source of reference when a problem arose that the team was unable to solve with their own knowledge base. An example of this reference is in the use of the computer software used to analyze certain parts of the design.
Design Alternatives

I. Electrical

Power Source

The buttons, LED, and UWB components all require a power source to function. Several considerations were taken into account when determining how to power to the handheld probe. Many different power sources were discussed and investigated. AC power from a wall outlet was never a viable alternative for a few reasons. A power cord is not inherently portable, a major detraction for a portable, hand-sized device. In addition, a power cord would be a cumbersome distraction to the doctor during surgery, and could potentially impede the effectiveness of the probe by getting in the way. Having a power cord would also necessitate an outlet being near enough the probe during use to allow it to be plugged in. With the improvements in battery technologies and the low power required by the probe, AC power would only hinder the implementation of the probe. After eliminating AC power as a design choice, the team focus turned to batteries.

The obvious next choice is some sort of battery or battery pack. Batteries make portability possible while still providing the necessary power to run the device. The next step was determining the most suitable battery for the team’s purposes. The three main types of batteries investigated were traditional alkaline batteries, nickel based batteries such as nickel cadmium (NiCd) and nickel metal hydride (NiMH), and lithium ion batteries (Li-ion). The main drawback of alkaline batteries is their need to be replaced after long periods of usage from loss of charge. The bulkiness of typical alkaline batteries would require a larger probe casing to fit the battery inside. Rechargeable alkaline batteries are available, but they suffer from the same bulkiness as regular alkaline batteries. Rechargeable alkaline batteries also suffer from
decreasing capacity with each charge-discharge cycle, meaning diminished performance with time. In addition they have a limited ability to handle current, and are best suited for lighter duty applications, such as flashlights. For these reasons alkaline batteries were not considered as suitable power sources for the surgical probe [10].

The two leading types of chemistry used in rechargeable batteries are nickel based and lithium based. There are two main styles of nickel-based batteries, Nickel-Cadmium and Nickel-Metal Hydride. NiCd batteries use nickel oxide hydroxide and metallic cadmium as electrodes. They are a very robust battery, more difficult to damage than other rechargeables. In consumer products they compete directly with alkaline batteries, with the added lifespan due to their rechargeable nature being a large advantage. If treated properly, NiCd batteries can provide over 1000 charge/discharge cycles. This life span off sets the slightly higher up front cost of the batteries. Fast charge is preferable in NiCd batteries because it improves battery life and effectiveness. Charging the batteries for prolonged periods will cause serious damage to the battery. If a NiCd battery experiences overcharging, severe battery damage can occur. Loss of the battery’s maximum energy capacity (called the memory effect) can occur due to cadmium crystal formation. The cadmium in the cell is present as small, fine crystals. With overcharging, new crystals can form and grow on the electrolyte within the cell. These increase internal resistance, thus depressing voltage and resulting in a rapid discharge. Though all rechargeable batteries have a finite life span and will lose a small amount of storage capacity each cycle, with the memory effect this process can be accelerated, causing a drop in battery performance and decreased time between cycles. Many battery manufacturers prevent this from happening by integrating a thermal charge cut-off. During charging, an endothermic process, the battery remains cool; as the battery nears full charge the battery temperature will raise. At a certain
temperature the charger will shut off, signaling full capacity. When fully charged, NiCd batteries have about 1.2 V per cell, which is the lowest of the batteries investigated, but NiCd batteries maintain a relatively stable terminal voltage during discharge. Other batteries experience a voltage drop during use that falls below 1.2 V, making NiCd a consistent choice. Since NiCd batteries have been around longer than other rechargeable battery technologies, their cost is relatively low. Disadvantages of NiCd batteries are their low energy density relative to other rechargeable batteries (namely NiMH and Li-ion) and a somewhat high self-discharge rate when not in use [10].

The nickel-metal hydride battery is the other nickel-based technology for rechargeable batteries. The only chemical difference is the use of a hydrogen-absorbing alloy instead of cadmium for the electrode. This eliminates the possibility of crystal formation and the memory effect from disturbing battery performance. The use of a metal alloy rather than cadmium makes the batteries more stable during storage and transportation, as well as being more environmentally friendly. NiMH batteries have the same nominal voltage compared to NiCd, but up to 40% more energy density. However, this improved energy density comes at the cost of durability. Using NiMH batteries at high load reduces their lifespan, which is already lower than NiCd at about 200-300 cycles. These batteries also have a time-limited life span of about three years, depending on ambient temperature. Higher temperatures reduce the life span of NiMH batteries more quickly. NiMH batteries also suffer from a high self-discharge rate, so they cannot be stored for long periods in a device without charging. Charging NiMH batteries takes longer than NiCd, but can reach full charge in 2 to 4 hours. NiMH batteries are also more expensive than NiCd [10].
The third type of battery researched was Li-ion, the newest of the three technologies and also the most expensive. Li-ion batteries are made using a nonmetallic graphite anode, a metal oxide cathode, and lithium ions. As the lithium ions are transported back and forth between the cathode and anode, the transition metal is oxidized during charging, and the reduction of this metal provides the electricity during discharge. There are a multitude of advantages of Li-ion batteries. The low atomic mass of lithium means the batteries are lightweight, and have nearly twice the energy density of NiCd batteries and significantly more than NiMH. Li-ion batteries have a higher cell voltage, 3.6 V, than either of the nickel based chemistries, meaning battery packs can be designed with only one cell. Unlike the nickel based batteries, Li-ion requires much less maintenance. The memory effect is not an issue with Li-ion batteries, and the discharge rate is lower than that of either NiCd or NiMH. Li-ion batteries can also be made in a multitude of shapes and sizes, which makes them easier to integrate into the design of the probe. The major drawback of Li-ion batteries is its fragility. Li-ion batteries have circuits to protect them from discharge below a threshold voltage. Irreversible damage can occur if the battery discharges too much, so a circuit is integrated into the battery to prevent cell voltage from dropping too low, and to limit peak voltage during charging. Capacity deterioration is continual from the moment the battery is made and the batteries typically fail after 2 or 3 years. This life span can be increased through proper treatment of the battery. Temperature has the biggest effect on battery life, with higher temperatures degrading batteries faster. At prolonged high temperatures, Li-ion batteries can be volatile, leading to rupture or explosion. Despite the drawbacks, Li-ion is the battery of choice for mobile technology, some power tools, and many types of medical equipment [10].
When deciding on the power source for the probe, NiCd, NiMH, and Li-ion batteries were the main contenders. Calculating the power consumption of the electrical components was the first task. The total power consumption for the tag architecture is 145 mAh at 6 V. The design utilizes a small LED on the probe that will signal that the device is turned on. LEDs are more energy efficient than other bulbs, and are also easier to fabricate on a small scale. The LED chosen operates at 20mAh at 5V (0.1 W) or 16.67mAh at 6V. This combined with the power requirements of the tag means the team needs 161.67mAh at 6V. In order to power the probe for at least an hour, a battery is needed with a power rating at least that high. Knowing the power consumption of the probe allowed the team to know how much power the battery needed to provide. A comparison chart comparing energy density, life cycle, cost, efficiency, size, power, and other factors of the three different types of batteries was created in order to determine the best choice for the probe (Table 2).
<table>
<thead>
<tr>
<th></th>
<th>Nickel-cadmium</th>
<th>Nickel-metal-hydride</th>
<th>Lead-acid sealed</th>
<th>Lithium-ion cobalt</th>
<th>Lithium-ion manganese</th>
<th>Lithium-ion phosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric Energy Density (Wh/kg)</td>
<td>45-90</td>
<td>60-120</td>
<td>30-50</td>
<td>150 - 190</td>
<td>100 - 135</td>
<td>90 - 120</td>
</tr>
<tr>
<td>Internal Resistance in mΩ</td>
<td>100 to 2001 6V/pack</td>
<td>200 to 3001 6V/pack</td>
<td>&lt;1001 12V/pack</td>
<td>150 - 3001 pack 100 -130 per cell</td>
<td>25 - 75² per cell</td>
<td>25 - 50² per cell</td>
</tr>
<tr>
<td>Cycle Life (to 80% of initial capacity)</td>
<td>1500²</td>
<td>300 to 5002 3,4</td>
<td>200 to 300³</td>
<td>300 - 500³</td>
<td>Better than 300 - 500³</td>
<td>&gt;1000 lab conditions</td>
</tr>
<tr>
<td>Fast Charge Time</td>
<td>1h typical</td>
<td>2 to 4h</td>
<td>8 to 16h</td>
<td>1.5 - 3h</td>
<td>1h or less</td>
<td>1h or less</td>
</tr>
<tr>
<td>Overcharge Tolerance</td>
<td>moderate</td>
<td>low</td>
<td>high</td>
<td>Low. Cannot tolerate trickle charge.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-discharge / Month (room temperature)</td>
<td>20%⁶</td>
<td>30%⁶</td>
<td>5%</td>
<td>&lt;10%⁶</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell Voltage Nominal Average</td>
<td>1.25V</td>
<td>1.25V</td>
<td>2V</td>
<td>3.6V 3.7V</td>
<td>Nominal 3.6V Average 3.8V</td>
<td>3.3V</td>
</tr>
<tr>
<td>Load Current peak best result</td>
<td>20C 1C</td>
<td>0.5C or lower</td>
<td>5C 0.2C</td>
<td>&lt;3C 1C or lower</td>
<td>&gt;30C 10C or lower</td>
<td>&gt;30C 10C or lower</td>
</tr>
<tr>
<td>Operating Temperature °C (discharge only)</td>
<td>-40 to 60°C</td>
<td>-20 to 60°C</td>
<td>-20 to 60°C</td>
<td>-20 to 60°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance Requirement</td>
<td>30 to 60 days</td>
<td>60 to 90 days</td>
<td>3 to 6 months¹¹</td>
<td>not required</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>Thermally stable, fuse recommended</td>
<td>Thermally stable, fuse recommended</td>
<td>Thermally stable</td>
<td>Protection circuit mandatory; stable to 150°C</td>
<td>Protection circuit recommended; stable to 250°C</td>
<td>Protection circuit recommended; stable to 250°C</td>
</tr>
<tr>
<td>Toxicity</td>
<td>Highly toxic, harmful to environment</td>
<td>Relatively low toxicity, should be recycled</td>
<td>Toxic lead and acids, harmful to environment</td>
<td>Low toxicity, can be disposed in small quantities</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Battery Comparison Chart [10]

After comparison, Li-ion was initially chosen as the power source. The high energy density made it ideal for the desired application, where size and weight are important for the usability of the probe. The ability of Li-ion batteries to be made in many shapes eases the design process by allowing the battery to be made to fit the design, rather than vice-versa. The low maintenance of the battery reduces the overall maintenance on the probe, improving usability. The bulkiness of NiCd batteries was the biggest disadvantage compared to the others, as well as the need for well-monitored charge/discharge cycles. NiMH batteries showed improvements over NiCd in the energy density category, but their short life span and high self-discharge rate...
were major drawbacks. Research into the power sources of other medical devices supported this
decision, as lithium technology is the chemistry of choice for handheld devices.

Initially the team decided rechargeable batteries would be the best solution for the probe
for a couple of reasons. Operating rooms would not need to keep extra batteries around to
replace old ones, as would be the case with alkaline batteries. Rechargeable batteries would also
be able to be recharged to full capacity while not in use, meaning the probe would be able to
function at full or near full power throughout the surgical procedure. There are many varieties of
rechargeable batteries, with a main difference being the time it takes to recharge. Fast charge
batteries can typically be charged to full capacity in about an hour, whereas slow charge batteries
require anywhere from four to 14 hours. Fast charge batteries would make it possible for the
probe to be used at full charge more often during a given day due to the short charge time [10].

Once the decision was made to use Li-ion batteries, further research into their application
within the design was necessary. There are different types of metals used within Li-ion batteries
as the cathode: cobalt, manganese, nickel-cobalt manganese, and phosphate. The differences
between the cathodes are summarized in Table 3.
The different metal chemistries balance high energy density and high load capacity, depending on the requirements of the system. NCM and manganese tolerate higher temperatures better than traditional cobalt based Li-ion batteries. NCM based batteries are a newer technology, and therefore much more expensive. They are not readily available for many uses, since the technology is still under development. For this reason, a manganese based battery was chosen for the design [10].

The autoclave process presents a design constraint that has a large effect on the battery. Since nickel and lithium battery chemistries are temperature sensitive, the battery needs to be able to be easily removed, or include some sort of insulation to protect it. This problem was solved by Eagle-Picher industries, which has created an autoclavable battery pack that is compatible with Li-ion battery technology. The company has been in the battery business since 1922 and is a leading supplier of medical batteries. Using their technology, autoclavable Li-ion battery power is possible for the surgical probe.
II. Spatial Arrangement

The spatial arrangement of the tags is an important issue to address to ensure the accuracy of the navigation. The goal in mind when determining the number of tags and spatial arrangement of the tags was to minimize the error while ensuring the arrangement was reasonable enough to be implemented. Each individual tag was analyzed using an average error of two millimeters.

The first constraint presented was the minimum number of tags. In order to constrain the three-dimensional location of the probe tip relative to the tags, a minimum of four tags was to be used. The second constraint presented was the maximum number of tags. In order to ensure the ease of design and build of the probe, it was agreed upon by the team that no more than six tags could be used. This is a result of the conclusion that more tags would complicate the electric system without any substantial advantage gained in reduction of error in the true location of the probe tip. Additionally, the team agreed that more than six tags would begin to crowd the limited space within the probe where the electrical system and the tags were to be located.

In order to analyze the different spatial arrangements using between four to six markers, a method needed to be determined. The method used for this analysis was Arun’s method. It is a constrained version of an affine transformation. While an affine transformation takes into account rotations, translations, dilations, and shears, the Arun method accounts for rotations and translations [11]. This is a reasonable analysis method as the tags relative to their probe tip will be subjected to many rotations and translations. Further, it is reasonable to not utilize the full affine transformation because the rigid probe will not be undergoing dilations and shears.

Matlab software was used to analyze the arrangements as it could perform many computations without extreme difficulty. Using a function in Matlab that performs the Arun
method, various spatial arrangements with four to six tags were analyzed. The spreadsheet shown in Table 4 illustrates the effectiveness of each arrangement tested in minimizing the error. This spreadsheet shows the effects of varying distance between tags on the amount of error incurred. The graphs shown in Figures 1 and 2 created by the data in Tables A1 through A9, in the appendix, illustrate the lack of effects on varying the distance between the probe tip and the nearest tag. The concern of length is virtually irrelevant as compared to the effects the tag geometry has on the error. One can observe this by the nearly horizontal lines created by the graphs displayed in Figures 1 and 2.
Table 4: This table displays the average ($\mu$) of 600 random samples of rotation and translation in locating the location of the probe tip. Also shown is the standard deviation ($\sigma$) between each 100 samples. The small, medium, and large designates the distance between the tags. Each spatial orientation is represented in the figures section of this paper for reference. All measurements are in millimeters.
Figure 1: This figure plots the errors for each spatial arrangement analyzed using Matlab. The x-axis represents the varying distance between the probe tip and the nearest tag. The observance of relatively horizontal represents little effect of distance between the probe tip and the tags on the error.

Figure 2: This figure is an isolated portion of Figure 25 that allows one to better see the lack of effect that varying distances between the probe tip and its tag. This figure shows three spatial arrangements with each analyzed at three different distances.
III. Materials

Material selection is a key component of the probe design. Therefore, many considerations needed to be investigated in order to choose a specific material for the probe construction. Initially the team discussed the idea of glass being the outer covering of the probe. Glass would provide a sturdy, protective case for the electrical components inside. Additionally, glass would ideally produce neither degradation of signal strength nor an unwanted frequency shift. However, it is believed that by using glass as the construction material many problematic situations would arise during assembly. If glass were to be used, the glass casing would have to be annealed. And, since the electrical tags must be within the casing, it can accurately be assumed that the annealing process would harm, if not destroy, the tags as they are being closed within. So, an alternate method of casing the tags within the glass covering would have to be utilized. Even if a reasonable method were proposed, the team believes that the projected method cannot protect the glass enough to keep it from breaking. Also, the expense of this proposed method of capsulation could be reduced by selecting a different material. For these reasons, glass capsulation was removed from the list of possible materials. In addition to exploring glass as a possible material for construction, other hermetic materials such as metal were considered. Although some of the troubles from above could be eliminated, other similar and predictable problems could and would most probably present themselves.

IV. Ergonomics

The idea of an LCD screen was discussed. One thought was that it would be a good idea for the doctor to be able to see the bone being mapped out while the points were being taken. That visibility would obviously be a benefit. Though this would be a neat thing to put in, there
would be a few significant disadvantages. The first would be the space needed. The team wants the device to be as small as possible, but an added LCD screen would cause the device to be significantly bigger. The LCD screen would have to be big enough to be visible, or else it is useless. This means that the screen would have to be larger than the space the device has to accommodate it. Also, the LCD would require significant power consumption. The probe works on a very low power system as it stands without the screen. Only a small battery is needed. However, an LCD screen would boost the power consumption, calling for a larger battery, which would also consume space. Ultimately, it was decided that the LCD screen, though sleek, would cause too much burden to the device, and it was left out.

Many of the products examined were considered, but decided against. For instance, Figure 3 shows an actual RF probe developed by Stryker. This probe has the same disadvantage as the gun in Figure 4: minimal control.

![Figure 3: Stryker Surgical Navigation Probe](http://www.stryker.com/en-us/products/OREquipmentTelemedicine/SurgicalNavigation/SurgicalNavigationSystems/NavSuite/006104)
Though this is probably the most comfortable fit, it is much harder to control the tip. The tip would be the part touching the bone, and therefore there needs to be considerable control over it. Holding a device in this way was decided to have the least control, and because of that, this idea was discarded. Making the device smaller was decided against due to the goal of making a sleek device. Also, a very small pen-sized object would not necessarily accommodate all surgeons.
Description of Final Design

I. Electrical

Electrical Components

The surgical navigation probe being designed utilizes ultra-wideband radio frequencies for localized indoor positioning. Ultra-wideband (UWB) technology became an area of interest when the FCC opened the 3.1-10.6 GHz and 22-29 GHz frequency bands in 2002. UWB signals transmit information over a large bandwidth, with information modulated by pulses through UWB antennas. These pulses are essential to the UWB system, and generally utilize fixed widths and shapes, which are created by a pulse generator. Very narrow pulses enhance system performance by improving range resolution with high bandwidth. Using hyperbolic positioning, or Time Difference of Arrival, a base station can detect the UWB sensor position with high accuracy. Sub-millimeter accuracy has been shown to be possible for 1-D, and centimeter accuracy in 2- and 3-D. Potential higher accuracy is achievable through advanced signal manipulation techniques, which will be discussed further [4].

The system being designed uses a carrier signal that resides at the upper end of the 3.1-10.6 GHz band at 8 Ghz. The upper end of the band reduces the RF wideband components used in the transmitter and receiver. A very narrow (300 pico-second) Gaussian pulse is created by a step-recovery diode based pulse generator. This pulse modulates the carrier signal through an UWB monopole antenna (Figure 5) [12].
Multiple base stations within the indoor environment (in this case, an operating room) receive the modulated pulse signal through a Vivaldi antenna (Figure 6).

The signal is then passed through a low noise amplifier and demodulated to I/Q signals. The I/Q signals go through a low pass filter and are sub-sampled with an UWB sampling mixer. This extends the signals to a larger time scale (μs) without affecting the pulse shape. In order to achieve mm-range accuracy, the mixer achieves sampling rates of 100 GS/s or greater. The last step is conversion of the signal using an analog to digital converter [4].

**Electronics Housing**

One of the main design problems the team encountered was the autoclave. Since the circuit board controlling the antennas is sensitive to water and heat, it needed to be able to
removed before the sanitation process could begin. With this in mind, a stainless steel electronics housing was designed. This housing serves two functions: providing a place within the probe for the electronics to be securely located while in use and also creating a “package” that could easily be removed from the probe entered the autoclave. The housing can be seen in Figure 7.

![Figure 7: Electronics housing](image)

Looking at the box, the circuit board would rest on the beige surface in the middle of the box. The holes on the sides of the box are where the six SMA connectors would be attached. These SMA connectors would run from the antennas to box by an RF coaxial cable. Since the autoclave process would not affect the performance of the antennas or the coaxial cable, the SMA connections on the box can easily be removed from the box so it can be taken from the probe [6]. A lid (not pictured) would screw onto the top of the box, effectively sealing the circuit board inside. On the suggestion of Alex Zhang, an engineer in the University of Tennessee antenna lab, Tronser Inc. was contacted in order to fabricate the electronics box. Jim Dowd, an engineer with the company, gave his approval of the above design. He provided a cost estimate to the group also. After an initial setup fee of $250, construction of each housing would cost $20
and the lid would cost $7.50 if less than twenty pieces were to be made. If more than 20 were to be made, the setup fee would be eliminated.

**Input System**

In order to control the device, some sort of input mechanism is necessary that could either withstand the autoclave or be removed like the electronics box. Removing the buttons would be impractical and affect the ability of the probe to be sterilized, so integrating them into the probe would be necessary. This required finding a button system that could withstand the autoclave. Memtron Input Components creates customized button systems and specializes in medical devices. They offer a multitude of different conformations for all different applications. The team decided to use their tactile membrane switch for the probe design (Figure 8).

![Figure 8: Tactile Membrane Switch [13]](image_url)

This switch is constructed to withstand harsh environments, like the operating room and autoclave. Using a polyester overlay, they can be embossed with multi-colored graphics for clear operational use. A raised polyester bubble offers feedback to the user about button activation. The buttons are expected to last for 5 million activations, which would give them a life of about 2-3 years, according to the company. There are also a multitude of technologies
available for communication with the other electronics within the probe, such as RF and infrared. Since they are custom built, it is possible to specify the purpose and layout of each button [13]. Currently four buttons are being incorporated in the probe: a power switch, a selection switch for choosing individual points, a trace button allowing the surgeon the ability to trace and store multiple body points, and an undo button in order to “erase” accidental or unnecessary point selections.

**Power Source**

A change in power supply was also necessitated. To comply with the customers’ wishes, and also due to increased power requirements, two AAA alkaline batteries were chosen to provide power. Since the electronics will be removed prior to autoclaving anyway, this did not constrain the battery choice. The housing for the batteries will attach alongside the electronics box, supplementing the “electronics package” idea and facilitating an easy removal of all moisture-sensitive components. Also, despite the need to replace used AAA batteries, they are the least costly battery alternative, and do not require special battery manufacturers to purchase.

**II. Spatial Arrangement**

Due to the effectiveness in the prism’s reduction of error, this spatial arrangement geometry was originally chosen for use in the probe. The prism is shown in Figures 9, 10, and 11.
Figure 9: Prism orientation of markers (side view)

Figure 10: Prism orientation of markers (perspective view)
One can notice the drastic effectiveness of the prism orientation in reduction of the error in comparison to all of the other spatial arrangements analyzed by examining Table 4 on page 26. Additionally, one can notice that the small, medium, and large distances between tags produced significantly less error than all of the other arrangements which produced more error than these spatial arrangements.

A concern arose during the research about a possibility for the error to be magnified as the distance between the probe tip and the tags increased. Therefore calculations were performed producing results shown in Tables A1 through A9. These nearly constant averages for each spatial arrangement under the $\mu$ column show that the error is not affected at any significant level by the distance between the probe tip and the tags.

As a result, since the geometry of the spatial arrangement was the main determining factor in the error produced, the prism was used. This orientation is illustrated in Figures 9, 10,
and 11. Since the calculations shown in the tables discussed were calculated with small equaling two centimeters, it is known that the tags in reality cannot be placed any closer than that and any concern regarding an increase in error should the tags be in the immediate presence of other tags can be neglected. Yet, the electrical properties must be analyzed to ensure that coupling by the tags’ signals do not cause more error than desired. Further, the large category used for error analysis is much larger, at two meters, than the team will be designing the actual probe. This leaves the design left with addressing interference by the tags themselves to investigate.

After investigation of the possible interference cause by the tags themselves, it was determined significant coupling was occurring. Therefore, adjustments were made to the design. While keeping the general prism design, its exact dimensions were tweaked in order to investigate the best orientation to minimize the coupling effects. Then, the accuracy was checked if it was determined to be a good candidate. The final orientation decided upon by the group was the staggered prism aligned as shown in Figure 12. This staggered conformation results in increasing the error by only 0.1 millimeters relative to the previous traditional prism conformation.
III. Materials

After deselecting materials such as glass, steel, and other metals, the team decided that the capsule needed to be constructed from a plastic. Plastics are less expensive than most materials, do not require annealing, and seem to be easier to construct while protecting the tags. Furthermore, the list of possible materials can be made smaller because of the autoclaving process. As material possibilities were examined, four considerations were explored thoroughly. The first consideration was whether the material could endure autoclaving. Obviously, the probe has to be able to be sanitized. Autoclaving conditions were selected as the most extreme conditions under which the probe was to be exposed. Therefore, if the probe could endure multiple autoclave cycles, the probe could be easily sanitized by the operating room’s method of choice. This condition was therefore the first to be explored. Easily deducible, if a plastic is going to be used to construct the probe’s capsule, it must be able to survive extreme heat.
Plastics that show either minimal or no degradation during heating are known as thermoplastics due to their high melting temperatures. From a list of thirty commonly known thermoplastics, a list of eight possible thermoplastics that could be used for construction was created [8]. The list was as follows: Polypropylene, Polyethylene, Acrylonitrile butadiene styrene, Polycarbonate, Polyamide, Polyetheretherketone, Polyphenylene sulfide, and Liquid Crystal Polymer.

Along with minimizing degradation, the material must maximize transmittance. The permeability, therefore, must allow for the signal to be transmitted freely from the probe. All the plastics researched from the proposed list above allow the signal to pass with negligible effect on strength and shift. Radio frequencies are able to pass through objects in the operating room. Ultra-wideband frequency was chosen for this project because it allows for the most accurate signal that can pass through all the selected candidate plastics. Another consideration that was investigated was the materials’ biological safeness. Once again, each of the eight selected thermoplastics is considered biologically inert under normal conditions of the operating room and an autoclave. By this, it is meant that if the patient were to come into direct contact with the probe, none of the selected plastics would have adverse affects on a patient in surgery. The final consideration that was observed was the material’s ability to adequately seal off all electronics. The selected plastics are all capable of being molded into any shape, which would allow any configuration of electronics to be contained.

Since the selected eight thermoplastics all adequately qualify as a plausible material for construction of the probe, the material that overall seems to out perform the others was selected [9]. This material is Polyetheretherketone, also known as PEEK. PEEK, like the other seven thermoplastics, has excellent chemical resistance and very low moisture absorption. However, PEEK far exceeds the others’ wear and abrasion resistance and unaffectedness when continually
exposed to hot water or steam. These conclusions can be drawn from PEEK’s data sheet as seen in Table 5.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>1.32</td>
</tr>
<tr>
<td>Shrinkage, in/in, ⅛ in. thick</td>
<td>0.01</td>
</tr>
<tr>
<td>Shrinkage, in/in, ¼ in. thick</td>
<td>0.014</td>
</tr>
<tr>
<td>Water Absorption, % 24 hrs</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**MECHANICAL**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact, Izod, Notched (Ft-Lb/ln)</td>
<td>1.2</td>
</tr>
<tr>
<td>Impact, Izod, Unnotched (Ft-Lb/ln)</td>
<td>16</td>
</tr>
<tr>
<td>Tensile Strength (Psi)</td>
<td>13,000</td>
</tr>
<tr>
<td>Tensile Elongation (%)</td>
<td>150</td>
</tr>
<tr>
<td>Tensile Modulus (Psi x E+6)</td>
<td>0.6</td>
</tr>
<tr>
<td>Flexural Strength (Psi)</td>
<td>17,500</td>
</tr>
<tr>
<td>Flexural Modulus (Psi x E+6)</td>
<td>0.5</td>
</tr>
<tr>
<td>Compressive Strength (Psi)</td>
<td>NA</td>
</tr>
<tr>
<td>Hardness (Rockwell R)</td>
<td>NA</td>
</tr>
</tbody>
</table>

**ELECTRICAL**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric Strength (V/Mil)</td>
<td>400</td>
</tr>
<tr>
<td>Dielectric Constant (@ 1 MC dry)</td>
<td>3.4</td>
</tr>
<tr>
<td>Dissipation Factor (@ 1 MC dry)</td>
<td>0.004</td>
</tr>
<tr>
<td>Arc Resistance (sec)</td>
<td>40</td>
</tr>
<tr>
<td>Volume Resistivity (ohm-cm)</td>
<td>10E##</td>
</tr>
</tbody>
</table>

**THERMAL**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Deflection Temp 264 psi (F)</td>
<td>340</td>
</tr>
<tr>
<td>Heat Deflection Temp 66 psi (F)</td>
<td>NA</td>
</tr>
<tr>
<td>Flammability</td>
<td>V0</td>
</tr>
<tr>
<td>Thermal Expansion (In/In/F) x E-5</td>
<td>3.000</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>NA</td>
</tr>
</tbody>
</table>

**WEAR**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear Factor</td>
<td>NA</td>
</tr>
<tr>
<td>U L yellow card</td>
<td>NO</td>
</tr>
</tbody>
</table>

Table 5: Properties of PEEK [15]

Additionally, to confirm the conclusion from consideration two, signal transmittance, tests were conducted using HFSS 10 software. The results, when compared to the baseline results from the electrical section above, show that the material does not impede the signal as it travels to the receiver because the results match the baseline tests.
Figure 13: Freq: 8 GHz, Theta: -180 – 180, Phi: 90

Figure 13 shows the results displayed for frequency 8GHz while theta ranges from -180 to +180 and phi is set to 90. Figure 14 shows the results displayed for frequency 8 GHz while phi ranges from 0 to +360 and theta is set to 90.

Figure 14: Freq: 8 GHz, Theta: 90, Phi: 0 – 360

Similarly, Figures 15 and 16, and Figures 17 and 18 portray the same information for the same ranges and settings except the frequencies are set to 10 GHz and 6 GHZ, respectively.
Figure 15: Freq: 10 GHz, Theta: -180 – 180, Phi: 90

Figure 16: Freq: 10 GHz, Theta: 90, Phi: 0 – 360
Figure 17: Freq: 6GHz, Theta: -180 – 180, Phi: 90

Figure 18: Freq: 6GHz, Theta: 90, Phi: 0 – 360
Figure 19 shows the dB readouts for a frequency sweep from 5 GHz to 11 GHz. These figures are important because they, when compared to their counterpart in the electrical section, show that by adding a PEEK capsule around the electrical components, the desired output is roughly unchanged. Therefore, these results support the conclusion that PEEK is an acceptable material to use for construction of the capsule. Note: The values for the frequency sweep between 5-7 GHz do not compare well with their counterparts. However, this is believed to be irrelevant due to the fact that the frequencies that will be used in the projected model will be between 8-11 GHz. The data compares very well for the frequencies between 8-11 GHz.

Since PEEK was selected as the material best fit to construct the prototype, the team began contacting sales representatives at various companies. The team’s initial contact at BMJ Mold and Engineering suggested that the prototype be constructed by a company that specializes in thermoplastic production. After researching multiple options, the team decided to request the desired help from Oxford Polymers. Initial contact with the company led to doubtful belief that
Oxford Polymers would be the choice for probe construction. However, after being bounced around within the business, the team finally was given a stable point of contact that was very helpful. The team described the goals of the design project, and it was believed that the requests that had been made now looked hopeful. Soon after a small amount of time had passed, Oxford Polymers contacted the team to suggest that the work be continued with their partner corporation, Oxford Performance Materials (OPM).

Once again the team made contact with the new company, and, once again, the e-mails and phone calls seemed unpromising. Yet, after two weeks had passed, the team was put in touch with the Director of Application Development, Mr. Tony Decarmine. During the following weeks, the team and Mr. Decarmine discussed the goals of the project and set out a plan of attack. Mr. Decarmine believed that OPM would be able to accommodate the team’s target prototype. The team supplied Mr. Decarmine with all of the appropriate specifications that would be needed to construct the desired probe, including a detailed CAD model. OPM had seemed to be the perfect fit for the team’s prototype. Even better, OPM was planning to construct the prototype from their patented, improved Polyetherketoneketone known as Oxpekk. Oxpekk material is known for its excellent abrasion resistance, minimum detrimental stress shielding, compatibility with all sterilization methods, compressive strength which is twice that of PEEK, and being a chemically inert & non-absorbable polymer [16]. Oxpekk and the team’s original Polyetheretherketone that was to be used for construction have matching constants of coefficients and, therefore, allow signal transmittance to be at a maximum. The team was informed that while signal transmittance would not change, Oxpekk provides characteristics that far exceed those of PEEK [16]. This new material that OPM suggested seemed to match the team’s design goals perfectly.
Mr. Decarmine had initially stated that OPM could construct the team’s probe while staying within the senior design allotted budget. However, recently Mr. Decarmine, with much regret, informed the team that OPM would not be able to complete the prototype for the original amount he had quoted. The team informed Mr. Decarmine that he should continue to plan for OPM to construct the prototype because the team was allotted additional funds. To ensure that OPM was accurately quoting the prototype with their second quote, the team initiated contact with other companies to receive additional quotes from outside sources. The team received quotes from four other thermoplastic corporations. Boedeker Plastics, Inc., Advanced Industrial, Röchling Sustaplast LP, and Solvay Advanced Polymers, L.L.C. each provided the team with accurate quotes. The quotes from the materials companies are shown in Table 6.

<table>
<thead>
<tr>
<th>Material Company</th>
<th>PEEK Price per foot (3in diameter)</th>
<th>Price for Labor and Color Change</th>
<th>Total Price for Finished Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boedeker Plastics, Inc.</td>
<td>$697.90/ft</td>
<td>$1507.26</td>
<td>$2903.06</td>
</tr>
<tr>
<td>Advanced Industrial</td>
<td>$658.43</td>
<td>$1600.00</td>
<td>$2916.86</td>
</tr>
<tr>
<td>Röchling Sustaplast LP</td>
<td>$472.05 (minimum 35 ft)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Solvay Advanced Polymers, L.L.C.</td>
<td>$712.47</td>
<td>$1522.25</td>
<td>$2947.19</td>
</tr>
<tr>
<td>OPM</td>
<td>N/A</td>
<td>N/A</td>
<td>$2500.00</td>
</tr>
</tbody>
</table>

Table 6: Price Comparison for Construction of Prototype

The quotes suggest that Mr. Decarmine’s second quote was reasonable. Mr. Decarmine informed the team that it would cost approximately $2,500.00 to receive a completely assembled prototype of the team’s desired color. The other companies would only quote the team for the material and said that the labor to shave the prototype and a color change would more than double the price for the material. Each company quoted their selection of PEEK to be over $650.00 per foot. The team needs two feet of material, needs the material to be shaved into
form, and desires a color change from the standard pale brown. So, it is clear that Mr. Decarmine’s quote of $2,500.00 is acceptable since it is all inclusive.

The team selected a stainless steel trammel point to act as the prototype’s probe tip. The steel material is readily available, inexpensive, and easy to maintain. The stainless steel tip perfectly aligns with the team’s design goals. Steel has excellent abrasion resistance, virtually resilient to stress, and is compatible with all sterilization methods. The tip can be easily threaded into the probe for removal, if necessary. The probe tip is four and a half inches long with a base of three eights of an inch and extends to a small point.

The final material needed for construction of the prototype probe is an epoxy. An epoxy was selected to hold the antennas in their appropriate grooves. The team selected a high temperature adhesive to accomplish this need. The team chose to utilize Cotronics Corporation’s Duralco 4460. Duralco 4460 is formulated with Cotronics’ unique, polymer system to provide the ultimate in high temperature chemical, electrical and moisture resistance. It has superior adhesion and can easily form protective coatings, with 600°F service, which will be necessary for autoclaving. The epoxy also offers high bond strength, high temperature stability, low moisture absorption and low shrinkage. The application of the epoxy is very user friendly. And, most importantly, the liquid adhesive forms ultra thin bond lines and is ideal for coating and encapsulating [14]. For these reasons the team chose Duralco 4460 to adhere the antennas within the probe.

IV. Ergonomics

In working to find the direction of the final design, many things have been taken into consideration. The uses and the usability of the probe were analyzed. This involved the size,
aesthetics, and overall look of the device. In addition to these things, the features of the design were considered. The features, such as buttons and switches, are the key to making the probe work properly. The placement, size, and material of the features are important to the comfort and look of the device. This section will detail the thought processes involved with each of the steps.

The first step was to figure out the uses. Many uses were considered. The probe will be used to map out the knee, so the first order of business was to create a portion that would be able to touch the bone and gather the data. The first idea was to make an antenna out of the base of the probe. Because this seemed the most logical solution, it remained. It was necessary to have a tip, and the tip needs to be at the end of a long piece. Since the tip will literally be deep inside the knee, it only made sense for the tip to be at the end of a long probe tip. The length of the probe tip is still being determined, as the length will affect the readings. The longer the better, but the longer it is, the more the accuracy will be hindered. This is an obvious point, but a very important one.

Then, the less obvious uses of the device were determined. It was known that the device would map the bone, but the team had to decide how the mapping was to occur. There were two basic options: the tip could register a few single points and from those points map out the bone, or the tip could be run across the bone and create a cloud of points. There are benefits and shortcomings of both. When considering the option of the single point method, a few things were brought up. This single point method would paint just as accurate of a picture as the cloud method. Instead of having to trace the bone, it would be simply a point and click method. This method would only require a few seconds. However, there are a few shortcomings. There is a risk of accidentally dragging the marker, which could cause an error. Also, the points would
have to be specific; it would not work to simply click on random points. This also gives the chance of error. The cloud method has a number of benefits. The marker could be dragged over basic areas instead of specific points. This could save a little time, but the risk of error is greater. If the tip was accidentally lifted from the bone or dragged over a crevice, there would be an error. The signal would be broadcasting no position, and the whole image would be inaccurate, causing the surgeon to have to redo the mapping. These options had to be weighed to decide on which would be the most appropriate. Ultimately, it was decided that the device should be capable of doing both. The surgeon is the customer, and the surgeon should have the ability to choose which method they prefer. Therefore, both were incorporated into the device.

Doctors are prone to mistakes. As stated above, this device provides a fair amount of opportunities for these mistakes. It was known that it would be necessary for doctors to be able to fix their mistakes when they made them. Because of this, the team decided that there needed to be a way for the data to be cleared, allowing the user to start over.

The usability of the device was very important. If surgeons look at the device and see that it is ugly, they will obviously choose something that looks nicer. This is just human nature. It is also human nature to want something comfortable. No one would choose to use a bottle sized object when a pen sized one is available. In the same sense, something that fits comfortably in the hand will be chosen over something that can't be easily gripped. This was a huge part of the considerations when designing the probe. To begin, the team decided to look at other objects on the market today that are handheld and comfortably used. All of these devices seen in Figures 20-25 were carefully examined, both by looking at them and even holding them.
Figure 20: Panasonic 7021 Electric Razor (www.sellerkey.com)

Figure 21: Remington MS 2100 (www.ciao.co.uk/Remington_MS_2100_Micros_6326864)
Figure 22: Wii Controller (www.mattbrett.com)

Figure 23: Logitech Harmony Remote Control
(http://img.tomshardware.com/us/2005/05/17/logitech_harmony_pilots/harmony688-1.jpg)
The remote control in Figure 23, though too large, had a very good feature that the team plans on implementing into the device. The remote control can be held with the hand both on the side and on top. This allows the device to be more versatile. Though holding it with the hand on...
top provides a bit more control, holding it on the side also allows for a great deal of control. The way the remote is held is the way that the team wants the device held. Also, the remote has an indentation in the middle that is very comfortably fitting.

Ultimately, the shell of the design is going to be modeled after the electric razors seen in Figures 20 and 21. This shape accomplishes almost everything (as far as usability is concerned) that the probe should accomplish. The size will be slightly scaled down, but the shell allows for gripping on both the side and the top. Also, electric razors are ambidextrous, which is very important. The two razors fit very nicely in the average hand. The size of those razors is approximately 6x3x1.5 inches. The extra length of the antenna is a big factor in scaling the length down. Unfortunately, the antenna cannot fit inside a model of this size. Early in the process, though, this was not known. The originally proposed CAD drawing of this model can be seen in figure 26.

Figure 26: First design iteration

The mold of the device is not the only important factor. As stated above, the probe should look sleek. Doctors should look at the probe and be impressed with how it looks. The color is important. A sleek white accomplishes the task of looking professional as well as “hip.”
However, the shape should have a modern look to it instead of simply being an electric razor. To search for inspiration, the team searched for images of space age models. Figures 27-29 show a few of the fiction models that were observed. Though only the mold of the device is completed at this point, the team hopes to accommodate it to take on some of these fun characteristics. This remains the goal, though it has changed significantly as the project has proceeded forth.

Figure 27: Star Trek Phaser
Figure 28: Star Trek Phasers (http://www.ex-astris-scientia.org/gallery/stmagazine/phasers2.jpg)
The last feature that falls into the category of usability is the buttons and switches. These are obviously vital, because if the device can’t be turned on, it cannot be used. In order to have all of the features that have been discussed, it was decided that at least three buttons were needed: a point-and-click button, a trace button, and an undo/clear button. In addition to these, the team decided that there also needed to be a button to power the device on and off. The placement of these buttons was important. It was decided that the on/off button should be on the topside of the device. It does not necessarily need to be visible because it will only be used when the device needs to be powered on or off, but it is certainly beneficial for it to be seen. The other buttons, however, definitely need to be visible. The buttons should be activated when touching the bone, not before. If they are activated before, the device is taking a reading of air, causing an error as discussed before. So, when the device is inside the knee touching the bone, the doctor should be able to see which button he or she is pushing. Therefore, the buttons for these functions should be placed on the topside of the device.
The buttons need to be an adequate size as well. They need to be visible and easy to push, but not so big that the device is overwhelmed with buttons. One idea for the buttons was to create crevices and fill them with rubber. The rubber should act as a stopper to the crevices so that nothing can seep into them. When compressed, the rubber should activate the functions without allowing fluids to seep in the crevices. Another idea that was considered was to have a plastic sheet covering the feature activators. When the indentions on the plastic sheet are compressed, it would activate the specific button. This is the same kind of thing used in the remote control for the HP laptop seen in Figure 30, and, as discussed elsewhere, is the method that the team has chosen.

Figure 30: Bluetooth Expresscard Media Remote
(http://uk.gizmodo.com/expresscardmediaremotelarge.jpg)

All of these ideas were terrific theoretically. However, as the second semester of this project commenced, the device was forced to endure some major ergonomic adjustments. A big error in the first device stemmed from the lack of space available for the antennas. It was originally planned to place the tags inside the head of the device and the electrical box inside the handle. Unfortunately, the head was far too small to contain all six antennas in the desired
arrangement and the handle had too much space to only be occupied by the electrical box. In essence, the space in the head was too crowded and the space in the handle was not being utilized. In addition to the lack of space in the head, the team also deemed that the head (though hollow) was too bulky and made the device top heavy. These things led the team to decide to remove the bulky head and shift the placement of the antennas.

Another negative aspect of the first iteration was its ability to be sterilized and the accessibility of the model. For instance, the way the model was designed, it was going to be very difficult to place the antenna inside. It was loosely discussed that there would be a small opening in the head in which the manufacturers could place the antenna, but this was never followed up. When rehashing this idea, the team decided that it was far too small of a space to expect perfect antenna placement from the outside. Therefore, the team decided that there needed to be another way to insert the antenna. The inaccessibility of the inside, though, was moot compared to the sterility issues the probe faced. The probe tip was to be inserted in a whole on the head of the probe. However, the head was hollow in order to allow the antenna to fit inside, and the head also had an opening to give the antenna access to the electrical box. What this meant was that any liquid that snuck through the probe tip whole could bleed all the way into the handle of the device. This is an FDA nightmare. Blood and other harmful liquids had an entry to, but no exit from, the probe. This also had to be alleviated.

The original device did show the team a few things that were good. For instance, the size of the probe was nearly perfect for what the team was hoping to accomplish. It filled the hand but did not overwhelm it, much like the aforementioned electric razors and remote controls. The arch on the underside of the probe was also deemed good. The arch provided comfort for both methods of handling (top grip and side grip). If holding the probe on the top (Figure 31) the arch
fit the contour of the average sized hand, making it easy and comfortable to hold. If holding the probe from the side (Figure 32) the arch provide a resting place for the three middle fingers. The arch allows a good deal of diversity in the way that the device was held.

Figure 31: First iteration (top view)

Figure 32: First iteration (side view)
The second iteration of the device called for correcting these mistakes and building on the positives. The first thing that was done to the device was removing the bulky head. The original head, which was approximately a 3 x 2 x 2 inch box, was done away with, curing the unnecessary bulk at the tip of the probe. The team decided to move the antenna down to the unused space in the handle, and it was designed so that the antenna would flank the electrical box. Basically, it was decided that everything should move to the handle. However, this meant that the handle had to increase in size. The original designed rounded off the bottom of the probe right after the arch, making a smooth bottom portion. The second iteration called for adding more space at the bottom as well as the top so that the antenna would fit. The size of the probe increased even more when the dimensions of the antenna increased slightly. The biggest increase in size was seen in the width and depth of the device, which increased from 3 x 1.5 to 3.5 x 3 inches. This is obviously a significant jump, and it is something that has caused some trouble. The reasoning behind this size will be discussed shortly.

The next improvement was to make the probe accessible. The team wanted to find a way to make the sterilization easy without making the device too complicated. The solution for this was to split the model in half. The idea was to manufacture the model in two pieces and clip them together when the device was in use. Two halves allow easy placement of antenna, easy removal of the electrical box during sterilization, and easy conceptual visualization. Clipping the pieces together opens up the possibility that liquid could enter the probe during use, but opening up the model so that the inside is directly autoclaved cures this problem. Overall, the team decided that the two half concept was the best option.
Even though the model was now going to be sterilized easier, it was still important to find a place for the probe tip. A small box-like head was placed on top of the handle in order to ensure a probe tip placement location. The second iterated head was much smaller than in the original design. The head is an integral part of the device. Because accuracy is the number one priority for the customer, the probe tip must be secured and unmovable. In order to secure the probe tip, the head was solid and allowed .8 inches for the probe tip base depth. This ensures that the probe tip will not move around and that it will remain firmly in the same location.

Figures 33 and 34: Bottom and Top halves of second iteration

The two halves of the second iteration of the model can be seen in Figures 33 and 34. It can be seen that the arch of the handle has a platform stretch across the width of the probe, and that notches are placed on top of the platform. Similarly, the top half of the probe shows these same notches. As mentioned earlier, opening the model up made the removal of the electrical box easier. These notches and platform provide a way to hold the electrical box securely inside.
the device. The notches are raised enough and positioned so that, when the probe is close, the electrical box will fit neatly inside and not move. However, when the device is opened, the electrical box can simply be picked out and put aside while the model is being autoclaved. This is one feature of the second iteration that is very convenient. The other features that should be noted are the colored boxes located in the device. The boxes provide the support and location of the actual antenna tags. When the antennas are inside the device, they must be firm and unmoved. The boxes and corresponding supports give the antennas a fixed location. The gap is designed to be a good fit for the antenna, and the antennas are going to be epoxied in to ensure fixation. The arrangement of the antenna corresponds to the prism arrangement seen in the Spatial Arrangement section.

A few problems arose, however, with the second iteration. The first involved the coupling of the antennas, which is discussed in the electrical section. In order to fix this, the design shifted from a simple prism placement to a skewed prism arrangement. The third iteration compensated for this by placing inclined antenna holders on the lower half and a perpendicular antenna holder on the upper half. There are two sets of three antennas in the model. In each set of three, it was determined that there could be a half inch vertical overlap between them. In order to save as much space as possible, these exact measurements were used. The width of the probe was also done so that the space was conserved as much as possible. The antennas have a horizontal distance of .1 inches separating them. This was determined to cure the coupling, but it did make the probe larger yet again. Another problem stemmed from the location of the SMA cables that are to be attached to the antenna. Very little room was available to place these cables. It was determined that approximately 1 inch was needed for the SMA cable attachments, which meant that each of the supports had to have an extra inch built in for
them. The last problem with the second iteration was the head. Though it was not tremendously bulky, it provided no consistency in the model. This was cured by making the head more of an arch while still maintaining the same properties of the second iteration head. The third, and final, iteration can be seen in Figures 35 and 36.

Figures 35 and 36: Bottom and top views of final iteration

When the specifications were met with the other portions of the project, the overall aesthetics of the model went down. For instance, the model was forced to be more box-like in order to incorporate all of the antennas into the handle. Also, the size of the model increased drastically due to the aforementioned problems that kept arising. Because of all of this, the final model is perfect for testing, but will be slimmed down and shifted as the technology advances. As the technology advances and the size of the antennas (and SMA cables) decrease, the model
will become smaller and more usable. Until then, however, the only way to incorporate all of the necessary functions was to enlarge the model, knowing that it can be modified and shrunk.
Testing and Results

Testing Monopole Antenna

The performance of the monopole antenna, which will be the UWB antenna within the probe, was tested using an electrical engineering software package called HFSS10. A 3D model of the antenna was created in the program and tested in the frequency domain in order to get baseline results for the monopole antennas. The far field radiation patterns of the antenna in air could be simulated using the program, using discrete frequencies of 6, 8, and 10 GHz. The radiation patterns were obtained for both an E cut and an H cut. In an E cut, the radiation pattern is represented by polar coordinates in the y-z plane. It is generated by varying theta from -180°-180° while maintaining phi at a constant 90°. The H cut is the opposite: phi ranges from 0-360° and theta remains a constant 90°. The radiation patterns from these three discrete frequencies can be seen in Figures A1-A7. The large circular pattern for the E cut graphs represents the omni-directional nature of the monopole antenna. The rectangular plot shows the results from doing a frequency sweep from 5-11 GHz and showing the S11 return loss (Figure 37).

Figure 37: Return Loss
This is a measure of how much of the signal energy is reflected versus sent. As such, the lower S11 values are the better, since this means there is a low amount of energy being reflected. At -10dB, the energy reflected is about 10% of the energy transmitted (using 10log(Pout/Pin)) [6]. For a monopole UWB antenna, -10dB is an acceptable value. For the test frequencies (6,8,10 GHz) the S11 values are at or below -10dB’s, indicating a properly functioning antenna.

Once the baseline simulations were run on the antenna in air, the model could be augmented to simulate the effects of the probe casing surrounding the antenna. In order to do this, a box was created to surround the antenna with the specific material properties of PEEK. The simulations were run again, this time with the signal from the antenna passing through PEEK box and into the vacuum. Far field radiation plots for these simulations, using the same E and H cuts, were created in order to compare the performance of the signal to the baseline plots. These new plots can be seen in Figures 13-18 of the materials section of the description of the final design. A frequency sweep was also simulated for the PEEK surrounded antenna (Figure 19). As can be seen from the radiation plots, the material casing did not greatly impede the signal radiation. The S11 values are still in an acceptable range, so the material is not reflecting the signal.

After getting baseline results for a single antenna within the material, it was important to run simulations with all the antennas included. Knowing that a six pointed prism would yield the most accurate results for the probe, the team experimented with different antenna configurations within the probe. The first configuration had two antennas in the X-Y plane, and a third in the X-Z, all facing different directions. This configuration can be seen in Figure 38.
The distance between the antennas marks the length of the probe handle. Using a newer version of the HFSS software, this configuration was simulated with a PEEK box surrounding it to mimic the probe. In this configuration the team found unacceptable levels of mutual coupling between the antennas. In closely spaced antennas, mutual coupling reduces their radiation patterns, and as such can reduce the accuracy of the antennas. Reducing this effect requires increasing the space between the antennas. Mutual coupling is thought to deteriorate the channel, which ultimately reduces the attainable capacity of the antenna [17]. Ultimately, reducing the mutual coupling effects will ensure higher accuracy. Using the HFSS software different antennas configurations, within the constraint of the six point prism, were simulated in order to find an arrangement that reduced the mutual coupling among the antennas. The best configuration tested involved altering the planar orientations of the antennas. The new configuration can be seen in Figure 39.
The antennas are at 120° from each other, which maximizes the distance between them. The antennas are also offset in the X direction, which again increased the space between them. The thought was that the increased space would reduce the amount of mutual coupling, which according to the simulations run in HFSS, turns out to be true. When the error measurement for this new configuration was run in Matlab, the error difference was small. Another important feature of this new configuration placed the excitations at the far end of the antenna and further away from the other excitations. A similar configuration as this was also simulated, but the offset in the X direction was doubled. In Figure 40 below, a comparison of the mutual coupling effects is shown for the antenna in the X-Z plane (designated “1”).
The three different lines represent the coupling between the different excitations on the antenna, with “2” and “3” being the angled antennas. The blue line (indicated “Rough”) shows the results with no offset in the X direction. The red skew lines represent the chosen configuration, and the black “bigger” lines represent what happens when the offset in the X is doubled. The “skew” and “bigger” results are similar; only the “skew” results for the relationship between antennas 1 and 2 being lower nearly through the entire range of frequencies. By using the smaller configuration, it will allow the overall size of the probe to remain smaller.

In addition to measuring the mutual coupling, the far field radiation patterns were also determined for the three configurations represented above using the HFSS software. For a fair comparison of the different radiation patterns, they were all normalized in Microsoft Excel and imported into a graphing program called Microcal Origin. The comparison graphs can be seen in Appendix 1, but the important thing is that the skewed configuration did not have adverse effects. Figures 41 and 42 show the radiation patterns for 8 GHz, for the X-Z and angled antennas, respectively.
Figures 41 and 42: X-Z and angled antenna attenuation

So, with the help of HFSS, the new configuration of antennas within the probe was determined.

Testing Antenna Spatial Arrangement

An analysis of the testing on the spatial arrangement of the antennas was included in the second section of the description of the final design. Justification of the chosen arrangement was also included in this section. To summarize, the testing concluded that the most accurate configuration was the six tagged prism. A compromise had to be made between accuracy and the effects of antenna coupling. This resulted in an additional 0.1 millimeter of error above the possible minimum of 1.1 millimeters. Thus, an accuracy of 1.2 millimeters was obtained while resolving the coupling effects.
Conclusions and Discussion

Currently the team’s prototype is a 3-D printout from an FDM machine. While the team was not able to have a market ready prototype created as originally planned, the team did gain valuable knowledge about how to make this happen. In order to achieve the greatest possible accuracy, the team determined that six antennas were required. Through electrical simulation testing it was determined that in order to avoid the negative effects of mutual coupling between the antennas, they needed to be spaced further apart than initially planned. In order to accommodate this, the handle of the probe was larger than originally desired. To save money and time, the team determined that having the probe manufactured by the plastic company would be a futile effort. The team is not discouraged though, because the current design suffers in size only; the accuracy of the antennas was not compromised. Future work to remedy this situation will involve work on two fronts: decreasing the size of the internal electronics, and finding a better way to reduce mutual coupling. The coaxial cables and SMA connectors required for communication between the circuit board and the antennas is currently cumbersome and bulky. If there were a more compact way to make this connection, the probe would be able to shrink in size. In order to prevent the mutual coupling that attenuated antenna performance, greater space was created between the antennas. This also created bulkiness and contributed to the overall size of the probe. The team was able to establish valuable contacts for creating the finished probe when the encountered problems have been resolved.
References

   <http://www.medtronicnavigation.com/util/glossary.jsp#N>

Twentieth IEEE International Symposium on Computer-Based Medical System,

for Wireless Personal Area Networks, Document # IEEE 802.15-02/133rl (March 2002).


Temperatures in Polymers: Application to Thermoplastic Systems." Journal of


Appendix 1: Figures

Electrical Figures:

Figure A1: Freq: 8 GHz, Theta: -180 – 180, Phi: 90

Figure A2: Freq: 8 GHz, Theta: 90, Phi: 0 – 360
Figure A3: Freq: 10 GHz, Theta: -180 – 180, Phi: 90

Figure A4: Freq: 10 GHz, Theta: 90, Phi: 0 – 360
Figure A5: Freq: 6 GHz, Theta: -180 – 180, Phi: 90

Figure A6: Freq: 6 GHz, Theta: 90, Phi: 0 – 360
Angled Antenna Configuration Radiation Plots

Figure A7: 6 GHz E-cut

Figure A8: 6 GHz H-cut
Figure A9: 8 GHz E-cut

Figure A10: 8 GHz H-cut
Figure A11: 9.5 GHz E-cut

Figure A12: 9.5 GHz H-cut
X-Y Plane Antenna

Figure A13: 6 GHz E-cut

Figure A14: 6 GHz H-cut
Figure A15: 8 GHz E-cut

Figure A16: 8 GHz H-cut
Figure A17: 9.5 GHz E-cut

Figure A18: 9.5 GHz H-cut
Figure A19: Return Loss
Mutual Coupling

Figure A20: Mutual Coupling of antenna 1

Figure A21: Mutual coupling of antenna 2
Figure A22: Mutual coupling of antenna 3
Spatial Arrangement Figures

Figure A23: This figure displays the spatial arrangement of four markers in one plane.

Figure A24: This figure displays the spatial arrangement of four markers in three dimension resulting in a tetrahedron shape.
Figure A25: This figure displays the spatial arrangement of five markers in one plane.

Figure A26: This figure displays the spatial arrangement of five markers in one plane.
Figure A27: This figure displays the spatial arrangement of five markers in different planes resulting in a pyramid shape.

Figure A28: This figure displays the spatial arrangement of six markers in one plane.
Figure A29: This figure displays the spatial arrangement of six markers in one plane in orientation normal to that of the preceding figure.

Figure A30: This figure displays the spatial arrangement of six markers in one plane resulting in a prism with it triangular bases facing up and down relative to the probe tip.
1 function [R,T] = arun(set1, set2)
2 clear all;
3 N = length(set1);
4 p_ip = set1'; % p_ip: model points
5 pp = set2'; % pp: image points
6
7 pp = (1/N)*sum(p_ip'); % p: Mean position of image points
8 p = (1/N)*sum(p_ip'); % p: Mean position of model points
9
10 for i = 1:N
11   q_ip(:,i) = p_ip(:,i) - pp;
12
13   q_ip(:,i) = p_ip(:,i) - pp;
14 end
15
16 q = (1/N)*sum(q_ip');
17
18 H = zeros(3,3);
19 for i = 1:N
20   H = H + q_ip(:,i)'q_ip(:,i); end
21
22 [U, S, V] = svd(H); % Singular value decomposition
23
24 X = (V'S)'V';
25 if det(X) < 0 % Check for rotation/reflection
26   Vp = V;
27   Vp(:,2) = -Vp(:,2);
28   X = (Vp'V');
29 end
30
31 R = X;
32
33 [R,T] = IOrun(modelCoord, worldCoord);  % function to find the least square calculated translation vector
34
35 end

Figure A31: This figure is a screen shot of the Matlab code used for the Arun function.

Figure A32: This figure is a screen shot of the Matlab code used for the analysis of each spatial arrangement. The code for each individual spatial arrangement was altered accordingly by simply inputting the spatial arrangement’s coordinates into the modelCoords matrix.
Figure A33: This figure is a screen shot of the Matlab code used for the creation of the axes in an inventor file to represent the locations of the tags and markers.
function createVSphere(points, radius, modelN, modelName, color)
    % First create the filename and open the file
    file = sprintf('sphere\%s\%s\%s\%d\%s', modelN, modelName, color);
    fid = fopen(file, 'w+);
    fprintf(fid, '#Inventor V2.0:
    for i=1:size(points, 1)
        fprintf(fid, 'set position (%f, %f, %f);
        fprintf(fid, 'transform rotate (%f, %f, %f);
        fprintf(fid, 'sphere (
        end
    fprintf(fid, 'transform translate (%f, %f, %f);
    fprintf(fid, 'translate (%f, %f, %f);
    fprintf(fid, 'end
    fclose(fid);

Figure A34: This figure is a screen shot of the Matlab code used for the creation of the spheres in an inventor file to represent the locations of the tags and markers.

Figure A35: This figure is a screen shot of the Matlab code used for the creation of the visual representation of each spatial arrangement shown above.
Figure A36: This figure plots the errors for each spatial arrangement analyzed using Matlab. The x-axis represents the varying distance between the probe tip and the nearest tag. The observance of relatively horizontal represents little effect of distance between the probe tip and the tags on the error.
Appendix 2: Tables

Spatial Arrangement Tables

**Markers:** 4  
**Orientation:** One plane, square

<table>
<thead>
<tr>
<th>Probe Tip</th>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>10</td>
<td>1.8574</td>
</tr>
<tr>
<td>Small</td>
<td>1010</td>
<td>1.8470</td>
</tr>
<tr>
<td>Small</td>
<td>5010</td>
<td>1.8621</td>
</tr>
<tr>
<td>Medium</td>
<td>100</td>
<td>1.8356</td>
</tr>
<tr>
<td>Medium</td>
<td>1100</td>
<td>1.8329</td>
</tr>
<tr>
<td>Medium</td>
<td>5100</td>
<td>1.8376</td>
</tr>
<tr>
<td>Large</td>
<td>200</td>
<td>1.8355</td>
</tr>
<tr>
<td>Large</td>
<td>1200</td>
<td>1.8382</td>
</tr>
<tr>
<td>Large</td>
<td>5200</td>
<td>1.8339</td>
</tr>
</tbody>
</table>

Table A1: This table displays the average ($\mu$) of 600 random samples of rotation and translation in locating the location of the probe tip. Also shown is the standard deviation ($\sigma$) between each 100 samples. The small, medium, and large designates the distance between the probe tip and the tags. All measurements are in millimeters.

**Markers:** 4  
**Orientation:** Tetrahedron

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>1.6559</td>
</tr>
<tr>
<td>Small</td>
<td>1.6604</td>
</tr>
<tr>
<td>Small</td>
<td>1.6523</td>
</tr>
<tr>
<td>Medium</td>
<td>100</td>
</tr>
<tr>
<td>Medium</td>
<td>1100</td>
</tr>
<tr>
<td>Medium</td>
<td>5100</td>
</tr>
<tr>
<td>Large</td>
<td>200</td>
</tr>
<tr>
<td>Large</td>
<td>1200</td>
</tr>
<tr>
<td>Large</td>
<td>5200</td>
</tr>
</tbody>
</table>

Table A2: This table displays the average ($\mu$) of 600 random samples of rotation and translation in locating the location of the probe tip. Also shown is the standard deviation ($\sigma$) between each 100 samples. The small, medium, and large designates the distance between the probe tip and the tags. All measurements are in millimeters.
<table>
<thead>
<tr>
<th>Markers: 4</th>
<th>Orientation: Tetrahedron</th>
<th>( \mu )</th>
<th>( \sigma )</th>
<th>( J_1 )</th>
<th>( J_1 )</th>
<th>( J_1 )</th>
<th>( J_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>10</td>
<td>1.6743</td>
<td>0.0036</td>
<td>1.6379</td>
<td>1.6345</td>
<td>1.6739</td>
<td>1.6724</td>
</tr>
<tr>
<td>Small</td>
<td>1010</td>
<td>1.6738</td>
<td>0.0086</td>
<td>1.6543</td>
<td>1.6519</td>
<td>1.6568</td>
<td>1.6580</td>
</tr>
<tr>
<td>Small</td>
<td>5010</td>
<td>1.6739</td>
<td>0.0087</td>
<td>1.6535</td>
<td>1.6511</td>
<td>1.6749</td>
<td>1.6849</td>
</tr>
<tr>
<td>Medium</td>
<td>100</td>
<td>1.6654</td>
<td>0.0129</td>
<td>1.6769</td>
<td>1.6701</td>
<td>1.727</td>
<td>1.6799</td>
</tr>
<tr>
<td>Medium</td>
<td>1100</td>
<td>1.6610</td>
<td>0.0088</td>
<td>1.6629</td>
<td>1.6320</td>
<td>1.6589</td>
<td>1.6584</td>
</tr>
<tr>
<td>Medium</td>
<td>5100</td>
<td>1.6688</td>
<td>0.0051</td>
<td>1.6705</td>
<td>1.6703</td>
<td>1.7074</td>
<td>1.6983</td>
</tr>
<tr>
<td>Large</td>
<td>200</td>
<td>1.6654</td>
<td>0.0126</td>
<td>1.6441</td>
<td>1.6392</td>
<td>1.6669</td>
<td>1.6726</td>
</tr>
<tr>
<td>Large</td>
<td>1200</td>
<td>1.6673</td>
<td>0.0138</td>
<td>1.6913</td>
<td>1.6591</td>
<td>1.6942</td>
<td>1.6911</td>
</tr>
<tr>
<td>Large</td>
<td>5200</td>
<td>1.6603</td>
<td>0.0057</td>
<td>1.6613</td>
<td>1.6588</td>
<td>1.6922</td>
<td>1.6928</td>
</tr>
</tbody>
</table>

Table A3: This table displays the average (\( \mu \)) of 600 random samples of rotation and translation in locating the location of the probe tip. Also shown is the standard deviation (\( \sigma \)) between each 100 samples. The small, medium, and large designate the distance between the the probe tip and the tags. All measurements are in millimeters.

<table>
<thead>
<tr>
<th>Markers: 5</th>
<th>Orientation: One Plane</th>
<th>( \mu )</th>
<th>( \sigma )</th>
<th>( J_1 )</th>
<th>( J_1 )</th>
<th>( J_1 )</th>
<th>( J_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>10</td>
<td>1.6292</td>
<td>0.0063</td>
<td>1.5238</td>
<td>1.5229</td>
<td>1.6299</td>
<td>1.6238</td>
</tr>
<tr>
<td>Small</td>
<td>1010</td>
<td>1.6255</td>
<td>0.0138</td>
<td>1.5281</td>
<td>1.5276</td>
<td>1.6375</td>
<td>1.6326</td>
</tr>
<tr>
<td>Small</td>
<td>5010</td>
<td>1.6282</td>
<td>0.0081</td>
<td>1.6236</td>
<td>1.6161</td>
<td>1.6338</td>
<td>1.6346</td>
</tr>
<tr>
<td>Medium</td>
<td>100</td>
<td>1.6179</td>
<td>0.0041</td>
<td>1.6163</td>
<td>1.6214</td>
<td>1.6111</td>
<td>1.6175</td>
</tr>
<tr>
<td>Medium</td>
<td>1100</td>
<td>1.6166</td>
<td>0.0133</td>
<td>1.6202</td>
<td>1.5993</td>
<td>1.6235</td>
<td>1.6321</td>
</tr>
<tr>
<td>Medium</td>
<td>5100</td>
<td>1.6187</td>
<td>0.0102</td>
<td>1.6243</td>
<td>1.6239</td>
<td>1.6961</td>
<td>1.6290</td>
</tr>
<tr>
<td>Large</td>
<td>200</td>
<td>1.6174</td>
<td>0.0091</td>
<td>1.6230</td>
<td>1.6358</td>
<td>1.6140</td>
<td>1.6218</td>
</tr>
<tr>
<td>Large</td>
<td>1200</td>
<td>1.6189</td>
<td>0.0051</td>
<td>1.6266</td>
<td>1.6186</td>
<td>1.6151</td>
<td>1.6163</td>
</tr>
<tr>
<td>Large</td>
<td>5200</td>
<td>1.6165</td>
<td>0.0034</td>
<td>1.6151</td>
<td>1.6163</td>
<td>1.6212</td>
<td>1.6110</td>
</tr>
</tbody>
</table>

Table A4: This table displays the average (\( \mu \)) of 600 random samples of rotation and translation in locating the location of the probe tip. Also shown is the standard deviation (\( \sigma \)) between each 100 samples. The small, medium, and large designate the distance between the the probe tip and the tags. All measurements are in millimeters.
Table A5: This table displays the average ($\mu$) of 600 random samples of rotation and translation in locating the location of the probe tip. Also shown is the standard deviation ($\sigma$) between each 100 samples. The small, medium, and large designates the distance between the probe tip and the tags. All measurements are in millimeters.

<table>
<thead>
<tr>
<th>Markers: 5</th>
<th>Orientation: Pyramid</th>
<th>Translation Max Factor = 10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>Small</td>
<td>10</td>
<td>1.4171</td>
</tr>
<tr>
<td>Small</td>
<td>1010</td>
<td>1.4211</td>
</tr>
<tr>
<td>Small</td>
<td>5010</td>
<td>1.4157</td>
</tr>
<tr>
<td>Medium</td>
<td>100</td>
<td>1.4159</td>
</tr>
<tr>
<td>Medium</td>
<td>1100</td>
<td>1.4195</td>
</tr>
<tr>
<td>Medium</td>
<td>5100</td>
<td>1.4241</td>
</tr>
<tr>
<td>Large</td>
<td>200</td>
<td>1.4194</td>
</tr>
<tr>
<td>Large</td>
<td>1200</td>
<td>1.4150</td>
</tr>
<tr>
<td>Large</td>
<td>5200</td>
<td>1.4151</td>
</tr>
</tbody>
</table>

Table A6: This table displays the average ($\mu$) of 600 random samples of rotation and translation in locating the location of the probe tip. Also shown is the standard deviation ($\sigma$) between each 100 samples. The small, medium, and large designates the distance between the probe tip and the tags. All measurements are in millimeters.

<table>
<thead>
<tr>
<th>Markers: 6</th>
<th>Orientation: One Plane</th>
<th>Translation Max Factor = 10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>Small</td>
<td>10</td>
<td>1.7506</td>
</tr>
<tr>
<td>Small</td>
<td>1010</td>
<td>1.7607</td>
</tr>
<tr>
<td>Small</td>
<td>5010</td>
<td>1.7468</td>
</tr>
<tr>
<td>Medium</td>
<td>100</td>
<td>1.7238</td>
</tr>
<tr>
<td>Medium</td>
<td>1100</td>
<td>1.7227</td>
</tr>
<tr>
<td>Medium</td>
<td>5100</td>
<td>1.7261</td>
</tr>
<tr>
<td>Large</td>
<td>200</td>
<td>1.7199</td>
</tr>
<tr>
<td>Large</td>
<td>1200</td>
<td>1.7171</td>
</tr>
<tr>
<td>Large</td>
<td>5200</td>
<td>1.7214</td>
</tr>
</tbody>
</table>
Table A7: This table displays the average ($\mu$) of 600 random samples of rotation and translation in locating the location of the probe tip. Also shown is the standard deviation ($\sigma$) between each 100 samples. The small, medium, and large designates the distance between the probe tip and the tags. All measurements are in millimeters.

<table>
<thead>
<tr>
<th>Markers: 6</th>
<th>Orientation: One Plane</th>
<th>Translation Max Factor = 10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>Small</td>
<td>10</td>
<td>1.4949</td>
</tr>
<tr>
<td>Small</td>
<td>1010</td>
<td>1.4984</td>
</tr>
<tr>
<td>Small</td>
<td>5010</td>
<td>1.4933</td>
</tr>
<tr>
<td>Medium</td>
<td>100</td>
<td>1.4854</td>
</tr>
<tr>
<td>Medium</td>
<td>1100</td>
<td>1.4937</td>
</tr>
<tr>
<td>Medium</td>
<td>5100</td>
<td>1.4939</td>
</tr>
<tr>
<td>Large</td>
<td>200</td>
<td>1.4911</td>
</tr>
<tr>
<td>Large</td>
<td>1200</td>
<td>1.4955</td>
</tr>
<tr>
<td>Large</td>
<td>5200</td>
<td>1.4858</td>
</tr>
</tbody>
</table>

Table A8: This table displays the average ($\mu$) of 600 random samples of rotation and translation in locating the location of the probe tip. Also shown is the standard deviation ($\sigma$) between each 100 samples. The small, medium, and large designates the distance between the probe tip and the tags. All measurements are in millimeters.

<table>
<thead>
<tr>
<th>Markers: 6</th>
<th>Orientation: Prism</th>
<th>Translation Max Factor = 10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>Small</td>
<td>10</td>
<td>1.3809</td>
</tr>
<tr>
<td>Small</td>
<td>1010</td>
<td>1.3775</td>
</tr>
<tr>
<td>Small</td>
<td>5010</td>
<td>1.3798</td>
</tr>
<tr>
<td>Medium</td>
<td>100</td>
<td>1.3742</td>
</tr>
<tr>
<td>Medium</td>
<td>1100</td>
<td>1.3777</td>
</tr>
<tr>
<td>Medium</td>
<td>5100</td>
<td>1.3687</td>
</tr>
<tr>
<td>Large</td>
<td>200</td>
<td>1.3717</td>
</tr>
<tr>
<td>Large</td>
<td>1200</td>
<td>1.3702</td>
</tr>
<tr>
<td>Large</td>
<td>5200</td>
<td>1.3754</td>
</tr>
<tr>
<td>Markers:</td>
<td>Orientation: Prism</td>
<td>Translation Max Factor = 10</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>Small</td>
<td>10</td>
<td>1.1585 1.1588 1.1445 1.1523 1.1549 1.1467</td>
</tr>
<tr>
<td>Small</td>
<td>1010</td>
<td>1.1529 1.1452 1.1631 1.1414 1.1513 1.1436</td>
</tr>
<tr>
<td>Small</td>
<td>5010</td>
<td>1.1507 1.1541 1.1480 1.1575 1.1534 1.1505</td>
</tr>
<tr>
<td>Medium</td>
<td>100</td>
<td>1.1416 1.1431 1.1460 1.1538 1.1522 1.1517</td>
</tr>
<tr>
<td>Medium</td>
<td>1100</td>
<td>1.1453 1.1460 1.1458 1.1559 1.1532 1.1556</td>
</tr>
<tr>
<td>Medium</td>
<td>5100</td>
<td>1.1522 1.1582 1.1519 1.1483 1.1630 1.1480</td>
</tr>
<tr>
<td>Large</td>
<td>100</td>
<td>1.1415 1.1428 1.1534 1.1514 1.1574 1.1484</td>
</tr>
<tr>
<td>Large</td>
<td>1200</td>
<td>1.1407 1.1494 1.1470 1.1415 1.1546 1.1481</td>
</tr>
<tr>
<td>Large</td>
<td>5200</td>
<td>1.1439 1.1388 1.1447 1.1531 1.1649 1.1579</td>
</tr>
</tbody>
</table>

Table A9: This table displays the average (μ) of 600 random samples of rotation and translation in locating the location of the probe tip. Also shown is the standard deviation (σ) between each 100 samples. The small, medium, and large designates the distance between the probe tip and the tags. All measurements are in millimeters.
Appendix 3: Full Contact Information

Materials:

BMJ Mold & Engineering Co.
P.O. Box 2676
Kokomo, IN 46904-2676

Boedeker Plastics, Inc.
904 West 6th Street
Shiner, Texas 77984 USA

Advanced Industrial
11020 Bailey Rd.
Cornelius, NC 28031

Röchling Sustaplast LP
216 Philips Road
Exton, PA 19341

Solvay Advanced Polymers, L.L.C.
4500 McGinnis Ferry Road
Alpharetta, GA 30005-3914 USA

Oxford Polymers
221 South Street
New Britain, CT 06051

Oxford Performance Materials
120 Post Rd.
Enfield, CT 06082 USA

Tools for Working Wood
32 33rd Street 5th Floor
Brooklyn, NY 11232

Cotronics Corporation
131 47th Street
Brooklyn, NY 11232 USA

Electronics:

Micro Power Electronics, Inc.
13955 SW Millikan Way
Beaverton, OR 97005
Jim Dowd
Tronser, Inc.
3066 John Trush Jr. Blvd.
Cazenovia, NY 13035
Phone: 315-655-9528 Ext 221
Fax: 315-655-2149
E-mail: j.dowd@tronser.com
Web site: www.tronser.com

Memtron Input Components, Buttons
John Solgat
New Business Development
Memtron Input Components
Esterline Corporation
530 North Franklin
Frankenmuth, MI 48734
Phone # 989-652-2656
Fax # 989-652-2659
Cell # 989-284-8977
Email: Johns@memtron.com

Pasternack Enterprises
purchasing@pasternack.com
Phone: 949-261-1920
Fax: 949-261-7451