

Batteryless and Wireless Data Acquisition System

Submitted To

Dr. Valvano

Prepared By

Albert Marzullo

Anish Vaghasia

Corey Cormier

Makeila Sorensen

Michael Park

Thomas Ermis

**EE464 Senior Design Project
Electrical and Computer Engineering Department
University of Texas at Austin
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EXECUTIVE SUMMARY

This report details our team's development of a batteryless and wireless data acquisition system. Throughout the semester, we have been working to create a device that would greatly simplify and streamline the process of collecting internal data measurements from laboratory rats. Certain requirements and constraints shaped the design of our system from the beginning. Constraints on size and biocompatibility required a wireless and batteryless implant submodule that would collect data from within the rat. Additionally, requirements for responsiveness and user-friendliness influenced the design of the rest of the system.

Our team's design solution resulted in a three-module system that included an implant, a base station, and a web application. The implant module would be surgically placed underneath the skin of the lab rat. Its job is to respond to commands from the base station and return data measurements when requested. The base station module acts as a bridge between the implant and the web application. It receives commands from the web application and relays them to the implant from which it relays requested data back. The web application allows the user to indirectly control the actions of the implant within the rat, while also storing and displaying data for the user.

During the design implementation phase of our project, our team determined the specifics of each module and the components we would use. For the implant, we decided to use an RF430 microcontroller because of its low power minimums, wireless power and communication capabilities, and internal temperature sensor. We then chose the MMA8452 accelerometer for data measurements because of its low voltage minimums, I²C communication protocol, and, triple-axis acceleration measurements. For the base station, we picked the TRF7970 because of its compatibility with the Rf430, and the Raspberry Pi 3 because its internal Wi-Fi chip. Finally, for the web application we chose the Watson IoT platform due to its powerful support for IoT applications and easy interfacing with the Raspberry Pi.

In order to assess the success of our final design, our team developed a series of tests that would evaluate both the pieces of our system and the system as a whole. We performed testing on our system at three different granularities: component, module, and system. During component testing, the coil was tested against our required inductance of 3 μ H. During module testing, each of the three modules were tested separately. The implant was tested against its target resonant frequency of 13.56 MHz, and on its ability to power up and communicate within a minimum distance from the base station. The base station was tested on its ability to send and receive data from both the communication and the implant. The web application was tested on its ability to handle requests from the user and its responsiveness to said requests. Finally, the combined system was tested for responsiveness and ease of use. After testing was completed, our final design was able to meet the specifications of our problem and can be considered a working prototype.

To successfully finish our project on time, our team carefully planned out a schedule for development and testing. We first started by developing the implant and the base station in the

summer and co-developed the web application in the beginning of the fall semester. We managed our time efficiently and even had ten different versions of our implant PCB by the end of the semester. The official cost of our project is \$0 due to free parts and Dr. Valvano's sponsorship. The only major cost were the PCBs which Dr. Valvano paid for.

Because our system would eventually be placed into a live animal, there were certain safety and ethical concerns that are brought into consideration. Our device needs to be small and sterile for the comfort and safety of the animal. Additionally, the base station needs to turn off its antenna when it is not sampling data from the implant so it does not heat up the rat from the radio waves generated.

With the completion of a functional prototype of the project, we also recommend a few steps that can advance the project and eventually lead to exciting future applications. For the next steps, we recommend decreasing the size of the implant coil and increasing the size of the base station coil. We also recommend adding user authentication and data storage to the web application. Eventually this project can provide a great benefit in industries like healthcare and infrastructure.

1.0 INTRODUCTION

This final report explains the design, implementation, and analysis of our batteryless and wireless data acquisition system for research environments. The report also serves as a final summary of the work done as part of the senior design course this semester. This data acquisition system will aid in research environments that use lab animals for testing purposes. In normal lab environments, it can be extremely time consuming for researchers to take multiple precise internal measurements of lab animals for experimental purposes. Therefore, a system that allows the researcher to make quick, easy measurements from lab animals and efficiently process the data would provide a great benefit to many research companies.

The project was shaped by the varying needs of the client and the operating conditions by which the system will be operating in. These needs were used to shape the design, and steps such as risk analysis and modular testing were taken to improve the implementation of the project. The client, Dr. Valvano, originated the project and required a more efficient data collection method for lab environments. Due to part of the system being inside an animal, there were also certain environmental and performance specifications that shaped the operation of the system. The created design is a three subsystem approach made of an implant, a base station, and a web application. The implant will be surgically implanted inside the rat and will collect the data. This implant is wirelessly powered by and communicates with the base station. The base station in turn receives the data and wirelessly transfers the data to a web application, which stores and displays the information to the user. The validity of the subsystems, as well as the system as a whole, were determined with a suite of subsystem and system tests. By using careful time and cost management, the project was completed on time and under budget. The team was successfully able to implement their design and create a fully working prototype of the project. Finally, recommended steps have also been detailed to show how the project can be advanced further.

2.0 DESIGN PROBLEM

Current methods that scientists use to acquire and analyze data from laboratory rats are both inefficient and time consuming. Each time a scientist wants to collect data, he or she needs to

manually take measurements or samples from each rat involved in a given study. Once the samples have been processed, the scientist needs to filter through and analyze the results. Furthermore, this procedure needs to be consistently repeated to ensure that the data is current and accurate. Since certain studies may extend over long periods of time, these methods require an excessive amount of time spent just collecting and analyzing data from the rats. With this in mind, our team was tasked with designing a system that allows scientists to accurately and efficiently collect and view data from laboratory rats.

In order for our system to operate accurately and efficiently, both the overall system and the individual subsystems need to adhere to certain performance specifications. For example, because the system will be used by scientists in research laboratories, it is vital that the data collected is accurate, precise, and reliable. In addition, the process of collecting the data from the rat and displaying it back to the user needs to be responsive and user-friendly. Appendix A outlines the specifications for the overall system in more detail. In the following subsections, we describe the performance specifications for each of the three subsystems: the implant, the base station, and the web application.

2.1 Implant Specifications

Because the implant will be embedded in a rat, it must comply with the most stringent requirements and constraints. Most importantly, the implant must not adversely affect the rat. Therefore, it needs to be sterile, biocompatible, and small. To meet the size constraint, it must also be batteryless and wireless. Additionally, the implant must have a significant lifespan so that it will not need to be replaced throughout the duration of a study. Appendix A explains the specifications for the implant in more detail.

2.2 Base Station Specifications

Unlike the implant, the base station will be outside of the rat, most likely attached to the cage. The main purpose of the base station is to wirelessly power and communicate with the implant. Therefore, the base station needs to transmit power and data from minimum distance and at a minimum bandwidth. In addition, because the base station needs to accommodate the layout of

the laboratory, it needs to be portable. Appendix A describes the specifications for the base station in more detail.

2.3 Web App Specifications

In order to accommodate the number of users and volume of data traffic, the web application needs to be universal and scalable. First, it needs to run on a wide range of platforms and browsers so that a variety of users can access the web application regardless of the type of machine they are using. Second, the web application needs to be vertically and horizontally scalable so that it can handle large quantities of users and transactions. Appendix A outlines the specifications for the web application in more detail.

3.0 DESIGN PROBLEM SOLUTION

The system is comprised of three subsystems. As illustrated in Figure 1, the three subsystems are an implant, a base station, and a web application. The web application allows the user to request data from the implant. Once the data request is initiated, the web application sends a command to the base station. From there, the base station wirelessly powers the implant and relays the command. Upon collecting the requested data from the rat, the implant wirelessly transfers the data back to the base station. The base station then relays the data back to the web application. Finally, the web application displays the data back to the user.

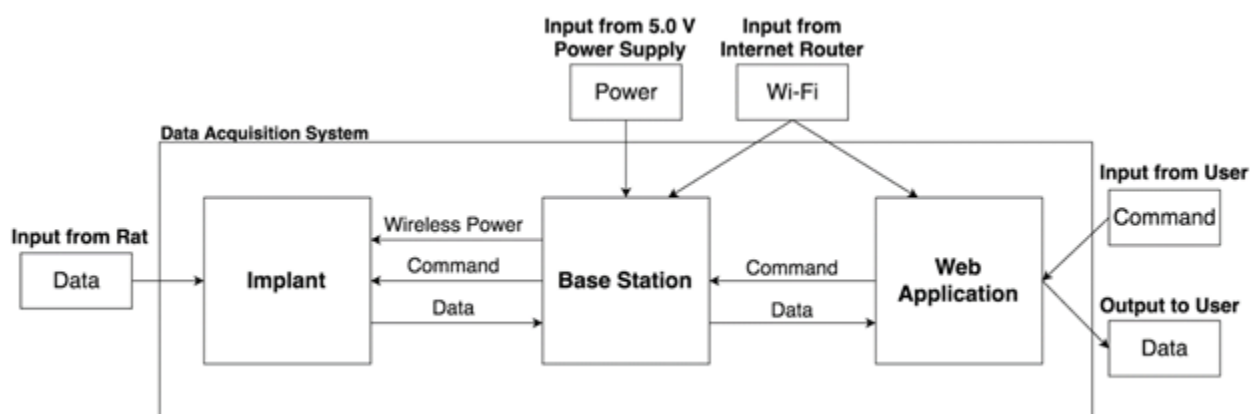


Figure 1. System Block Diagram

In the following subsections, we describe the design solution for each subsystem in more detail. For each subsystem, we explain its functionality and input and output specifications.

3.1 Implant Design

The purpose of the implant is to receive power and commands from the base station, collect the requested temperature or acceleration data, and transmit that data back to the base station. In order for the implant to perform these tasks, it adheres to certain input and output specifications. For example, the implant must receive enough power from the base station in order to function. In addition, the implant must be able to receive that power at a minimum distance from the base station in order for the implant to operate correctly while the rat moves around. Finally, the implant must be able to collect temperature and acceleration data from the rat, and send that data to the base station. Appendix A outlines the input and output specifications for the implant in more detail.

3.2 Base Station Design

The purpose of the base station is to wirelessly power the implant and interface the web application with the implant. In order for the base station to perform these tasks, it complies with various input and output specifications. For example, the base station receives power from an external power supply. In addition, the base station also has access to Wi-Fi so that it can connect to the internet. Furthermore, the base station must provide the implant with enough power for the implant to operate. Moreover, the base station receives commands from and sends data to both the web application and implant. Appendix A outlines the input and output specifications for the base station in more detail.

3.3 Web Application Design

The third subsystem is the web application, which also doubles as the user interface. The purpose of the web application is to allow the user to control and interact with implant. In order for the web application to perform this task, it, too, adheres to certain input and output specifications. For example, the web application receives requests from the user. In addition, it sends commands to and receives data from the base station. Finally, it stores the data in a database and displays the

data back to the user. Appendix A outlines the input and output specifications for the web application in more detail.

4.0 DESIGN IMPLEMENTATION

As previously mentioned, the system is comprised of three subsystems: the implant, the base station, and the web application. In the following subsections, we describe the design implementation for each subsystem in more detail. For each subsystem, we discuss our current implementation as well as alternative implementations that our team had considered.

4.1 Implant Implementation

The implant is a two-layer PCB that consists of a microcontroller for system control, a thermistor for temperature measurement, an accelerometer for acceleration measurement, and a coil to receive power from and communicate with the base station. For the microcontroller, we selected the TI RF430FRL152H (RF430) because of its wireless power transmission and communication capabilities, low power consumption, I²C communication interface, and 14-bit internal temperature sensor. Because the microcontroller includes an internal temperature sensor, there was no need for an external thermistor. For the accelerometer, we selected the NXP MMA8452Q (MMA) because of its low supply voltage requirements, low power consumption, I²C communication interface, and 12-bit triple axis acceleration measurements. Originally, we had selected the LIS3DH accelerometer for similar reasons. Unfortunately, we were unable to successfully interface the LIS3DH with our implant. For the coil design, we leveraged an online tool that calculates the inductance of a coil using Wheeler's approximation method. Although we desired an inductance of 3 μ H [2], because our coil traces used a spacing of 0.2 mm, the closest inductance we could achieve varied between 2.8 and 2.9 μ H. Therefore, we added a tuning capacitor with a range of 2 to 10 pF to our design. As depicted in Figure 2, on the next page, the microcontroller, accelerometer, and coil combine to make up the implant.

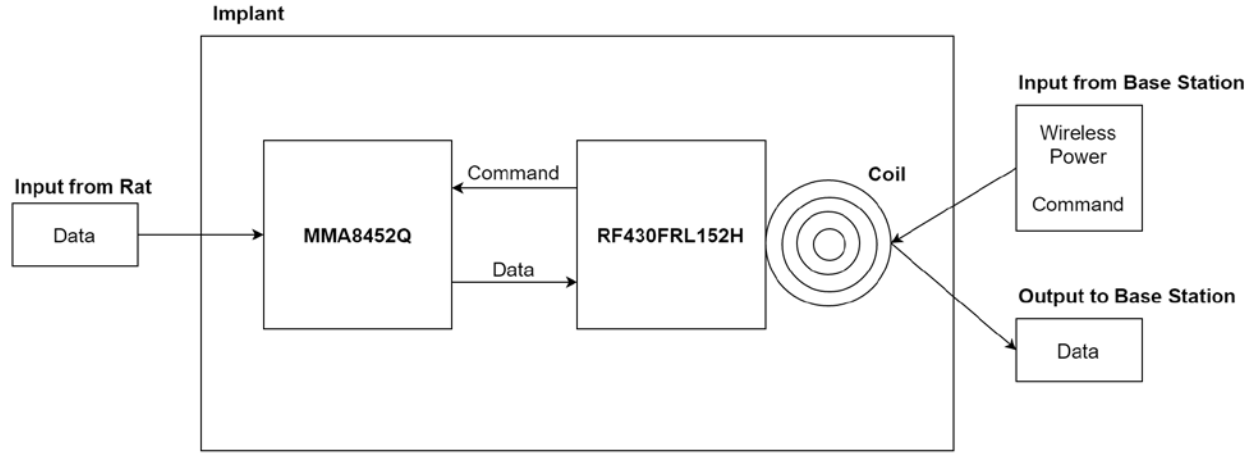


Figure 2. Implant Block Diagram

The implant receives power from the base station. When powered, the implant receives commands from the base station through the coil. If the command is for temperature, the implant uses internal ROM functionality to sample the internal temperature sensor. If the command is for acceleration, the implant uses I²C to sample the MMA. When the corresponding data has been collected, the implant sends the data back to the base station.

4.2 Base Station Implementation

Because the base station needs to be able to interface with both the implant and the web application, the base station consists of two parts. The first part is the TI TRF7970A (TRF) evaluation module, which is responsible for powering and communicating with the implant. We selected the TRF because of its compatibility with the RF430 and its USB interface. The second part is the Raspberry Pi 3 (RPi), which is responsible for communicating with the web application. Instead of the RPi, we could have selected a TM4C123, Arduino, or BeagleBone. However, we selected the RPi because of its USB interface, built-in Wi-Fi functionality, and compatibility with the IBM Watson Internet of Things Platform, which we will discuss more in depth in the following section. As depicted in Figure 3, on the next page, the TRF and RPi combine to make up the base station.

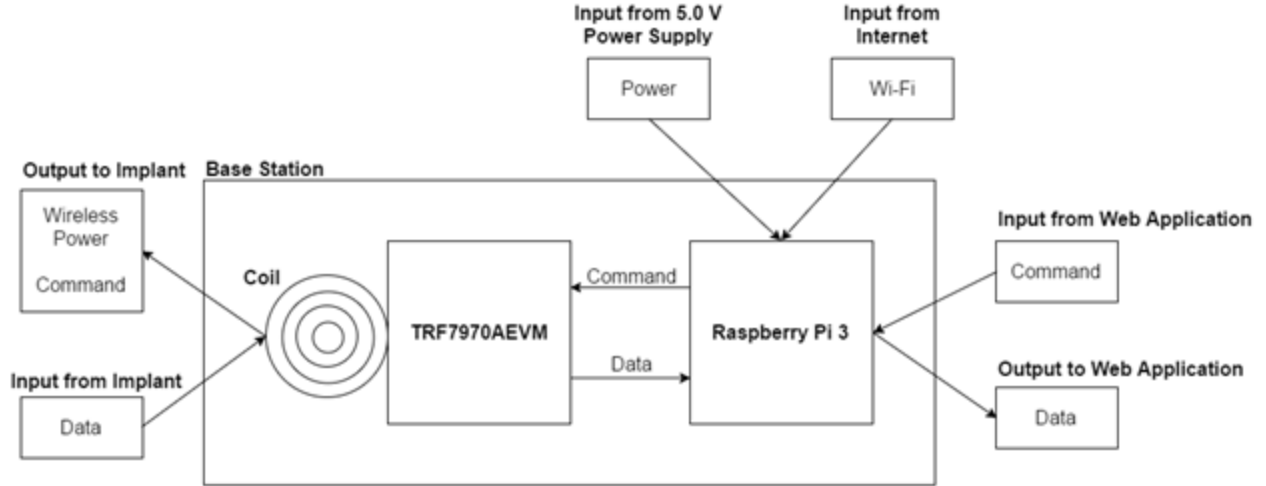


Figure 3. Base Station Block Diagram

On the RPi, there is a Python script listening for commands from the web application. The RPi then sends the commands to the TRF through USB. C-code on the TRF receives the command and sends it to the implant through the coil. When the TRF receives a response from the implant, it sends the data back to the RPi. The RPi then sends the data back to the web application.

4.3 Web Application Implementation

The web application is built on IBM Bluemix, a cloud platform for developing scalable web and mobile applications. We selected the Bluemix platform over Amazon Web Services and Microsoft Azure because of its robust catalog of application runtimes, services, and APIs. As depicted in Figure 4, on the next page, the web application consists of four components. Two of the components form the actual web application while the other two components are back-end services. For the web application, the first component runs on Node.js and leverages HTML, CSS, and JavaScript. It allows the user to request data from the implant and then processes and displays the returned data. The second component runs on Node-RED and leverages JavaScript to store the returned data into a database. For the back-end services, we used IBM Watson IoT Platform and IBM Cloudant. The IBM Watson IoT Platform allows the web application to send commands to and receive data from the base station over the MQTT messaging protocol, while IBM Cloudant offers powerful data storage and search capabilities.

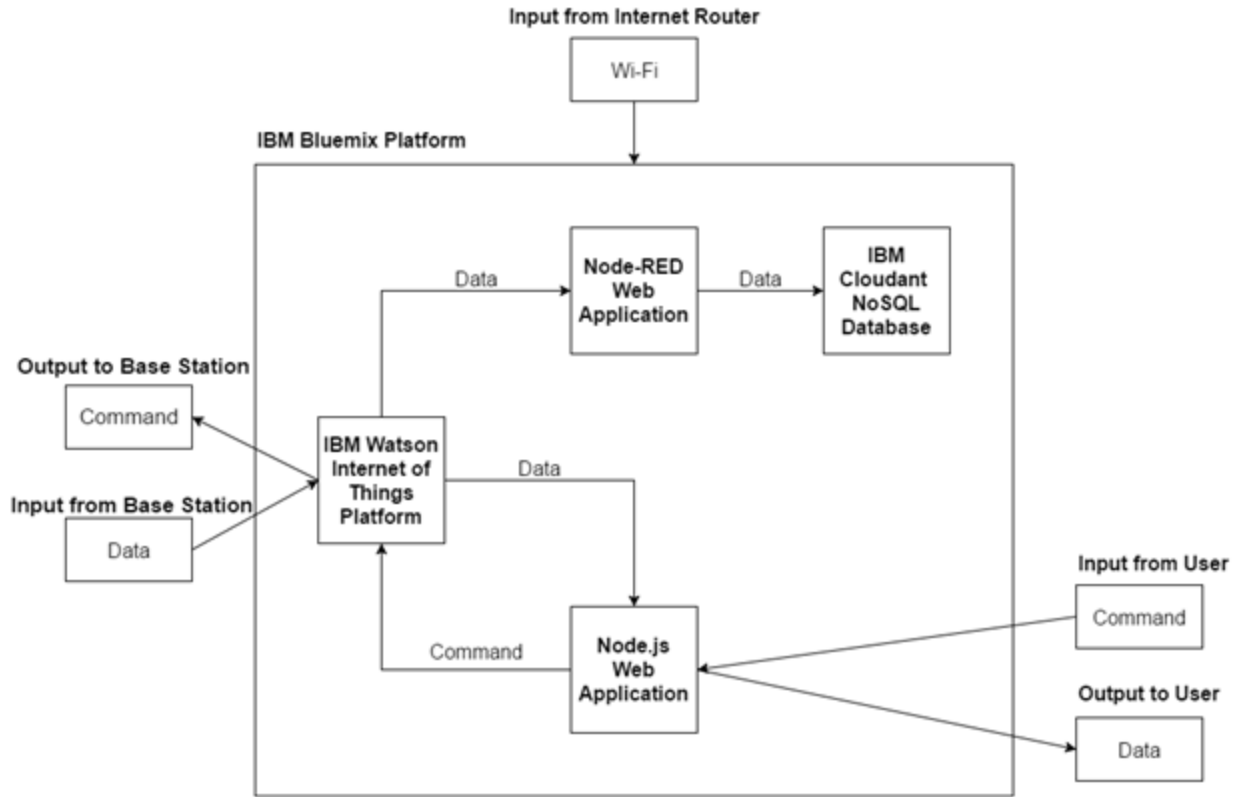


Figure 4. Web Application Block Diagram

5.0 TEST AND EVALUATION

In order to make a final assessment of our data acquisition system, we developed a testing plan that focused on the signals being passed throughout our system. Focus was put on the signals due to the high modularity of the system. On a larger scale, key components such as the coils were tested before moving on to the different modules of the system. Finally, a few tests were run on the system level, with multiple measuring points located at key areas to confirm correct functionality.

5.1 Component Acceptance Testing

Since most of the components of our system are tightly coupled, the coils were the only components that could feasibly be tested by themselves. Since the coils were designed on a PCB with a target inductance of $3\mu\text{H}$, this was the main quantity that needed to be tested. In order to confirm that the PCBs we ordered matched this expected value, Albert Marzullo and Corey

Cormier brought our PCBs to the Pickle Research Campus and used a network analyzer to determine the equivalent RLC circuit of our coils. From these tests we concluded that our coils were close, but slightly lower than the target 3 μH , ranging from 2.7 μH to 2.9 μH . We determined that these values were acceptable, as the slightly lower inductance of the coils could be compensated by the 2-10 pF tuning capacitor we added to our implant design.

5.2 Module Level Testing

Before integrating the different parts of the system, we conducted several tests to establish that each independent module functioned as expected. By controlling the inputs and measuring key outputs, we were able to validate the operations of each module. To ensure the accuracy of each test, tests solely relied on previously verified components or modules. Input signals and data manipulation were also controlled for the tests in order to show reliable results. The following sections expand on the tests we performed for the implant, the base station, and the web application.

5.2.1 Implant Testing

To confirm that the implant operates correctly, we tested the resonant frequency of the implant, the voltage output by the implant coil, and the operation of the RF430 chip. We first tested the resonant frequency of the chip as soon as all of the parts were soldered onto the implant. Albert Marzullo, Corey Cormier, and Mike Park did this by measuring the peak impedance of the implant using the network analyzer at the Pickle Research Campus. Since the inductance of the coils were a bit lower than we expected, the resonant frequency of the implants was slightly over the 13.56 MHz necessary to communicate with the base station. By adding capacitance to our implant with the 2-10 pF tuning capacitor, we were able to get the resonant frequency of our implants within 0.1 MHz of our desired frequency. We calculated the amount of capacitance we needed to add by using the equation

$$f_r = \frac{1}{2\pi\sqrt{LC}} ,$$

where f_r is the resonant frequency, L is the inductance, and C is the capacitance of the RLC circuit. After tuning the resonant frequencies of the implants to acceptable ranges, we tested the voltage generated by the implant coil when held above the base station evaluation board. By attaching oscilloscope probes across the implant coil, Corey Cormier was able to confirm that the voltage output was between 1.5 V and 3.3 V, which was in the operating range of the RF430, within the required distance of 5 cm. The coil voltage profile is depicted in Figure 5, on the next page. After determining that the RF430 was receiving the necessary voltage, we tested to see if the RF430 was functioning as we expected. To do this, Albert Marzullo first measured the V_{DD} voltage output of the chip. This voltage is supposed to be close to 1 V whenever the chip is powered on. Using a multimeter, Albert Marzullo confirmed that the V_{DD} on our RF430 was 1 V and that the chip was being powered on. Finally, Corey Cormier and Mike Park sent dummy data to the RF430 from the base station and had the RF430 echo the value back to the base station. When we successfully did this, we confirmed that the RF430 was able to communicate in both directions with the base station through the induction coils.

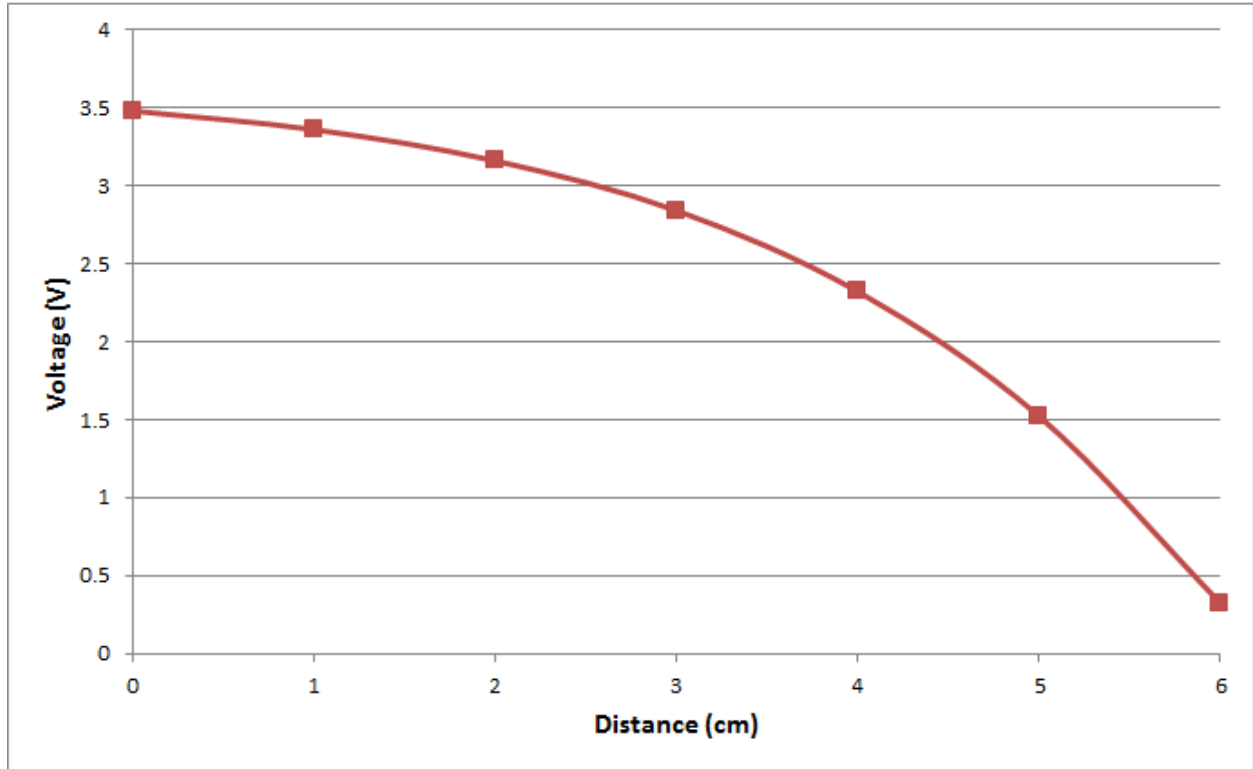


Figure 5. Coil Voltage vs. Distance

5.2.2 Base Station Testing

The quality of the base station was assessed based on its functionality and performance. The purpose of the base station is to wirelessly power the implant and to interface the implant and the web application. In order to ensure the functionality of the base station, Corey Cormier and Albert Marzullo leveraged an oscilloscope to measure the amount of power supplied, which should be 200 mW at maximum. In addition, Corey Cormier and Mike Park wrote C code and used an oscilloscope to test the wireless communication to the implant. Finally, Makeila Sorensen wrote Python scripts to test the base station's connection and communication with Watson IoT Platform and thus, the web application. We were able to confirm that the base station could transfer data to and from the implant and web application using the oscilloscope to monitor output lines on the base station and print statements to read out the data that was sent and received by the base station.

For performance, it is important that the base station is able to transfer and process data quickly. Therefore, we measured the time it takes for the base station to receive and process a command, the time it takes for the base station to publish a command, and the time it takes for the base station to receive, process, and relay an event. These measurements were taken by printing the timestamps immediately before and after test processes were executed, and calculating the difference. Combined, these processes took less than the maximum allowed time of 1 second.

5.2.3 Web App Testing

We evaluated the quality of the web application based on its accessibility, functionality, and performance. For accessibility, we tested that it can be accessed from different platforms and browsers. At a minimum, the web application needs to function on the Windows 7, Mac OS X, and Linux platforms, as well as the Chrome 49 and Firefox 45 browsers. These were simple binary tests that were performed by Tom Ermis. In addition, the web application needs to be horizontally and vertically scalable. The platform that we leveraged to build the web application allows us to automatically scale out by clicking a button to increase the number of instances and scale up by increasing the amount of memory per instance. Again, these tests were performed by Tom.

With regards to functionality, the web application needs to interface with the user, the Watson IoT Platform, and the Cloudant NoSQL Database. For the user interface, we tested that each of the input boxes and buttons perform the dedicated function. Makeila Sorensen tested this by entering in text and clicking on buttons to make sure the correct callback functions were initiated. In addition, the web application needs to be able to connect to, publish commands to, and receive events from the Watson IoT Platform. Makeila tested this functionality by printing debug statements to confirm when each of those tasks are executed and what data was transferred. Finally, the web application needs to be able to connect to, store data in, and retrieve views from the Cloudant NoSQL database. Makeila performed tests for the Cloudant NoSQL database similar to those for the Watson IoT Platform.

For performance, we evaluated the response time of the web application. First, Makeila Sorensen measured the time it takes for the web application to publish a command to the Watson IoT Platform. Second, she measured the time it takes for the web application to receive an event from the Watson IoT Platform. Third, Makeila measured the time it takes for the web application to store data in the database, as well as update the data on the web application. These measurements were performed by printing the timestamps immediately before and after the process executes and taking the difference. Combined, these processes took less than the maximum allowed time of 1 second.

5.3 System Level Testing

Once each subsystem had been tested independently, we combined the subsystems and conducted tests on the system as a whole. In order to do test the flow of our system, Corey Cormier will first attach an oscilloscope to the communication channel of the implant so he can view the data that the implant is collecting. Similarly, Corey will attach an oscilloscope to the communication channel of the base station so that he can verify the data that the base station is receiving. Makeila Sorensen will then send power and data commands from our web application to collect data from the implant. As the implant collects data and the web application displays it, Corey Cormier will compare the data displayed on the oscilloscopes to that displayed on the web application and confirm that they match. All components interacted correctly, and our system's returned value was 95% accurate when compared to measurements taken with a digital thermometer.

Once our system was functioning correctly, Makeila Sorensen and Anish Vaghasia ran a series of tests to confirm our system is both timely and versatile. In order to test for timely responses, Makeila Sorensen ran a series of automated scripts that called multiple commands from our web application simultaneously, effectively load testing our system. Makeila then observed the response times for our system under these conditions and ensured they were all under two minutes. Anish Vaghasia tested to make certain our system remains functional, both when the distances are varied between the implant and the base station coils and when our implant is

placed under different operating conditions. Ultimately, this suite of tests confirmed the correct operation of our system as a whole.

6.0 TIME AND COST CONSIDERATIONS

With careful planning and management of our project, we were able to work through the issues we encountered to successfully complete our project on time and with limited expense. Our team was given two major deadlines by which we needed to finish our project, the mid project demo and ECE open house. While we designed our project schedule to meet these deadlines, we unfortunately encountered a few issues while working. During the course of our project we went through about 10 different versions of our implant PCB. Each time we created a new version, new boards had to be shipped, which added weeks in delays to implant testing. We passed this hurdle by starting the process early and ordering the next version while the previous version was still in shipment. Our next issue occurred due to our assumption that soldering components to our implant PCB would be trivial. However, when we actually tried to solder components, not all of our components would work. The debug process caused further delays in our implant testing and, consequently, our system as a whole. We were able to mitigate these delays due to our planned buffer time and early completion date. Even with the delays we were able to finish the project by the two major deadlines.

Our project was sponsored by our faculty mentor, so there were no official budget constraints that had to be met. Our team also took advantage of the school's close relationship with TI to order free parts and components. Our major expenses actually came from ordering PCB's and miscellaneous items. However, because all costs were paid for by Dr. Valvano, he requested all items that needed to be purchased be approved by him. This introduced a small time delay when we had to seek Dr. Valvano's approval to order new part but did not cause any major issues.

7.0 SAFETY AND ETHICAL ASPECTS OF DESIGN

There are several major safety and ethical concerns that factor into the design of our system. First, the frequencies at which our system is powered and communicates and the communication protocol it follows need to adhere to the standards set forth by the Federal Communications

Commission (FCC). Second, because part of our system will be embedded into an animal and, eventually, a human, our system also needs to comply with the Animal Welfare Act of 1966 (AWA) and the regulations set forth by The Food and Drug Administration (FDA). Finally, as engineers, it is also important that as a team, we, and our system, adhere to the Institute of Electrical and Electronics Engineers (IEEE) Code of Ethics.

The FCC has specific regulations describing the available frequencies that our system can use for power and communication as well as the communication protocol that it can use. For example, the only frequency bands that have been designated for use under specified conditions are those between 9 kHz and 275 GHz [2]. In addition, the FCC also limits the maximum electromagnetic field that a human can be exposed to for radio frequencies between 300 kHz and 100 GHz [3]. As previously mentioned, our implant and base station communicate at 13.56 MHz, thereby complying with the aforementioned standards. Furthermore, wireless power transfer devices operating at frequencies above 9 kHz are considered to be intentional radiators and are therefore subject to Parts 15 and 18 of the FCC rules [4]. In order to ensure the legality and safety of our system, it is important to adhere to the rules of the FCC.

Several major safety and ethical concerns stem from embedding a device into an animal. First, it is important that all animals intended for research are treated humanely. Therefore, all research laboratories need to meet the minimum standards for the animal's housing, water, feeding, sanitation, ventilation, and handling [5]. Second, implants pose several safety hazards to the animal. For example, if the implant is not sterile or biocompatible, it could adversely react with tissues and organs [6]. For the scope of our project, we simply coated the implant in silicon in order to make it biocompatible. In addition, it is possible that the implant could migrate under the skin and throughout the body [6]. Furthermore, the implant could have unintended consequences at locations adjacent to and downstream of the implant site, as well as along all paths to and from the implant site [7]. However, such risks can be reduced by complying with the regulations set forth by the AWA and FDA.

There are also several safety and ethical concerns that result from a possible future application, embedding a device into a human. First, implants are a possible violation of an individual's right to bodily integrity [8]. Therefore, the device should only be embedded into a person with his or her clear consent. Second, implants are a possible infringement of an individual's right to privacy [6]. Because the device communicates personal data, it is essential to design a secure system that will safeguard against the possible misuse of that data. Third, the implant could be a source of interference with other medical technologies and devices [6]. Again, in order to mitigate such risks, it is necessary to conform to the standards set forth by the FDA.

Finally, because we are a team of engineers and because our system will be integrated into animal and human life, it is important that we adhere to the IEEE Code of Ethics. It is our responsibility to make decisions "consistent with the safety, health, and welfare of the public" [9]. In addition, we must "disclose promptly factors that might endanger the public or the environment" [9]. Furthermore, we must "be honest and realistic in stating claims or estimates based on available data" [9]. Because the technology we develop has the potential to affect the quality of life throughout the world, it is essential that we obey these policies, among others.

Please refer to Appendix C for a description of the relevant FCC, AWA, and FDA regulations and for the IEEE Code of Ethics.

8.0 RECOMMENDATIONS

While the team was able to create a fully functioning prototype of the project, there are a few recommended steps that will bring the project to more of a stable, operational form. The recommended steps revolve around each of the three separate modules. In its current state, the implant is able to fully meet the specifications created at the start of the project. However, since the module will be going inside of a lab animal, a smaller form is more desirable. To do that, the size of the induction coil in the implant should be decreased. This will allow for the implant to be designed much smaller. Another desirable aspect would be to increase the range for which the implant and base station can communicate. This can be done by increasing the size of the induction coil on the base station. An increased range will increase the usability to the system.

Finally, since the users for this project will be researchers in a lab environment, the usability of the web app should also be improved. Therefore, adding user authentication and data storage will allow for an application that will act as a much better fit for research environments.

9.0 CONCLUSIONS

This final report has detailed the design, implementation, testing, and evaluation of our implanted data acquisition system for research labs. We created our proposed solution to fit the needs of the client and the design problem. Dr. Valvano needed a system that would be accurate and efficient for a laboratory environment. The problem required that the implant subsystem can be powered and communicate wirelessly. The final design consists of a three-part system: the implant, the base station, and the web application. The implant is small enough to fit inside a lab rat and has attached sensors to collect the temperature and acceleration data. The implant and the base station both have inductor coils attached to wirelessly send power, data, and commands between the two subsystems. The base station sends the data to a web application where it can be viewed by a user and relays commands from the user to the implant. The web application provides a layer of abstraction between the operation of the system and the user, thus allowing for ease of use.

Careful testing and evaluation of the project was also done to ensure validity of the system based on the design specifications created by this team. In this report we outlined exactly what requirements our data acquisition system needed to meet, and did meet, in order to be considered successful. These specifications were created upon careful review of the client's needs and the project's environmental considerations. Due to careful time and cost management the project was kept under budget and on schedule. Careful consideration for safety and ethical factors was also performed for the project due to the environment it will be operating under. Finally, we recommended changes for each of the modules that will best further advance the project. While just a prototype now, the project has exciting future applications in industries like healthcare and infrastructure. It is sure to make its mark on the world.

REFERENCES

- [1] (2014, December 22). *Guidance for Industry and FDA Staff – Class II Special Controls Guidance Document: Implantable Radiofrequency Transponder System for Patient Identification and Health Information* [Online]. Available: <http://www.fda.gov/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/ucm072141.htm>
- [2] “Single Layer Planar Spiral Coil Inductor Calculator” [Online]. Available: http://www.circuits.dk/calculator_planar_coil_inductor.htm
- [2] *Radio Spectrum Allocation* [Online]. Available: <https://www.fcc.gov/engineering-technology/policy-and-rules-division/general/radio-spectrum-allocation>
- [3] *Radio Frequency Safety* [Online]. Available: <https://www.fcc.gov/general/radio-frequency-safety-0>
- [4] (2013, May 31). *RF Exposure Considerations for Low Power Consumer* [Online]. Available: https://apps.fcc.gov/kdb/GetAttachment.html?id=gDJO4az8eyw84%2BguyjPd%2Bw%3D%3D&desc=680106%20D01%20RF%20Exposure%20Wireless%20Charging%20Apps%20v02&tracking_number=41701
- [5] Tadlock Cowen. (2013, June 12). *The Animal Welfare Act: Background and Selected Animal Welfare Legislation* [Online]. Available: <http://nationalaglawcenter.org/wp-content/uploads/assets/crs/RS22493.pdf>
- [6] (2014, December 22). *Guidance for Industry and FDA Staff – Class II Special Controls Guidance Document: Implantable Radiofrequency Transponder System for Patient Identification and Health Information* [Online]. Available: <http://www.fda.gov/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/ucm072141.htm>
- [7] (2015, October 14). *Guidance for Industry and FDA Staff: General Considerations for Animal Studies for Medical Devices* [Online]. Available: <http://www.fda.gov/downloads/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/UCM466358.pdf>
- [8] K. R. Foster and J. Jaeger. (2007, March 1). *RFID Inside: The Murky Ethics of Implanted Chips* [Online]. Available: http://repository.upenn.edu/cgi/viewcontent.cgi?article=1098&context=be_papers

- [9] *IEEE Code of Ethics* [Online]. Available:
<http://www.ieee.org/about/corporate/governance/p7-8.html>
- [10] A. Stammers, "The Blood Count and Body Temperature in Normal Rats", *The Journal of Physiology*, vol. 61, no. 3, pp. 329-336, 1926.

APPENDIX A - SPECIFICATIONS

APPENDIX A - SPECIFICATIONS

The following appendix provides elaboration on the system and component specifications of the data acquisition system. Table A-1 describes the specifications our system must meet at a system level. Table A-2, Table A-3, and Table A-4 each describe implant, base station, and web application specifications that must be met respectively. Finally, Table A-5 and Table A-6, Table A-7 and Table A-8, and Table A-9 and Table A-10 describe the input and output specifications of our implant, base station, and web application respectively.

Table A-1. System Specifications

Name	Description	Specification
Maximum Response Time	Maximum length of time in which the system has to respond to the user	2 minutes
Measurement Accuracy	Accuracy of the temperature and acceleration measurements	$\geq 95\%$

Table A-2. Implant Specifications

Name	Description	Specification
Minimum Lifespan	Minimum length of time in which the implant has to operate from the time of implantation	6 months
Sterility	Minimum sterility assurance level of the implant	SAL of 10^{-6} [1]
Biocompatibility	Minimum standard of biocompatibility of the implant	ISO 10993 [1]
Maximum Length	Maximum length of the implant	8 cm
Maximum Width	Maximum width of the implant	8 cm
Maximum Height	Maximum height of the implant	0.3 cm
Operating Temperature	Range of temperature in which the implant has to operate	0° to 45° C

Table A-3. Base Station Specifications

Name	Description	Specification
Maximum Length	Maximum length of the base station	30 cm
Maximum Width	Maximum width of the base station	30 cm
Maximum Height	Maximum height of the base station	30 cm
Operating Temperature	Range of temperature in which the implant has to operate	0° to 45° C
Distance	Distance at which the base station is required to wirelessly power and communicate with the implant	8 cm
Minimum Bandwidth	Minimum frequency at which the base station and implant have to be able to wirelessly communicate	1 Hz

Table A-4. Web Application Specifications

Name	Description	Specification
Platforms	Minimum platforms the web application needs to be accessed on	Windows 7, Mac OS X, Linux
Browsers	Minimum browsers the web application needs to be accessed on	Chrome 49, Firefox 45
Scalability	Level of scalability offered by the web application	Horizontal, Vertical

Table A-5. Implant Input Specifications

From	Name	Description	Specification
Base Station	Wireless Power	Amount of power transferred within a certain distance	Range <ul style="list-style-type: none"> ● 0 to 200 mW ● 0 to 8 cm Accuracy <ul style="list-style-type: none"> ● ± 0 mW ● ± 0.01 cm
Base Station	Command	Command to collect data from the rat	See Table B-1 “Command Specifications” in Appendix B “Further Specifications”
Rat	Data	Data collected from the rat	See Table B-2 “Data Specifications” in Appendix B “Further Specifications”

Table A-6. Implant Output Specifications

To	Name	Description	Specification
Base Station	Data	Data collected from the rat	See Table B-2 “Data Specifications” in Appendix B “Further Specifications”

Table A-7. Base Station Input Specifications

From	Name	Description	Specification
Power Supply	Power	Power supply for the base station	Value ● 5.0 V ● 1 A Accuracy ● ± 0 V ● ± 0 A
Internet Router	Wi-Fi	Wi-Fi for the base station	Wi-Fi
Web Application	Command	Command that collects data from the rat	See Table B-1 “Command Specifications” in Appendix B “Further Specifications”
Implant	Data	Data collected from the rat	See Table B-2 “Data Specifications” in Appendix B “Further Specifications”

Table A-8. Base Station Output Specifications

To	Name	Description	Specification
Implant	Wireless Power	Amount of power transferred within a certain distance	Range <ul style="list-style-type: none"> ● 0 to 200 mW ● 0 to 8 cm Accuracy <ul style="list-style-type: none"> ● ± 0 mW ● ± 0.01 cm
Implant	Command	Command to collect data from the rat	See Table B-1 “Command Specifications” in Appendix B “Further Specifications”
Web Application	Data	Data collected from the rat	See Table B-2 “Data Specifications” in Appendix B “Further Specifications”

Table A-9. Web Application Input Specifications

From	Input	Description	Specification
Internet Router	Wi-Fi	Wi-Fi for the web application	Wi-Fi
User	Command	Command to collect data from the rat	See Table B-1 “Command Specifications” in Appendix B “Further Specifications”
Base Station	Data	Data collected from the rat	See Table B-2 “Data Specifications” in Appendix B “Further Specifications”

Table A-10. Web Application Output Specifications

To	Output	Description	Specification
Base Station	Command	Command to collect data from the rat	See Table B-1 “Command Specifications” in Appendix B “Further Specifications”
User	Data	Data collected from the rat	See Table B-2 “Data Specifications” in Appendix B “Further Specifications”

APPENDIX B - FURTHER SPECIFICATIONS

APPENDIX B - FURTHER SPECIFICATIONS

The following appendix provides further elaboration on the major inputs and outputs of the data acquisition system. Table B-1 describes the properties of the command that is sent from the web application to the base station and from the base station to the implant. Table B-2 describes the properties of the data that is sent from the implant to the base station and from the base station back to the web application. Finally, Table B-3 describes the specifications for the different types of data that are being sent.

Table B-1. Command Specifications

From	Name	Description	Specification
Web Application	Base Station ID	Unique identification number for the base station that the command was sent to	16 digit sequence of numbers
Base Station	Implant ID	Unique identification number for the implant that the command was sent to	16 digit sequence of numbers
Web Application	Data Type	Name of measurement	String
Web Application	Data Timestamp	Date and time the command was sent to the base station	Year, Month, Day, Hour, Minute, Second, Millisecond

Table B-2. Data Specifications

From	Name	Description	Specification
Web Application	Data ID	Unique identification number for the data	16 digit sequence of numbers
Web Application	Base Station ID	Unique identification number for the base station that the data came from	16 digit sequence of numbers
Base Station	Implant ID	Unique identification number for the implant that the data came from	16 digit sequence of numbers
Implant	Data Type	Type of the data	String
Rat	Data Value	Value of the data	See Table B-3 “Data Type Specifications” in Appendix B “Further Specifications”
Base Station	Data Timestamp	Date and time the data was received by the base station	Year, Month, Day, Hour, Minute, Second, Millisecond

Table B-3. Data Type Specifications

Type	Description	Specification
Temperature	Measured temperature of the rat	Range <ul style="list-style-type: none"> • 0° to 45° C Accuracy <ul style="list-style-type: none"> • $\pm 0.01^{\circ}$ C
Acceleration	Measured acceleration of the rat	Range <ul style="list-style-type: none"> • ± 2 g Accuracy <ul style="list-style-type: none"> • 0.01 g

APPENDIX C – APPLICABLE STANDARDS

APPENDIX C – APPLICABLE STANDARDS

Federal Communications Commission

The FCC regulates interstate and international communications by wire, cable, radio, television, satellite across the United States. Because our system needs to use radio frequencies to power itself and to communicate, it is important that our systems adheres to the FCC rules. Below are three excerpts from the FCC that highlight the regulations our system needs to comply with.

“...Currently only frequency bands between 9 kHz and 275 GHz have been allocated (i.e., designated for use by one or more terrestrial or space radiocommunication services or the radio astronomy service under specified conditions)...” [2].

“...On August 1, 1996, the Commission adopted the NCRP's recommended Maximum Permissible Exposure limits for field strength and power density for the transmitters operating at frequencies of 300 kHz to 100 GHz. In addition, the Commission adopted the specific absorption rate (SAR) limits for devices operating within close proximity to the body as specified within the ANSI/IEEE C95.1-1992 guidelines...” [3].

“...Depending on the operating configurations, wireless power transfer devices may need to be approved under FCC Rule Parts 15, 18 or both. Devices authorized under Part 15 may not transmit in the 90-110 kHz band, which is restricted under §15.205. Part 18 of the rules permit devices operating in the Industrial, Scientific and Medical (ISM) band to generate and use RF energy locally to perform work...” [4].

Animal Welfare Act of 1966

The AWA ensures that animals intended for research, bred for commercial sale, commercially transported, or exhibited to the public, are treated humanely. Because part of our system will be embedded into an animal, it is necessary that our system complies with the AWA. Below are two excerpts from the AWA that highlight the standards our design needs to abide by.

“...The Animal Welfare Act...expanded animal coverage to include all warm-blooded animals determined by the Secretary to be used for experimentation or exhibition...” [5].

“...The law directs the Secretary to set new minimum standards of care for handling, housing, feeding, water, sanitation, ventilation, and so forth...The law provides that research facilities must have procedures that minimize pain and stress to the animals, and describes practices considered to be painful...” [5].

Food and Drug Administration

The FDA is responsible for protecting the public health by ensuring the safety and security of food, human and animal drugs, and medical devices. Because part of our system will be embedded into an animal and, eventually, a human, it is essential that our system adheres to FDA standards. Below are several excerpts from the FDA that highlight the relevant standards our system needs to conform to.

“...We recommend that the transponder and inserter be sterile with a sterility assurance level of 10^{-6} ...” [6].

“...We recommend that you ensure the biocompatibility of the patient-contacting parts of your device...” [6].

“...FDA recommends that you identify key biologic response variables at regional sites, at locations adjacent to the implant site, and along all paths to and from the point of implantation...” [7].

“...FDA recommends that you evaluate whether or not the device can have effects 365 remote from the site of placement or use...” [7].

“...We recommend that you conduct testing of the implanted transponder to demonstrate that the transponder will not migrate after implantation...” [6].

“...We recommend that your specifications for a compatible database address the following four components of information security: Confidentiality, Integrity, Availability, and Accountability...” [6].

“...We recommend that you demonstrate the basic EMC of the device (i.e., transponder and scanner together) by performing EMC testing...” [6].

“...We recommend that you demonstrate the magnetic resonance imaging compatibility of your device...” [6].

IEEE Code of Ethics

The purpose of IEEE is to advance educational and technological excellence and innovation for the benefit of humanity. Because we are a team of engineers and our system will be integrated into animal and human life, it is important that we abide by the IEEE Code of Ethics. Below is the full IEEE Code of Ethics.

“We, the members of the IEEE, in recognition of the importance of our technologies in affecting the quality of life throughout the world, and in accepting a personal obligation to our profession, its members and the communities we serve, do hereby commit ourselves to the highest ethical and professional conduct and agree:

- 1. to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment;*
- 2. to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist;*
- 3. to be honest and realistic in stating claims or estimates based on available data;*
- 4. to reject bribery in all its forms;*
- 5. to improve the understanding of technology; its appropriate application, and potential consequences;*

- 6. to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations;*
- 7. to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others;*
- 8. to treat fairly all persons and to not engage in acts of discrimination based on race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression;*
- 9. to avoid injuring others, their property, reputation, or employment by false or malicious action;*
- 10. to assist colleagues and coworkers in their professional development and to support them in following this code of ethics [9].”*