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SUBJECT: Prior Art Report for Developing a Wireless Power Transmission and Communication System for Implantable Devices in a Rat

INTRODUCTION

The purpose of this report is to document the foundation for our design and existing science and technology that could improve it. The methods that scientists currently use to collect data from laboratory rats are highly inefficient. Therefore, Dr. Valvano needs a system that will allow scientists to monitor and analyze that data more effectively. The primary goal of our project is to create a system that functions as a medical implant, but is also small enough to be embedded in a rat for an extended period of time. Our team plans to implement such a system in the fall semester of 2016.

In order to meet the design requirements and constraints that were outlined in our Problem Statement, our team conducted research on prior art involving wireless power transmission and communication. In this report, we discuss how each prior art either provides a basis for our design or has the potential to improve it. For example, the size of the implant can be reduced by decreasing the number of sets of coils. In addition, power transmission can be strengthened by increasing the number of and changing the geometry of the coils. Furthermore, communication can be improved by using different frequencies to establish a connection and to transfer data of that connection. Ultimately, our prior art search helped to clarify the foundation for our design, as well as discover possible enhancements for it.

OVERVIEW OF THE DESIGN PROBLEM

The methods that scientists currently use to collect data from laboratory rats are highly inefficient. For example, each time a scientist needs to analyze data from a single rat, he or she has to repeatedly collect blood samples. Therefore, Dr. Valvano needs a system that will allow scientists to monitor and analyze that data more effectively. He requires that we reconstruct and improve upon the design of a three-part system that he and a graduate student, Andrew Wang, have partially implemented. The first component is a small batteryless and wireless implant that will be embedded into a rat. The second component is a base station that will use induction coils to wirelessly power and communicate with the implant. The third component is a user interface that will receive commands from a user and display the collected data. The idea is that a scientist would send a command from the user interface to the base station to power the implant. From there, the implant would collect data and communicate that data back to the base station and to the user interface for the scientist to analyze.

REVIEW OF PRIOR ART

During our research for prior art, we explored scientific literature, technical literature, and patents that focus on induction coils, wireless power transmission, and wireless communication. In the following sections, we summarize the six most valuable pieces of prior art. The first piece of prior art describes the existing design and implementation of our project that we are required to reconstruct and extend. The remaining five pieces of prior art describe how we can improve upon the existing design of our system.

Prior Art Exclusive of Patent Information

For prior art exclusive of patents, we found three pieces of scientific and technical literature that concentrate on inductive power transmission and communication. The first piece of literature describes the existing design and implementation that we are expected to recreate and extend. The second piece of literature highlights the benefits of using more than two coils for inductive coupling. Finally, the third piece of literature emphasizes the advantages of using coils with special geometry.

Wireless Power Transmission and Communication System [1]

In December 2014, Andrew Wang wrote his Master's thesis, "Wireless Power Transmission and Communication System for Implantable Devices in Rodents" [1]. Wang's thesis details the most recent design of the system that we are expected to reconstruct and improve upon. Dr. Valvano uploaded the thesis to a folder in UTBox, which he gave us full access to.

According to Wang, using induction coils as a power source for implants in rodents is advantageous over batteries because of its significantly smaller size and lighter weight. As depicted in Figure 1 below, the system proposed in the paper consists of a base station and an implant. The base station and the implant will each have a power circuit, a communication circuit, and a microcontroller. The power circuit on the base station uses one coil, which Wang refers to the Helmholtz primary coil, while the implant uses two coils, which Wang refers to as the implant secondary coils. Power is transmitted by inductive coupling from the Helmholtz primary coil to the implant secondary coil. Additionally, communication from the implant to the base station is achieved by impedance modulation of the implant transmitter coil back to the base station primary coil. To fully develop the communication system and keep it from consuming large amount of power, a simplex communication protocol is suggested for the prototype of the system.

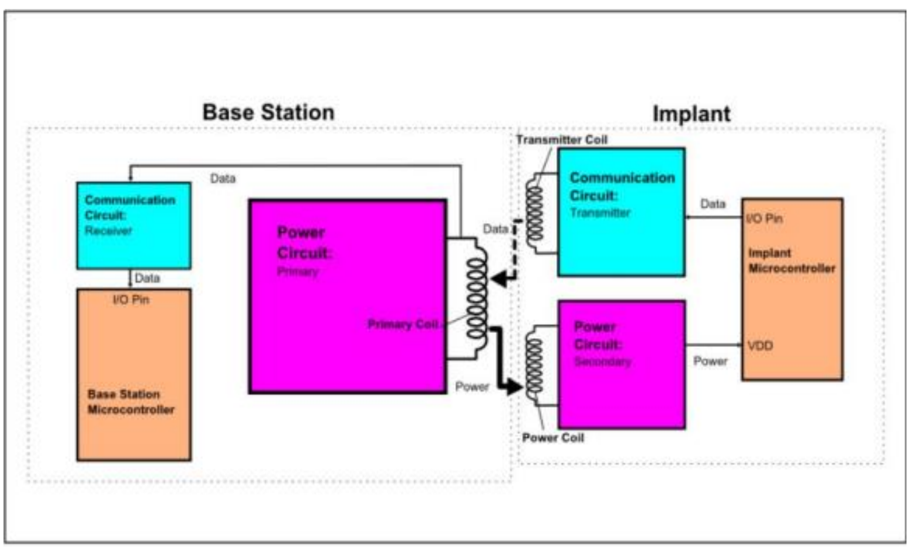

Figure 1: System Block Diagram [1]

The primary power circuit is composed of an oscillator circuit that generates an operational frequency of 6.78Mhz and a class E power amplifier. The secondary power circuit consists of a parallel LC tank circuit, Cockroft-Walton voltage multiplier, and a regulator. Together, the oscillator circuit and the class E amplifier sends AC current at 6.78Mhz into the primary coil to generate a magnetic field for inductive coupling to the implant secondary coils. The Cockroft-Walton voltage multiplier converts AC current to DC and powers the microcontroller on the implant through a regulator. The class E power amplifier is recommended because of its power efficiency of 100% and the operational frequency of 6.78Mhz is chosen to avoid parasitic effects on the implant as much as possible.

Wang's design serves as a foundation for our team's project. Therefore, it is ideal to employ the power circuits that are presented in the paper. For further application, adding more Helmholtz coils to the cage should be considered during the design phase in order to power the implant regardless of the orientation of the implant. Regarding data transmission, although the simplex communication protocol is suggested, our team should design and implement a half-duplex communication protocol because our ultimate goal is to create a user interface to control the implant.

On the Design of Efficient Multi-Coil Telemetry System for Biomedical Implants [2]

In 2013, Anil RamRakhyani and Gianluca Lazzi published “On the Design of Efficient Multi-Coil Telemetry System for Biomedical Implants" [2]. This article explores the benefit of using more than two inductor coils for wireless power transmission and communication. It can be found by searching for “Inductive Power Transmission and Communication” in the IEEE Xplore database.

Systems that cannot contain a battery or a Bluetooth or WiFi module but require wireless power transmission and communication typically use two-coil based inductive coupling. However, these systems are limited by the source and load resistances. Therefore, this article proposes using inductive coupling with multiple coils. In order to corroborate this theory, the authors performed experiments on systems using two, three, and four coils for inductive coupling. After further calculations and analysis, the authors found that their results supported their theory. In comparison to systems with two-coil based inductive coupling, systems with three-coil or four-coil based inductive coupling offer greater power transmission and higher gain-bandwidth.

The existing design of our system uses two-coil based inductive coupling. However, the designs proposed in this article use more than two coils for inductive coupling. Based on the findings of this article, it is more advantageous to use more than two coils for inductive coupling. For example, greater power transmission increases the functionality of the system in regards to the amount of power transferred and the maximum distance between the base and the implant. In addition, the higher gain-bandwidth optimizes the signal performance of the system.

High Efficient Inductive Energy and Data Transmission System with Special Coil Geometry [3]

In 2009, C. Rathge and D. Kuschner published "High Efficient Inductive Energy and Data Transmission System with Special Coil Geometry" [3]. This article explores the benefit of using coils with special geometry for wireless power transmission and communication. It can be found by searching for "Inductive Power Transmission and Communication" in the IEEE Xplore database.

Systems that require both wireless power transmission and communication need a method for minimizing the interference between the magnetic fields of those two processes. As proposed in this article, such a minimization can be achieved by using two techniques in tandem. The first method uses frequency isolation for the power coils and for the communication coils. By designing the power coils and the communication coils to resonate at different frequencies, the corresponding magnetic fields have less of an effect on each other. The second method uses coils with special geometry for inductive coupling. As depicted in Figure 2 on the next page, the special geometry consists of an inner and an outer communication coil wound in opposite directions and a power coil wound in between the two communication coils. This setup also reduces the interface between the magnetic fields of the power coils and communication coils.

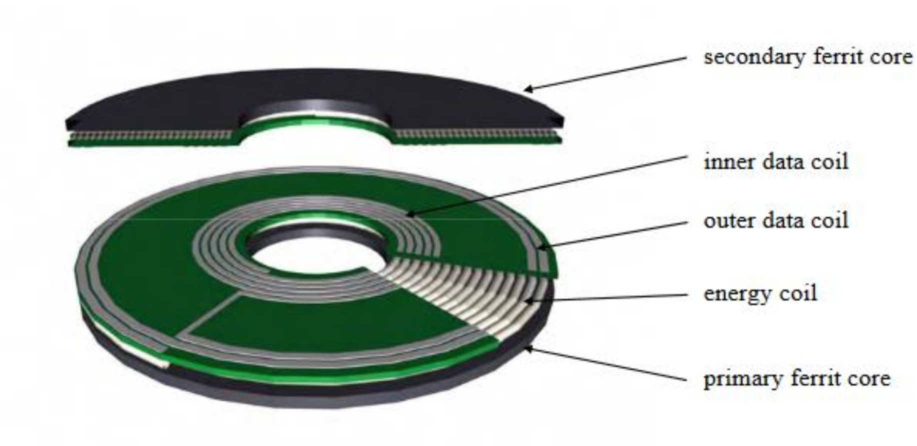

Figure 2: Special Coil Geometry for Minimal Interference [3]

The existing design of our systems uses separate coils for wireless power transmission and communication. By implementing the special coil geometry presented in this article, we can minimize the interference between the coils of the two processes. This will provide a stronger and more reliable power transmission and communication channel.

Patent Search and Findings

For prior art inclusive of patents, we found three patents that also focus on inductive power transmission and communication. The first patent describes how we can improve the existing design of our system by using one set of coils (instead of two) for both the power and communication. Similarly, the second patent highlights the benefits of using three coils (instead of two) for inductive coupling. Finally, the third patent emphasizes the advantages of using two different power levels (instead of one) for establishing a channel of communication and for transferring data over that channel.

Concurrent Wireless Power Transmission and Near-Field Communication [4]

On July 29th, 2010, Qualcomm Incorporated published the patent “Concurrent Wireless Power Transmission and Near-Field Communication” [4]. This patent does not have a patent number, which we have already confirmed with our teaching assistant, Steve Stone. However, the document identifier number is US 20100190436 A1 and the class and subclass for the patent are 455 and 41.1, respectively. This patent can be found by searching for “Wireless Power Transmission and Communication” using Google Patents.

This patent describes the benefit of using one set of coils for both wireless power transmission and communication. The design consists of a first electronic device that transmits wireless power and near-field communication and a second electronic device that receives wireless power and near-field communication concurrently. The transmitting electronic device consists of an antenna, rectifier circuitry, and near-field communication circuitry. The antenna is configured to resonate in a nearby magnetic field and generate a magnetically induced current. The rectifier circuitry is coupled to the antenna and is responsible for rectifying the induced current. The near-field communication circuitry is also coupled to the antenna and is responsible for demodulating any data on the induced current. The receiving electronic device consists of the same components that the transmitting electronic device does. However, the rectifier and near-field communication circuitry of the receiving electronic device are both coupled to the induced current so that they can operate concurrently.

This existing design of our project uses two sets of coils: one set for the wireless power transmission and one set for the wireless communication. In contrast, the design proposed in this patent only uses one set of coils for both processes. Because the implant needs to be small enough to be embedded into a laboratory rat, using only one set of coils would be preferable. Therefore, the latter design would be an improvement upon our existing design.

Three-Coil Topology for Wireless Power Transfer [5]

On May 14th, 2015, the Hong Kong Polytechnic University published patent number 9,281,119, “Three-Coil Topology for Wireless Power Transfer” [5]. The document identifier is US 20150130407 A1 and the class and subclass are 1 and 1, respectively. This patent can be found by searching for “Wireless Power Transfer” on the U.S. Patent and Trademark Office website.

The patent describes the benefit of using three-coil based inductive coupling for wireless power transmission. The system consists of a power source coupled with a primary coil, a repeater coil adjacent to the primary coil, and a receiver coil. The power source is in charge of powering only the primary coil. Because the power source is isolated from the other two coils, it experiences less voltage stress. First, the power source creates an alternating current through the primary coil.

Next, the current produces a magnetic field that is directed at the repeater coil. In turn, the magnetic field induces a greater alternating current through the repeater coil. This current then creates a stronger magnetic field that is directed at the receiver coil. As a result, the magnetic field induces an even greater alternating current through the receiver coil. Ultimately, this amplified current allows a device that is driven by the repeater coil to receive greater power.

The existing design of our system uses two-coil based inductive coupling, whereas the design presented in this patent uses three-coil based inductive coupling. The primary benefit of using three coils for inductive coupling is greater power transmission. Because the implant needs to receive enough power to drive a microprocessor, several sensors, and a communication antenna, it would be advantageous to use three coils. In addition, with three coils delivering more power to the implant, we would be able to decrease the size of the coil on the implant, yet still transmit the same amount of power as if we had only used two coils. On the other hand, we can use the increase in power to maximize the distance between and orientation of the base station and the implant.

System and Method for Communicating with an Implantable Medical Device [6]

On September 24th, 2015, Pacesetter Incorporated published patent number 9,289,614, "System and Method for Communicating with an Implantable Medical Device" [6]. The document identifier is US 20150265843 A1 and the class and subclass are 1 and 1, respectively. This patent can be found by searching for "Implantable Medical Device" on the U.S. Patent and Trademark Office website.

The patent describes a method for allowing an implantable medical device (IMD) to communicate and transfer data with an external device. The method uses two different frequencies to power the IMD at two different power levels. Which power level the IMD operates at depends on what is requested of the IMD. Before communication is initiated, the IMD runs on the first, lower power level produced by a lower frequency. During this state, the IMD constantly scans for a request signal from an external device. Once the IMD detects this signal, the IMD switches to the second, higher power level generated by a higher frequency. This allows for a data exchange between the IMD and the external device. When data no longer needs to be transferred, the external device sends a cessation signal to the IMD. Upon the detection of this signal, the IMD returns back to operating at the first power level.

The existing design of our project does not yet have a communication protocol between the base station and the implant. Integrating the design proposed in the patent with our existing design would allow for successful communication and data transmission between the implant and the base station. Therefore, this design proves extremely beneficial to our system.

IMPACT OF PRIOR-ART SEARCH ON DESIGN DECISION-MAKING

Our prior art search helped us to understand the current design of our system, as well as discover ways to improve upon it. From "Wireless Power Transmission and Communication System" [1], we confirmed how the induction coils, power circuitry, communication circuitry, and microcontrollers work together to provide basic wireless power transmission and communication between the base station and the implant. However, there are several design challenges the system still needs to overcome, such as size constraints, distance between and orientation of the base station and the implant, and a communication protocol. Fortunately, as described below, the remaining pieces of prior art have the potential to address a few of these issues.

The existing design for our system uses two sets of induction coils: one set for the wireless power transmission and the other set for the wireless communication. However, the patent "Concurrent Wireless Power Transmission and Near-Field Communication" [4] proposes that wireless power transmission and communication can be done using only one set of induction coils. Because the implant needs to be small enough to be embedded into a laboratory rat, a design using only one set of coils would be more advantageous to a design using two sets of coils. However, if we do use two sets of induction coils, we need to minimize the interference between the power and communication coils. A method for doing so is presented in "High Efficient Inductive Energy and Data Transmission System with Special Coil Geometry" [3].

For our current design, each set of induction coils consists of two coils: one coil for the transmission of power or data and the other coil for reception of power or data. However, the article "On the Design of Efficient Multi-Coil Telemetry System for Biomedical Implants" [2] proposes that it is more beneficial to use more than two coils (e.g. three or four coils) for inductive coupling. Similarly, the patent “Three-Coil Topology for Wireless Power Transfer” [5] also suggests that using three coils for inductive coupling is more beneficial. Both sources iterate that increasing the number of coils used for inductive coupling increases the power transfer efficiency and the gain-bandwidth. This allows for the maximum distance between the base station and the implant and the maximum variations in their orientation.

Finally, our existing design does not yet have a communication protocol between the base station and the implant. Therefore, it would be highly advantageous to integrate the method presented in “System and Method for Communicating with an Implantable Medical Device” [6]. By using two different power levels to establish a channel of communication and to transfer data over that channel, the base station can successfully communicate with the implant.

CONCLUSION

This report documents both the foundation for our design and existing science and technology that have the potential to enhance it. In order for scientists to more efficiently collect and analyze data from laboratory rats, Dr. Valvano requires that we design a system that consists of small medical implant with a long lifespan. In order to meet the design requirements and constraints that we outlined in our Problem Statement, our team conducted research on prior art involving inductive power transmission and communication. Using Wang’s most recent design as our basis, there are several ways we can improve upon it. First, we can reduce the size of the implant by using one set of coils for both the power transmission and communication instead of two. Additionally, we can strengthen the power transmission by increasing the number of and changing the geometry of the coils. Furthermore, we can improve the communication by using different frequencies to establish a connection and transfer data. Ultimately, our prior art search helped to clarify the foundation for our design, as well as discover possible advancements. The next step for our team is to use what we have learned to produce a preliminary design for the Oral Design Review.

REFERENCES

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