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Progress Report

BME 401 Senior Design
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Group 4

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A. Need and Specific Design Requirements

A.1 Brain-Computer Interfaces

Brain-computer interfaces (BCI) allow subjects to control devices using their own brain signals. Methods of BCI have evolved over time from using electroencephalography (EEG) to primarily single-unit (SU) recordings and most recently to the introduction of electrocorticography (ECoG) as a method of recording brain signals. The signals are sent through a series of filters and amplifiers to a digital signal processor where they are converted into an output communicating the user's intent. BCI is very useful for patients with severe motor disabilities because it gives them a way to communicate and interact with their environment through non-muscular means. BCI is also an extremely useful neuroscientific tool to investigate new hypotheses on cortical population representations.

A.2 Need for BCI Telemeter

The greatest limitation of current BCI methods is the need for cords to carry brain signals from the ECoG electrode array to the digital signal processor. The presence of this external wiring poses two major problems: the subject has limited mobility and the exposed leads carry a risk of infection. Subjects' movements are constrained when hooked up to the system; they can therefore not be connected for an extended length of time. Since the purposes of BCI are to allow a severely motor disabled person to communicate with his surroundings and to study brain activity in a laboratory, it is crucial to be able to record brain signals continuously and for the subject to have a full range of motion. In addition, the use of percutaneous leads exposes the central nervous system (CNS) to a high risk of infection, which is unsafe for the subject and can lead to encephalitis. There is a great need for a device to be created which could perform the tasks of ECoG BCI without the use of external wiring.

A.3 Project Scope and Design Requirements

A.3.1 Project Scope

To address the problems of percutaneous leads leading to CNS infection and limited subject mobility leading to limited recording time, a modular system is designed to process signals from the brain and wirelessly transmit them to an external receiver. A multi-channel system containing an Analog Signal Processing (ASP) module amplifies and filters the ECoG signals. The output of this module goes through an Analog-to-Digital converter (ADC) from which it is sent to a Digital Signal Processing (DSP) unit where a power spectrum is produced. A telemetry module transmits the processed signals to a receiving agent. When the transmitted power spectrum is transmitted to the computer or intermediate device, an algorithm compares the signal to baseline recordings and the modulations from baseline are used to establish brain control. The ASP, ADC, DSP, and telemetry modules are contained in a casing with a biocompatible film on the outside to allow for implantation in the body. An implanted rechargeable battery serves as the power source for the device.

A.3.2 Design Requirements

The proposed system will support the following features:

- Able to record signals with amplitude 1-10 μV with ability to distinguish modulation down to 300 nV

- Telemetry to PC for 8 ECoG channels in either raw (2000 Hz) or processed (20 Hz) modes
- Each of the 8 channels chosen from one of eight groups of 4 electrodes with reference chosen from one of four electrodes
- Bidirectional RF(radio frequency) link for system configuration, control, and data telemetry
- Low-noise electronics offering large Signal-to-Noise Ratio (SNR) and Common Mode Rejection Ratio (CMRR)
- Low-power, rechargeable battery-operated
- Variable RF data rates (and power consumption) of up to 500 kHz
- One week of typical use between recharge cycles
- Transmit signals at least 50 feet
- MSP430 Microcontroller
- TI CC1101 Transceiver
- Cost < $5,000

B. Statement of All Design Alternatives

B.1 ASIC Design

The ECoG signals recorded from the brain are transmitted through fiber optics to the BCI Telemeter. At this initial point in the system, the processing of the signals begins using the headstage module. The term "headstage" refers to processing block in which the signals are filtered and amplified. The purpose of the headstage module is to consolidate multiple analog integrated circuits along with the required digital signal processing DSP functions into a custom Application Specific Integrated Circuit (ASIC). This multi-channel ASIC will be paired with a commercially available Radio Frequency (RF) telemetry chip to transmit brain signals to an external computer.

The ASIC receives input from a 32-channel μECoG electrode array implanted epidurally on the subject's brain. The 32 electrodes are organized into eight groups of four electrodes. One electrode from each bank of four can be selected for processing and telemetering, leading to a total of 8 processed channels.

B.1.1 Multiplexers

An electronic multiplexer allows for several signals to share one device or resource, such as an ADC or communication line, instead of requiring one device per input signal. In contrast, an analog switch selects one of several analog signals and forwards the selected input on to the next component.

Eight channels are chosen from the 32 channels of the μECoG electrode array, one from each of the eight groups of four electrodes that share a reference. Analog switches select these channels before the signals are sent to the ASP block. From this point there are two options: eight separate ASP blocks can process the analog signals individually and send them to eight ADCs, or a multiplexer can be used to allow all eight channels to be processed by one ASP block and go on to one ADC. The schematic for the first option is shown in Figure 1 below.

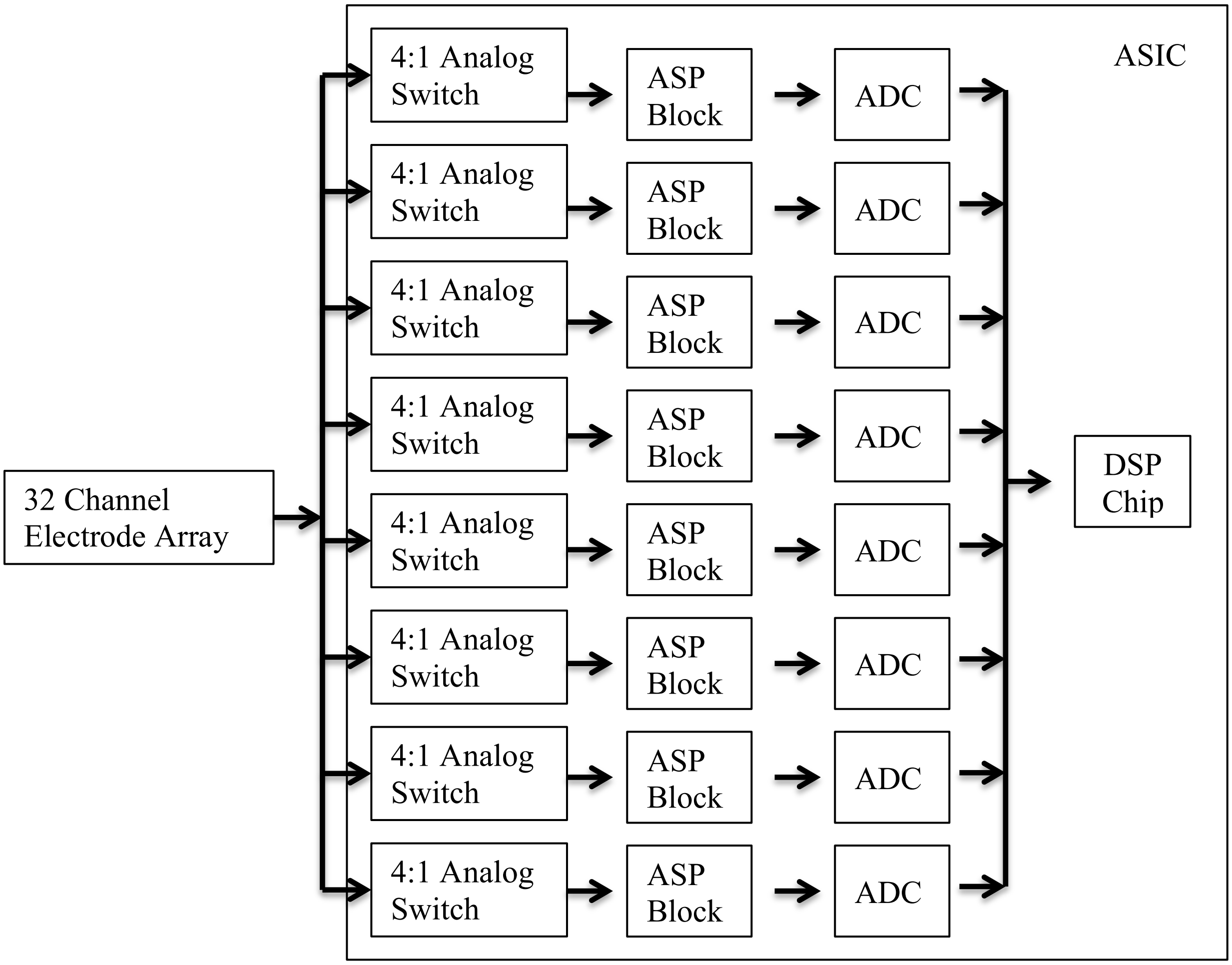


Figure 1: *Schematic for first ASIC option using eight 4:1 analog switches, eight ASP blocks, and eight ADCs leading to one DSP chip with eight inputs*

The disadvantage of this configuration is the high cost associated with buying eight ASP blocks and eight ADCs instead of one multiplexer, one ASP block, and one ADC. The advantage is a low risk of signal distortion by cross-talk between channels that can occur when a multiplexer is used.

The second design option involves placing an 8:1 analog multiplexer before the ASP block, after the eight channels have been selected. The schematic for the second option is shown in Figure 2.

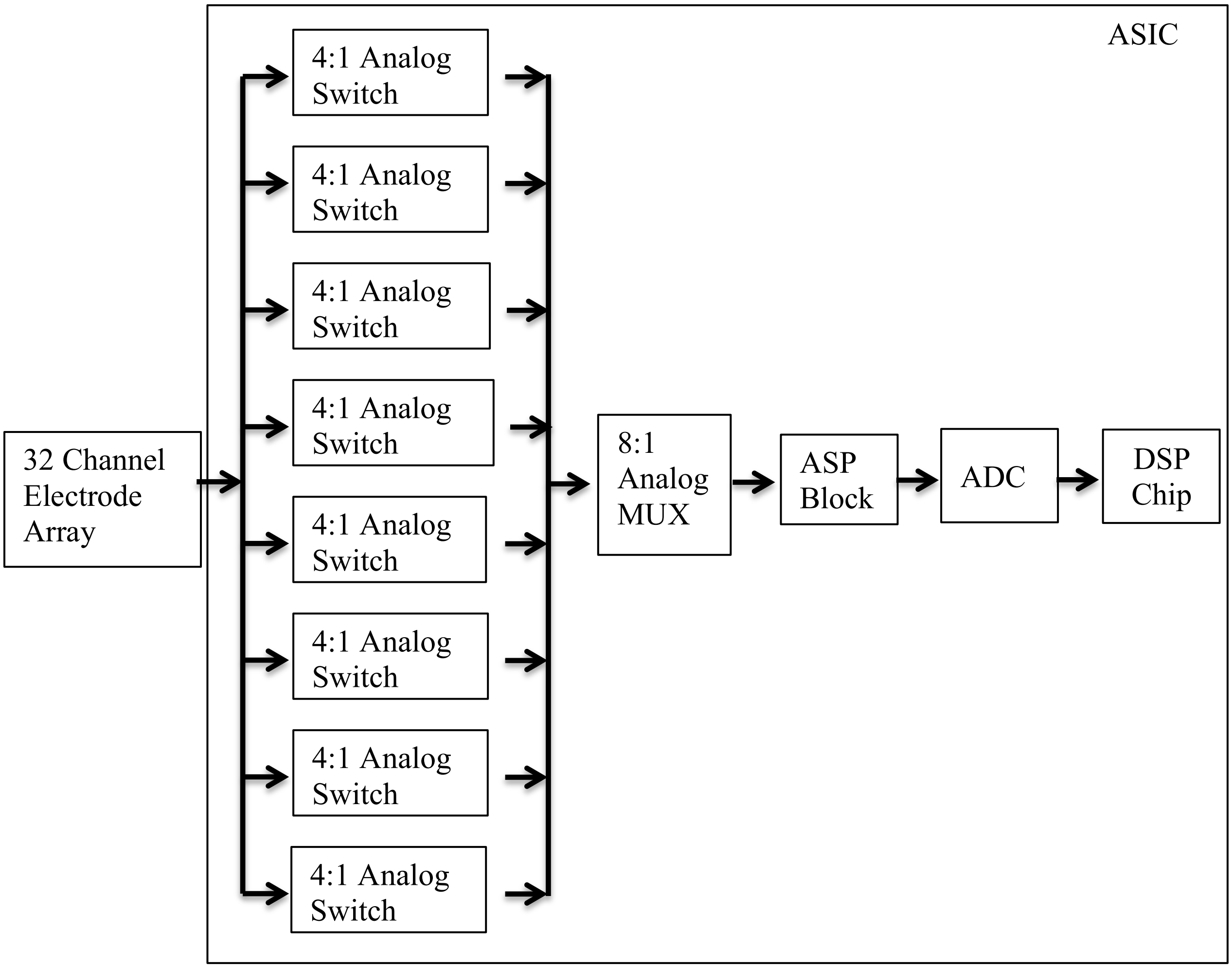


Figure 2: *Schematic for second ASIC option using eight 4:1 analog switches, an 8:1 analog multiplexer, one ASP Block and one ADC*

This configuration saves a significant amount of money and uses less space than that in Figure 1, however, using an analog multiplexer poses several potential problems. In all cases, multiplexing reduces the rate at which data can be acquired from an individual channel because of the time-sharing strategy used to switch between channels. Multiplexing does not provide simultaneous sampling across the inputs at the ADC, and as more inputs are added the maximum sampling rate per input is reduced. For example, if a system can read 1 input channel at 100 Hz, when reading 10 input channels it is limited to 10 Hz. Using one ADC for each input permits simultaneous sampling and ensures that there is no reduction in sampling rate as the number of inputs is increased. In addition, channel-to-channel cross talk is a non-ideal characteristic of analog switching networks. Cross talk develops when the voltage applied to any one channel affects the accuracy of the reading in another channel. At the position the multiplexer is implemented in the ASIC, the input impedance has not yet been reduced by buffer amplifiers, and the high source impedance can increase settling time and generate crosstalk between channels [5].

Speed and cross talk are always problems associated with implementing an analog multiplexer; by placing the multiplexer before the ASP block the multiplexed signal will be filtered and individual channels will be processed together. Using Time-Division Multiplexing (TDM), each subsequent signal is concatenated to the end of the previous channel, meaning that a long signal composed of many shorter signals pieced together travels through the ASP block. As this signal passes through the analog filter, the frequency data blends together as though it were being collected for one signal. This conglomeration of eight signals into one leads to signal distortion. Using Frequency-

Division Multiplexing (FDM), information from each channel is transmitted at a different frequency, splitting the total bandwidth into several sections. This separates channels more effectively in the time domain; however, the low-pass analog filters will completely attenuate channels that have been assigned to higher frequencies, making this an ineffective method for processing signals. For these reasons, multiplexing before the ASP block will lead to individual signal distortion and inaccurate brain control.

B.1.2 Analog Signal Processing Block

Two factors must be considered in choosing amplifiers to use in the ASP Block:

1. ECoG signals are in the microvolt range so even a small amount of noise dramatically influences control. Caution must be taken to amplify the signal of interest while attenuating the noise.
2. The electrodes used for ECoG are small and have large electrical impedances, on the order of a mega-ohm in the frequency band of interest [1].

Figure 3 demonstrates an operational amplifier configuration that leads to several different circuits shown in Table 1.

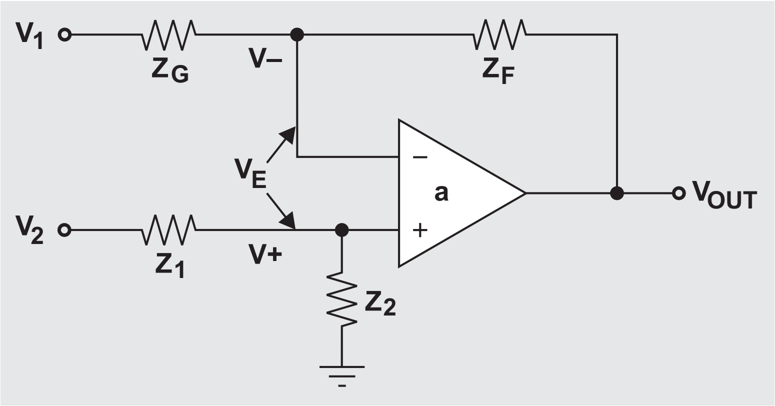


Figure 3: *An operational amplifier configuration that leads to several different circuits*

Table 1: *Description of different circuit types that can be made by changing component values in the operational amplifier*

Circuit Type	**V_1**	**V_2**	**Z_G**	**Z_F**	**Z_1**	**Z_2**
Inverting Amplifier	Input signal	Ground	Determined by gain	Determined by gain	Open	$Z_G \| Z_F$
Noninverting Amplifier	Ground	Input signal	Determined by gain	Determined by gain	$Z_G \| Z_F$	Open
Inverting Integrator	Input signal	Ground	R_G	C_G	Open	$Z_G \| Z_F$
Buffer	Ground	Input signal	Open	Short	Short	Open
Differential Amplifier	Input signal -	Input signal +	R_G	R_F	R_G	R_F

The input voltage coming into an op-amp sees an impedance load composed of the impedances of the input components and the amplifier input impedance. When the signal source has significant resistance, as the ECoG electrodes do, the external load on the input signal will have detrimental effects on the amplifier performance. Figure 4 models the transmission of a brain signal to the ASP block.

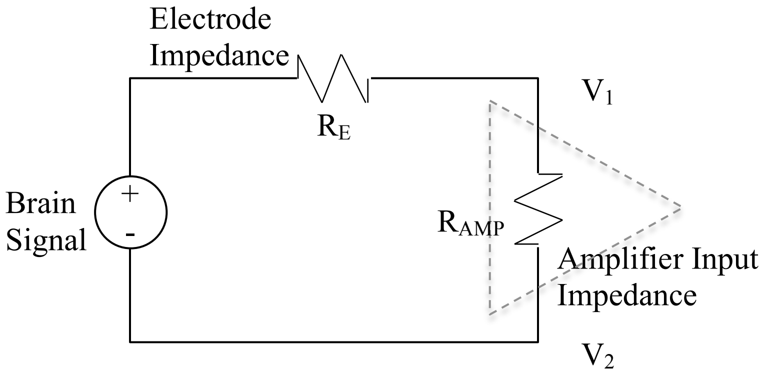


Figure 4: *Circuit model of the transmission of a recorded brain signal to the ASP block*

To accurately measure voltage, the input impedance of the amplifier should be considerably larger than the impedance at the recording site, or the electrode impedance. If this is not the case the signal could be attenuated and distorted.

B.1.2.1 Differential Amplifier

To address the need to simultaneously amplify signals and attenuate noise, ECoG signals are recorded as the difference between a single working electrode (channel) and a reference electrode. A differential amplifier is a type of electronic amplifier that subtracts the potential at one electrode from the potential at a reference electrode and amplifies the difference. Noise is common to both signals and is therefore removed when the signals are subtracted. A schematic of a differential amplifier is shown in Figure 5.

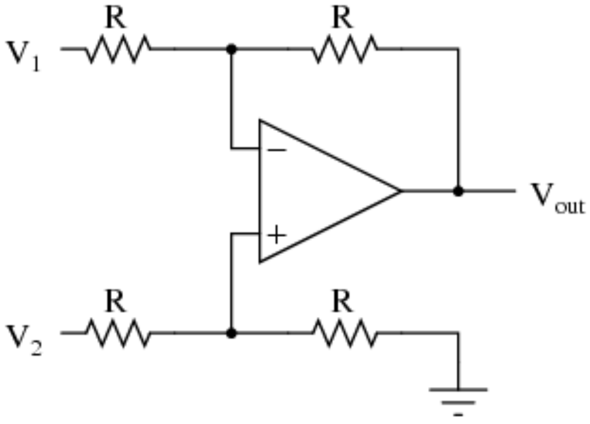


Figure 5: *Schematic diagram of a differential amplifier*

The common mode rejection ratio (CMRR) provides an index on the extent to which common signal components are attenuated from the signal; large CMRR values are desirable. Differential amplifiers have CMRRs greater than 100 dB and record high fidelity signals.

Using a differential amplifier at the front end of the ASP block would allow further amplification of the unadulterated signal for processing, leading to increased accuracy during brain control tasks. Differential amplifiers demonstrate high CMRR characteristics, but they do not offer the high input impedance needed to balance the impedance of the electrodes.

B.1.2.2 Buffer Amplifier

Voltage buffers have a gain of one, exceptionally high input impedance, and very low output impedance. A schematic of a unity gain buffer is shown in Figure 6.

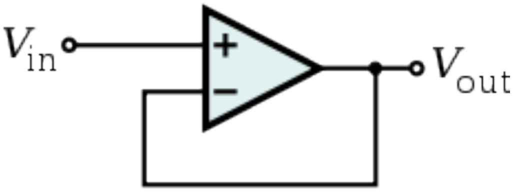


Figure 6: *Schematic of a unity gain buffer*

Placing a unity gain buffer at the front end of the ASP block lowers the signal impedance from 1 mega-ohm at the recording site to 50 ohms at output of the buffer [1]. This lowers the input impedance, allowing for further amplification with the signal dropping across the amplifier rather than the input resistance. Buffers supply an exceptionally high input impedance and very low output impedance, but they do not provide sufficient CMRR for brain control tasks.

B.1.2.3 Instrumentation Amplifier

Instrumentation amplifiers have high input impedance coupled with a high CMRR, making them an excellent choice for many instrumentation applications. A schematic of an instrumentation amplifier is shown in Figure 7.

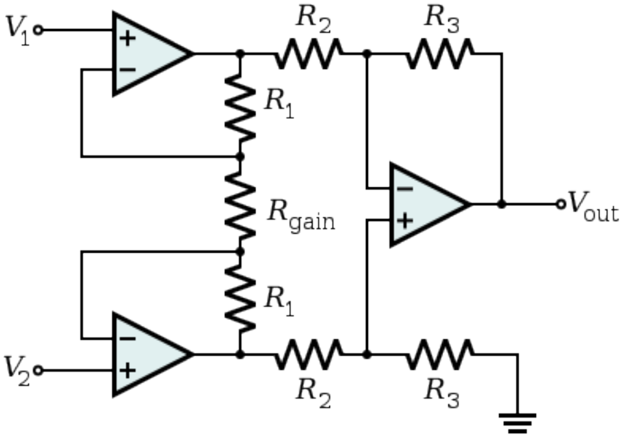


Figure 7: *Schematic for instrumentation amplifier*

An instrumentation amplifier is a type of differential amplifier that has been outfitted with buffers before each of its inputs, effectively lowering the source impedance and eliminating the need for higher input impedance in the differential amplifier. Additional characteristics of an instrumentation amplifier include a low DC offset, low drift, low noise, high open-loop gain, high CMRR, and high input impedance. The input buffers lower the impedance of the inputs V_1 and V_2 from one mega-ohm to around 50 ohms; the input impedance of the differential amplifier is then sufficiently larger than the source impedance. The common mode noise will be subtracted from the signal before further amplification.

B.1.3 Analog-to-Digital Converters

An ADC is a device that converts a continuous signal to a discrete-time digital representation. In the BCI Telemeter, analog brain signals must be digitized before being transferred to the DSP block. The analog output of the low-pass anti-aliasing filter is applied to an ADC, yielding a 1-bit 512 kHz data stream.

B.1.3.1 Resolution

Resolution is an important factor to consider when choosing an appropriate ADC. Resolution indicates the number of discrete values that can be produced over the range of analog values. Electrical resolution is expressed in volts; the minimum change in voltage required to guarantee a change in the output code level is called the least significant bit (LSB) voltage. The resolution Q of the ADC is equal to the LSB voltage.

The voltage resolution of an ADC is equal to the full-scale voltage range (FSR) divided by the number of discrete voltage intervals (N):

$$Q = \frac{FSR}{N} \qquad \text{(Equation 1)}$$

FSR and N are calculated as follows:

$$FSR = V_{High} - V_{Low} \qquad \text{(Equation 2)}$$

$$N = 2^M \qquad \text{(Equation 3)}$$

V_{High} and V_{Low} are the upper and lower limits of voltage that can be recorded and

M is the ADC's resolution in bits. An ADC with a resolution of 8 bits, for example, can encode an analog input to one of 2^8 discrete values.

B.1.3.1.1 16-bit Analog-to-Digital Converter

ECoG recordings have such small magnitudes – on the order of a microvolt – that significant amplification must occur before the signal reaches the ADC in order to ensure accurate digital processing.

The Moran laboratory at Washington University in St. Louis currently uses preamplifiers with 16-bit $\sigma - \Delta$ ADCs, or oversampling ADCs, to study ECoG BCI. A 16-bit ADC with $\pm\, 1V$ rails has the following characteristics,

$$Voltage\ Steps = N = 2^{16} = 65536$$

$$Resolution = Q = \frac{2\ Volts}{65536} = 30.5\ \mu V$$

To distinguish signal modulations down to 300 nV as stated in the specifications, the signal must be magnified more than 100x when using a 16-bit ADC with a 30.5 µV resolution. The calculation to find the necessary magnification factor is shown below.

$$\frac{\left(\frac{1000nV}{\mu V}\right) * (30.5\mu V)}{300nV} = 101.667$$

Several non-inverting operational amplifiers placed between signal acquisition and the ADC implement the required amplification for necessary resolution; however, they add noise to the system and cause less precise brain control.

ADCs do exist with resolution less than 16-bit, however these technologies will not be discussed in detail because they are not applicable for the requirements of the BCI Telemeter. While lower resolution ADCs are cheaper than those with higher resolution, the amount of amplification necessary for adequate signal processing would require several operational amplifiers. The introduction of each op amp into this design causes an increase in noise and an increase in the size of the device as a whole.

B.1.3.1.2 24-bit Analog-to-Digital Converter

Characteristics of a 24-bit ADC with $\pm\,1V$ rails are:

$$Voltage\ Steps = N = 2^{24} = 16{,}777{,}216$$

$$Resolution = Q = \frac{2\ Volts}{16{,}777{,}216} = 119.2\ nV$$

Using an ADC with this resolution would not require ECoG signals to go through any analog amplification after the common-mode noise has been subtracted and before being digitized. A 10X gain can be added to the initial instrumentation amplifier to bring the resolution down even lower to 11.92 nV. A resolution this low is more than sufficient for high accuracy data processing and transmission.

Although 24-bit ADCs are more expensive than their 16-bit counter parts, the cost of additional op-amps, resistors, and capacitors necessary in the 16-bit configuration raise the cost of the 16-bit ADC above that of the 24-bit ADC.

B.1.3.2 Architecture

ADCs can be classified into two main categories based on the sampling rate of the input analog signal: Nyquist-rate ADCs and over-sampling ADCs. Table 2 displays the classification of several ADC architectures.

The sampling theorem states that sampling frequency, f_s, must be greater than twice the maximum frequency of the input signal in order for the signal to be uniquely reconstructed without aliasing.

$$f_s < 2 * f_{max} \qquad \text{(Equation 4)}$$

The frequency $2*f_{max}$ is the Nyquist sampling rate, and half of this value, f_{max}, is the Nyquist frequency. Nyquist-rate ADCs operate with an input signal frequency close to half the sampling frequency and require a very sharp cutoff for the preamplifier or anti-aliasing filter. Though Nyquist ADCs are very fast, their resolution is limited by component matching and circuit non-idealities.

Over-sampling ADCs trade off resolution in time for increased resolution in amplitude [3]. Oversampling is implemented in order to achieve cheaper higher-resolution analog to digital conversion. The oversampling factor needed to have *n* additional bits of resolution is shown in Equation 5.

$$Oversampling\ Factor = 2^{2n} \qquad \text{(Equation 5)}$$

To implement a 24-bit converter, it is sufficient to use a 20-bit converter that can run at 256 times the target sampling rate. These ADCs oversample the desired signal and utilize digital filters to remove unwanted frequencies and to reduce the sample rate after the analog-to-digital conversion. For example, an oversampling ADC with a 100-ksamples per second conversion rate that uses 128X oversampling will sample the incoming analog signal at 12.8 mega-samples per second. Once digitized, the oversampled signal goes through a digital filter to remove frequency components at or above the Nyquist frequency, which is one-half of the ADCs output-sampling rate. A digital low-pass filter removes the high-frequency components and a data decimator removes the oversampled data. In an ADC with 128X oversampling, the decimator will retain 1 bit for every 128 bits that it receives; the final output is a serial bit stream. Oversampling helps avoid aliasing, improves resolution and reduces noise. Oversampling is best used when the bandwidth of interest is small and signal propagation is slow.

Table 2: *Classification of ADC architectures*

Conversion rate	Nyquist-rate ADCs	Over-sampled ADCs
Slow (10-100 Samples/sec)	Serial (ramp, dual-ramp) High resolution possible (< 14 bits possible)	Very high resolution (< 24 bits possible)
Medium (1-100 kSamples/sec)	Successive approximation Algorithmic (< 16 bits possible)	Moderate resolution (< 18 bits possible)
Fast (1 – 100 MSamples/sec)	Flash (< 14 bits possible)	Low resolution (< 6 bits possible)

Many measurement applications do not require the conversion rates possible with Successive-Approximation Register (SAR) converters, but they do need finer resolution. Oversampling ADCs can provide resolution as fine as 24 bits by trading off resolution for speed. ECoG recordings, for example, have magnitudes in the microvolt range, meaning that for accurate digital processing the signal must be amplified significantly before it is digitized, or it must be digitized with corresponding microvolt resolution. Physiological signals propagate relatively slowly so using an oversampling ADC is ideal for recording ECoG signals.

B.1.4 Digital Signal Processing Microchip

Digital signal processing algorithms typically require a large number of mathematical operations to be performed quickly and repetitively on a set of data. The DSP software for the BCI Telemeter is encoded on a microchip that uses the output of the ADC as its input. As a specification for this project, the DSP software required for the BCI

Telemeter has been provided, and preliminary testing has been done using a low power microcontroller.

DSP algorithms are traditionally implemented using DSP chips. While these are efficient at executing their purpose, they perform only one function in the system and can be both expensive and large. Microcontrollers are an alternative solution for implementing DSP algorithms in limited space and memory.

The microcode written for the BCI Telemeter is compatible with the Texas Instruments (TI) MSP430 Microcontroller given in the design specifications. The MSP430 MCU is designed specifically for ultra-low-power applications. Its flexible clocking system, multiple low-power modes, instant wakeup and intelligent autonomous peripherals enable true ultra-low-power optimization, dramatically extending battery life. The MSP430 family offers over 25 packages to ensure that it fits the needs of the device in which it is being used; it also supports devices as small as 3x3 mm [4]. The MSP430 Microcontroller nicely addresses the BCI Telemeter's power consumption specifications and limited space requirements.

B.2 Telemeter Design

The role of the telemeter is to wirelessly send brain signals from a transmitter on the ASIC to an external receiver. The specifications of the BCI Telemeter require implementation of the TI CC1101 Transceiver, which is compatible with the TI MSP430 Microcontroller being used. This is a low-power Sub-1 GHz RF Transceiver designed for wireless applications. RF Transmission uses radio waves to transmit signals from a transmitter to a receiver; an antenna must be used to send and receive signals. The TI

CC1101 Transceiver sends signals in the Industrial, Scientific, and Medical (ISM) band at 315, 433, 868, and 915 MHz [6].

B.2.1 Modulation Formats

Modulation allows the transmission of the processed signals at a specific frequency while keeping the frequency response of the ECoG data intact. The signal is sent from the transmitter to receiver in a carrier wave; once it reaches the receiver it is demodulated and the original signal is reproduced. The equation for a sine wave is:

$$e(t) = A * \sin(\omega t + \emptyset) \qquad \text{(Equation 6)}$$

Varying A in the carrier wave results in amplitude modulation (AM), varying the frequency, ω, results in frequency modulation (FM) and varying the phase shift, ϕ, results in phase-shift modulation (PM). Phase-shift modulation affects the sine wave in the same way as frequency modulation and is often placed under the heading of FM.

B.2.1.1 Frequency Modulation

Frequency modulation involves sending information over a carrier wave by varying the instantaneous output frequency of the transmitter. A frequency modulated wave consists of three or more frequency components added together as vectors to give the appearance of a sine wave with varying frequency in the time domain [7]. Frequency-shift keying (FSK) is a frequency modulation scheme in which digital information is transmitted through discrete frequency changes of a carrier wave [9]. The TI CC1101 Transceiver is capable of both binary FSK (2-FSK) and quaternary FSK (4-FSK) [6]. FM is less prone to interference than AM; however, physical barriers impact the quality of FM signals.

B.2.1.2 Amplitude Modulation

Amplitude modulation involves varying the strength of the carrier signal in relation to the signal of interest. An AM wave is the vector sum of three or more sine waves of different amplitudes, giving the appearance of a sine wave with varying amplitude in the time domain [7]. Amplitude-shift keying (ASK) is a method of AM in which a finite number of amplitudes are each assigned a unique pattern of binary digits. Each pattern of bits forms a symbol represented by a particular amplitude and recognized by the demodulator, which determines the amplitude of the received signal and maps it back to the symbol it represents, uncovering the original data [8]. The TI CC1101 Transceiver is capable of ASK [6]. Advantages of AM include a lower cost than FM and the ability to transmit signals over long distances.

B.2.2 Antenna

The most critical component of a wireless transmission system is the antenna. An antenna has two modes: the transmit mode in which it transforms electrical signals into RF electromagnetic waves propagating into free space, and the receiving mode in which it transforms RF electromagnetic waves back into electrical signals [12]. The antenna in the BCI Telemeter is responsible for communicating ECoG data from the ASIC to an external computer by sending electromagnetic waves in a specific frequency band.

The size of an antenna is based on the wavelength of the signal being transmitted; maximal power transfers occurs when the antenna is half -wavelength. A half-wavelength antenna is commonly referred to as a dipole antenna. One way to reduce antenna size is to place a quarter-wavelength antenna on a ground plane, which acts as the other quarter-wavelength and produces an effective half-wavelength antenna. A quarter-wavelength antenna is referred to as a monopole antenna. The TI CC1101 Transceiver is a low-power device operating below 1 GHz. The smallest size antenna that could be used with this transceiver is calculated below using equation 7.

$$Wavelength = \lambda = \frac{speed\ of\ electromagnetic\ wave}{frequency} \qquad \text{(Equation 7)}$$

$$\lambda = \frac{3 * 10^8 \frac{m}{s}}{1 * 10^9 \frac{1}{s}} = 0.3\ m$$

$$Antenna\ Length = \frac{\lambda}{4} = 0.075\ m = 7.5\ cm$$

Factors to consider when choosing an antenna include size, cost, and performance. The BCI Telemeter has significant size restrictions since it must be fully implantable, but high performance is crucial for transmitting high fidelity signals. The TI CC1101 Transceiver can support several types of antennas; the most common are printed circuit board (PCB) antennas, chip antennas, whip antennas, and wire antennas.

B.2.2.1 Printed Circuit Board Antenna

A printed circuit board (PCB) antenna is a very low cost option but is difficult to design to be both small and efficient. Designing a PCB antenna requires performing many simulations to obtain an acceptable solution, which can be difficult and time consuming [12]. The greatest advantage of a PCB antenna is its low cost, but disadvantages are its large size and that it is difficult to design. Figure 7 displays an example of a PCB antenna.

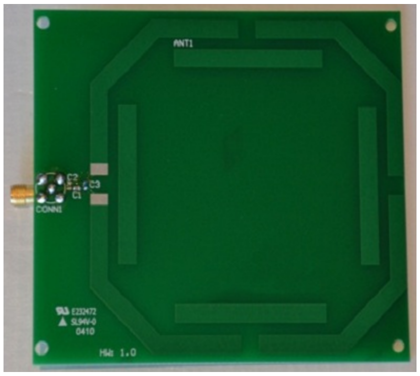


Figure 8: *PCB antenna*

B.2.2.2 Chip Antenna

A chip antenna is an excellent option when board space is limited; this antenna type supports small solution sizes even for frequencies below 1 GHz. One trade-off between a PCB and a chip antenna is that the chip antenna adds significantly to the bill of materials (BOM) and mounting cost. Additional matching components may also be needed to achieve optimum performance [12]. The greatest advantage of a chip antenna is its small size, disadvantages are that it provides moderate performance and is more expensive than a PCB antenna. An example of a chip antenna is shown in Figure 9.

Figure 9: *Chip Antenna*

B.2.2.3 Whip Antenna

If performance is the most important factor and size and cost are not critical, a whip antenna is a great option. Whip antennas are more expensive than chip antennas and require a connector on the circuit board [12]. Advantages of a whip antenna include high performance, but disadvantages are high cost and large size. An example of a whip antenna is shown in Figure 10.

Figure 10: *Whip antenna*

B.2.2.4 Wire Antenna

A wire antenna addresses the problem of large antenna size for frequencies below 1 GHz. Using a simple wire for the antenna is very cheap, and the wire can be formed around the mechanical housing of the application, making its length an irrelevant factor [12]. The greatest advantage of a wire antenna is its low cost, but its disadvantage is that the position of the antenna in the device must be closely controlled to prevent variability in performance [12]. An example of wire antenna is shown in Figure 11.

***Figure 11**: Wire antenna*

B.3 Battery Design

The device is fully implantable so it needs to have a rechargeable battery that can be charged from an external source as stated in the specifications. A rechargeable battery is useful because surgery is not required to repower the system once the charge has been depleted. High levels of power are continuously available between charges; once the battery’s charge is depleted, an external power source can reverse the electrochemical reaction. As a result the battery system does not restrict the lifetime of the device.

The battery is responsible for providing power to the entire system so if it does not function properly for any reason, none of the components in the device will work. Since the design specifications require that the device be small so that it can be implanted in a patient, the size of the battery is an important consideration. The dimensions of the battery influence the shape of the entire device. The battery must be hermetically sealed to prevent leakage, which could cause damage to the system and/or the health of the patient. The BCI Telemeter is an implantable device; therefore the entire device must be very safe to prevent the need for surgery in the case of an emergency.

To meet the specifications of low power consumption, continuous power delivery, and cost considerations, the battery must balance characteristics such as voltage, power delivery, discharge rate, efficiency, cycle life and energy density. The rest of this section outlines the possible options that make the battery safe, small, and energy efficient.

B.3.1 Battery Components

B.3.1.1 Cathode Material

Lithium battery cells contain many complex material structures and chemical reactions with the most significant characteristics being the capacity, stability, voltage and cost of the cathode material. If the battery is to be rechargeable, the reactions must be reversible; that is, if the load in the external circuit is replaced with a power supply, it should be possible to run the reactions at the cathode and the anode in reverse. The cathode reaction is as follows:

$$x\mathrm{Li}+ + xe- + \mathrm{Li\text{-}Pol} \text{------>} \mathrm{Li}_{(1+x)}Pol \text{------>} \text{discharge}$$

The cathode consists of a strong oxidizing agent that can absorb incoming lithium cations from the electrolyte while charging, and electrons from the external circuit while discharging. The cathode material contains a high level of oxygen bonded in various structures with metal atoms such as cobalt, nickel, vanadium, chromium, aluminum or manganese. With so many oxygen molecules near the cathode, a precaution must be taken into account to prevent a high temperature event from occurring. To avoid this, sulfur is often used as a strong oxidizing agent. Another advantage of using a sulfur combination is its very high energy density. The drawback of sulfur is that some of the intermediary Li-sulfur compounds are solvent in the electrolyte, which could lead to early deterioration of the internal components.

To obtain the best cathode material, there should be an optimization of cycle life, safety, cost, energy density and toxicity. To accommodate the high energy density specification, the best cathode materials should have a high capacity and high “voltage vs. lithium”. Measuring voltage vs. lithium compares the voltages produced when lithium ions are used to produce the current. Using this value is more accurate because cathode potentials vary with the ion used. Table 3 compares the characteristics of cathode materials.

Table 3: *Comparison of different cathode materials*

Cathode Material						
	Capacity (mAhr/g)	**Voltage v. Li (V)**	**Cycle Life**	**Safety**	**Toxicity**	**Cost**
Cobalt Oxide	140	3.6	Good	Poor	Med	High
NiCo Oxide	180	3.5	Good	Good	Med	Med
Layered Mn Oxide	190	3.8	Very Good	Very Good	Low	Low
Iron Phosphate	120	3.2	Very Good	Very Good	Low	Low
Lithium Sulfide	400	3	Poor	Poor	Low	Low

Table 3 compares the characteristics of different cathode materials in a lithium-ion battery system. The capacity measurement is based on practical use in medical devices. Measuring voltage vs. lithium compares the voltages produced when lithium ions are used to produce the current. Using this value is more accurate because cathode potentials vary with the ion used.

B.3.1.1 Anode Material

The anodic reaction in the negative electrodes occurs when lithium ions are reversibly placed within the chemical materials. This reversible electrochemical state is maintained over several of thousands of cycles in batteries that have optimal internal components. The number of ions it can contain within the anode and how quickly these ions can be exchanged determines the capacity of the battery. Therefore the desired characteristics of anodic materials are a large reversible capacity, low irreversible capacity, and a high rate of discharge. In addition, cost and safety are important tradeoffs when maximizing the energy characteristics.

Anodic electrodes are typically made from one of three types of carbon materials: graphite, hard carbon and soft carbon. Graphite is composed of stacked grapheme layers that form a crystalline structure with spacing around .33 nm. As a result of the structure pattern, graphite is an anisotropic material that stretches in one direction. Soft carbon is spaced a bit wider at .37 nm, while the grapheme layers are stacked but in a less sturdy structure than the crystalline patter of graphite. Hard carbon stacks are spaced the widest with distances greater than .39 nm. The non-crystalline structure of hard carbon is isotropic. The structural differences between these carbon structures contribute to the differing anodic properties. When the Li+ ions pass through the carbon structures, the ions become intercalated. The spacing between the layers affects the amount of lithium ions that can be stored in the material. In addition, the isotropic and anisotropic properties affect how the volume changes during charging and discharging. The volume changes dictate the rate at which the lithium ions move through the substances. The physical differences translate into capacity and charging rate differences that are quantified in table 4.

Silicon is another option that is being investigated in current research today. It provides a 5-10 fold increase in capacity over carbon and graphite electrodes. This increase is due to large volume increases and lithium intercalation, but the volume changes lead to disintegration of the material and battery failure can occur. Nanotechnology is being used to look into how the effects can be mitigated. Access to this research and subsequent studies increases the prices of the silicon method.

Table 4: *Table comparing different cathode materials*

Anode Materials				
	Graphite	**Soft Carbon**	**Hard Carbon**	**Silicon**
Capacity (mAh/g)	400	300	420	4200
Irreversible Capacity (mAh/g)	60	90	40	200
Efficiency (%)	92	77	85	95

Table 4 lists the efficiency, reversible and irreversible capacities of the carbon and silicon anodic electrodes. The physical differences between the materials leads to the energy and power differences within a battery.

B.3.1.3 Electrolyte

Polymer electrolytes are a combination of solid polymers and $LiPF_6$. The polymers are usually either polyehtyleneoxide (PEO) or polyvinylidene fluoride (PVDF).

B.3.1.3.1 Polyethyleneoxide

PEO refers to an oligomer or polymer of ethylene oxide. It has a low diffusivity, high viscosity, is flexible, and is water-soluble. Its low diffusivity often requires higher temperatures of operation. This can pose a risk because lithium is susceptible to igniting.

However, since PEO has a high viscosity even near its melting point, it reduces the chance of lithium ion interacting with each other at higher speeds. In addition, the relatively low diffusivity results in a lower conductivity. A low conductivity affects the discharge and charging rates between the cathode and anodes.

B.3.1.3.2 Polyvinylidene Fluoride

PVDF is a highly non-reactive and pure thermoplastic fluoro-polymer. These polymers are currently used widely in Li-ion batteries as binder materials in cathodes. Technology is moving towards incorporating this polymer into the lithium-ion-polymer system because it provides the possibility of high voltage operation and is electrochemically stable. These characteristics make it an efficient material to provide power and substantial voltage to the device. Being electrochemically stable, it provides extra stability to the excitable lithium ions, which reduces the flammability of the device and increases the safety. On the downside, the PVDF is costly, and doesn't provide the flexibility of other polymer systems.

B.3.2 Recharging System

B.3.2.1 Transcutaneous Energy Transfer

The specifications require the BCI Telemeter to be rechargeable through the skin. Transcutaneous Energy Transfer (TET) is a state-of-the-art power transfer system currently used by many high-powered implantable biomedical devices such as cardiac pacemakers and artificial heart pumps. This new method has been established so that devices can be charged without being plugged in. The TET system enables power transfer through the skin without direct electrical connectivity, which significantly reduces the chance of infection because there are no exposed areas of the skin. This is implemented through a transcutaneous transformer where the primary and the secondary coils of the transformer are separated by the patient's skin, providing two electrically isolated systems. A TET system is illustrated in Figure 12. The primary coil is located externally, while the secondary coil is implanted in the device. The electromagnetic field produced by the primary coil goes through the skin and produces an induced voltage in the secondary coil. This voltage is then rectified into power, which drives the internal chemical reaction in reverse.

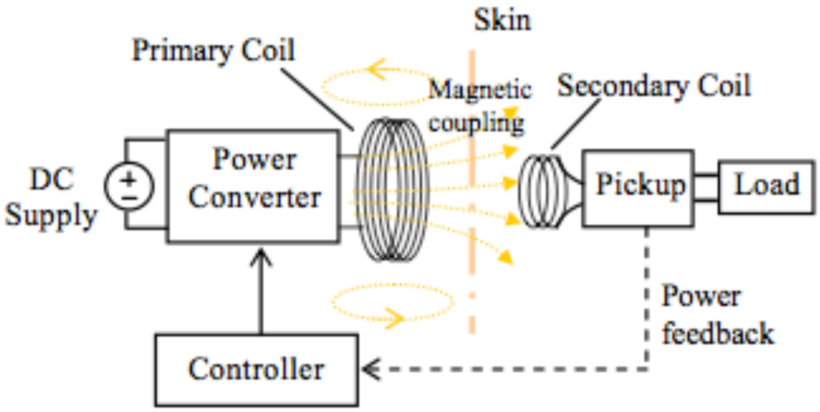


Figure 12: *Transcutaneous Energy Transfer system, primary coils are external, secondary coils internal. Recharging occurs through induction and magnetic coupling.*

B.3.2.1 Photovoltaic System

Another design alternative is a rechargeable system that is powered by light. This powering system is based on an electric accumulator, which is fed by the electric power generated by a photovoltaic converter inside the implantable device. Photovoltaic refers to a method of generating electrical power by converting solar/light energy into direct current electricity using semiconductors. Light impinges on the photovoltaic device through an optical fiber that runs to an area just beneath the skin. This method is beneficial for systems that operate outside or near a constant source of light. The downside of this method is that the there is not sufficient evidence it is safe. Being relatively new technology, the FDA and other governing bodies need to do a number of tests to pass this type of recharging technology. This will increase cost and potentially could lead to larger safety issues that have yet to be identified.

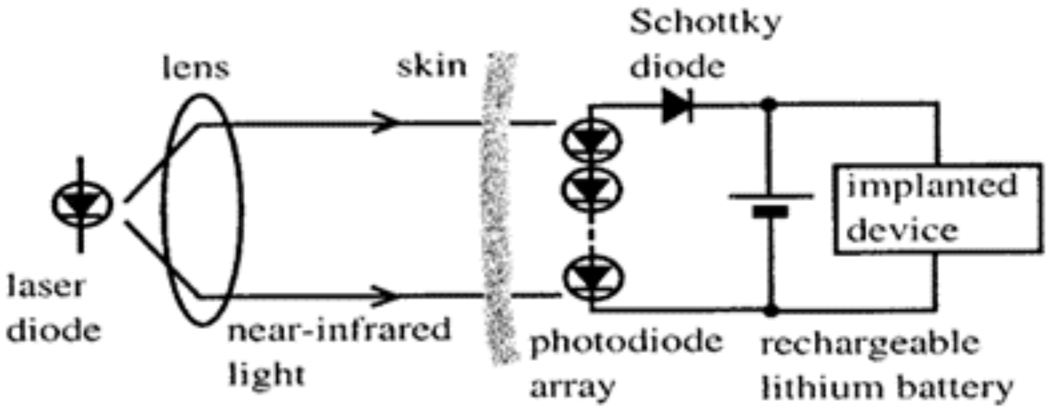


Figure 13: *Photovoltaic rechargeable system*

B.3.2.3 Wired Rechargeable Systems

Other design alternatives for recharging the battery are based on percutaneous connections with wires. This is how most medical devices are powered given that they can be plugged in or that they are located outside the body. Since the BCI Telemeter is fully implantable, this method would contradict a main specification of the system. Using this method would increase the risk of infection and would limit the mobility of the patient.

B.4 Casing Design and Specifications

This section focuses on the casing of the device, which is the part of the BCI Telemeter that has the most contact with the patient. In order for the device to be fully implantable, the casing must be biocompatible. For a material to be deemed biocompatible, any adverse reactions must be minimal, while resistance to biodegeneration must be high. This requires a biomaterial to interact as a natural material would in the presence of blood and tissue.

B.4.1 Titanium

A large portion of the biocompatible materials used for encasing biomedical devices are made from titanium or titanium alloys. Titanium is corrosion resistant, strong, lightweight, durable, cost effective, non-toxic, and non-ferromagnetic. Corrosion of implanted metal by body fluids results in the release of unwanted metallic ions, with likely interference in the processes of life. Corrosion resistance is not sufficient in itself to suppress the body's reaction to cell toxic metals or allergenic elements such as nickel, and even in very small concentrations from a minimum level of corrosion, these may initiate rejection reactions. Titanium is judged to be completely inert and immune to corrosion by all body fluids and tissue, and is thus wholly biocompatible.

B.4.2 Titanium Alloys

Titanium alloys have the same attributes as pure titanium except they offer a few added advantages. Depending on the ratio of additional alloy material, titanium alloys can provide physical and mechanical differences that result in increased strength, flexibility and resistance to cracking. Most alloys have a titanium percentage above 85%, so the reason some alloys may work better than others depends on where the metals are being used in the body.

The casing models made from titanium alloys can be improved even further by using a multilayered polymer biological film. These films are usually referred to as ‘hydrogels’. In a hydrogel-metal assembly, an intervening polymer network is used to bond together a water-swollen hydrogel layer to a biocompatible surface-modified metallic layer. The intervening polymer network has been chemically grafted to the inorganic material metallic layer through bi-functional linker molecules. This polymer layer adds extra protection for the patient because it lowers the friction, increases biocompatibility, reduces the potential for an adverse allergic or immune response, and reduces the chances of metals reacting within the body or blood.

C. Analysis Performed to Choose Design

C.1 ASIC Analysis

C.1.1 Multiplexer

Table 5 contains a Pugh Chart that compares options for multiplexer configurations. The input values range from 1-100 and are weighted based on the priority of the design specifications.

Table 5: *Pugh Chart comparing options for multiplexer configurations*

Multiplexer		
	8 Separate ASP Blocks	**Multiplex Signals Before ASP**
Signal Fidelity (x10)	95	35
Speed (x5)	85	65
Space (x3)	35	98
Cost (x2)	45	95
Total	1570	1159

Signal fidelity is weighted the highest because it is the contents of these signals that establish brain control. ECoG signals are very small (µV) and high accuracy is necessary to detect power modulations.

The speed in which the signals are processed and transmitted is weighted by a factor of five due to the fact that ECoG BCI is a closed loop system. The time that it takes for an ECoG channel to be processed and result in a cursor/robotic movement must be short enough that the subject can correlate the brain activity modulation with the elicited response. Also, for brain-computer interfaces to be practical in everyday life, they must be able to respond quickly to a patient's intended motion.

While the design specifications call for the device to be as small as possible, space considerations are not as important as maintaining the integrity of signal contents. Therefore, on the Pugh chart above in table 5, space considerations are only weighted by a factor of 3.

When performing analysis to choose multiplexer components, cost is weighted by a factor of 2 above. Cost must be considered, but cannot be the deciding factor when it comes to choosing amplifier components, so its weight is less than that of components that affect the signal quality.

Even though using eight separate ASP blocks and eight separate ADCs is more expensive and requires more space, the speed and signal quality that comes from this configuration makes it the desirable choice for the BCI telemeter.

C.1.2 Analog Signal Processing Block

Table 6 contains a Pugh Chart that compares options for the front end of the analog signal processing block. The input values range from 1-100 and are weighted based on the priority of the design specifications.

Table 6: *Pugh Chart comparing options for the front end of the ASP block*

Front End of ASP Block			
	Buffer	**Differential Amplifier**	**Instrumentation Amplifier**
Common Mode Rejection (x8)	0	98	98
Input Impedance (x5)	95	50	95
Cost (x2)	95	65	50
Total	665	1164	1359

Common mode rejection ratio is weighted the highest because when signals are so small, the noise has a larger effect on the signal. The common mode noise is subtracted from the signal to be processed using a differential amplifier, enabling further processing to amplify only the data that is used for control.

The input impedance is weighted by a factor of 5, because while we want the majority of our signal voltage to drop across the amplifier, if it does not due to high input impedance the frequency components will not be distorted, only the magnitude of the signal will be affected. The decrease in amplitude of a signal does not affect its digital processing, but it means that more analog amplifiers will be necessary to amplify the signal appropriately to achieve the required resolution for precise digital signal processing.

Cost is weighted by a factor of 2 in table 6 above. While an instrumentation amplifier is the most expensive integrated circuit (IC) that was explored, both of its characteristics, high common mode rejection and high input impedance, are required. Either an instrumentation amplifier is needed or a combination of buffer amplifiers and differential amplifiers is needed. Of these options, using an instrumentation amplifier IC ends up being cheaper and introduces less noise into the system.

C.1.3 Analog-to-Digital Converter

Table 7 contains a Pugh Chart that compares options of analog to digital converter resolution. The input values range from 1-100 and are weighted based on the priority of the design specifications.

Table 7: *Pugh Chart comparing options for ADC resolution*

Analog to Digital Converter			
	<16-Bit ADC	**16-Bit ADC**	**24-Bit ADC**
Resolution (x6)	10	80	98
Need for additional Analog Processing (x2)	0	60	90
Cost (x1)	90	65	50
Total	150	665	818

Resolution is weighted by a factor of six in the chart above because that it determines the voltage step size at the DSP and dictates the need for additional analog amplification. The specifications for the BCI Telemeter dictate that modulation down to 300nV must be detectable. This means that the lowest voltage step we can have must be less than 300nV. Given a specific ADC bit resolution, signal amplification must occur to increase the resolution and the signal-to-noise (SNR) ratio.

The "need for additional analog processing" parameter above is coupled with the ADC resolution. Therefore, the "need for additional analog processing" parameter scores will primarily account for the effects outside of those related to resolution. These include the introduction of noise associated with adding IC packages and the space necessary to host these additional packages.

The values assigned in the cost row above are based purely on the ADC device. As the maximum bit resolution of an ADC increases, the technology within the IC becomes more complex and the device becomes more expensive to produce. However, this parameter is un-weighted because when considering the cost associated with an ADC, the amount of analog processing necessary to amplify the signal pre-DSP should be taken into account. The use of the more expensive 24-bit ADC may end up yielding a cheaper device because the need to buy additional operational amplifiers becomes unnecessary.

Table 8 is a Pugh Chart that compares options of analog to digital converter architectures. The input values range from 1-100 and are weighted based on the priority of the design specifications.

Table 8: *Pugh Chart comparing options for ADC architectures*

Analog to Digital Converter – Type		
	Nyquist-Rate ADC	**Oversampling ADC**
Resolution (x10)	65	100
Accuracy (x5)	55	95
Speed (x1)	80	45
Cost (x2)	30	80
Total	1065	1680

Resolution is the most important factor when choosing an ADC in terms of ensuring high fidelity signal processing, so in the Pugh chart above, resolution has the highest weight. In practice, oversampling is implemented in order to achieve cheaper higher-resolution analog to digital conversion. Oversampling is an ideal solution to increasing the resolution.

The accuracy score of each ADC is weighted by a factor of five in table 8 above because the accuracy of signal processing is positively correlated with the accuracy of control. Oversampling ADCs negate the need for anti-aliasing filters to remove distorted, high frequency components by increasing the Nyquist frequency.

Speed has the lowest weight when considering which ADC architecture to choose for the BCI Telemeter. While oversampling ADCs trade resolution for speed, physiological signals propagate slowly and, due to their size, the increase in resolution outweighs the decrease in processing speed.

Cost is weighted by a factor of 2 in table 8 above. Oversampling ADCs are significantly cheaper than Nyquist-Rate ADCs. While cost is not the most important factor in choosing an ADC, the negative characteristics of choosing an oversampling ADC (speed) are significant in the BCI Telemeter's applications and do not outweigh the benefits of cheaper production.

Table 9: *Pugh Chart comparing overall ADC configurations*

Analog to Digital Converter - Overall				
	Nyquist-Rate 16-Bit ADC	**Oversampling 16-Bit ADC**	**Nyquist-Rate 24-Bit ADC**	**Oversampling 24-Bit ADC**
Resolution (x10)	65	80	90	95
Need for Additional Amplifiers (x3)	60	60	85	95
Cost (x1)	40	98	15	85
Total	870	1078	1170	1320

While the 24-bit Nyquist-rate ADC and the 24-bit oversampling are comparable in most of their characteristics, the lower cost of using an oversampling ADC makes it the better choice for the BCI Telemeter.

C.2 Telemeter

C.2.1 Modulation Formats

Table 10 is a Pugh chart outlining the parameters used to determine what format of modulation is best for the BCI Telemeter. The input values range from 1-100 and are weighted based on their priority.

Table 10: *Pugh chart comparing parameters of modulation format*

Modulation Formats		
	Frequency Modulation	**Amplitude Modulation**
Cost (x2)	60	90
Signal Quality (x5)	90	90
Transmission Distance (x1)	80	95
Total	650	725

Signal quality is weighted the highest because signals recorded from the brain are so small that signal fidelity must be as good as possible. Transmission distance is greater for AM than FM, but signals will not need to be transmitted large distances in the applications the BCI Telemeter is intended for, so transmission distance was given the lowest weighting. Cost is a factor in all decisions regarding the design, but in this case signal quality is much more important than cost. The result of the Pugh chart in Table 10 determine that amplitude modulation will be used to transmit signals from the ASIC to an external computer in BCI applications.

C.2.2 Antenna

Table 11 is a Pugh chart comparing various parameters that must be considered when choosing an antenna. The input values range from 1-100 and are weighted based on their priority in the design.

Table 11: Pugh chart comparing parameters of different antenna types

Antenna Type				
	PCB	**Chip**	**Whip**	**Wire**
Size (x8)	50	95	30	85
Cost (x2)	95	85	30	99
Performance (x5)	60	75	95	50
Total	890	1305	775	1128

The size of the antenna is the most important factor because of the limited space on the ASIC. At frequencies below 1 GHz the antenna must be at least 7.5 cm in length to obtain maximum power transfer. Antenna size can be altered in various ways to give an effective length of 7.5 cm depending on the type of antenna; it is possible to make chip antennas of very small size even with frequencies below 1 GHz. Performance is also a critical component to consider when choosing an antenna because signal fidelity is crucial in order for the BCI system to be successful. The whip antenna gives the highest performance score, but it is much too large to fit on an implantable device. The chip antenna offers the best size solution and scores second highest on performance. Overall, the chip antenna is the best option and will be used to transmit signals in the BCI Telemeter.

C.3 Battery

C.3.1 Battery Type

Tables 12a and 12b contain Pugh Charts that compare each battery type. The input values range from 1-100 and are weighted based on the priority of the design specifications.

Table 12 (a): *Pugh Chart comparing battery types (1-6)*

Battery Type						
	Lead Acid	**Alkaline**	**Nickel-Iron**	**Nickel-Cadmium**	**Nickel-Hydride**	**Nickel-Zinc**
Safety (x10)	5	60	55	25	30	45
Size (x7)	5	60	60	70	75	70
Energy Density (x5)	20	55	40	30	60	50
Power (x3)	30	10	32	50	70	98
Efficiency (x3)	80	65	65	75	50	66
Discharge Rate (x3)	30	95	5	10	12	20
Cycles (x3)	70	50	65	70	100	30
Life (x1)	90	75	100	60	10	50
Voltage (x1)	90	80	70	70	80	8
Totals	995	2110	1841	1635	1911	1890

Table 12 (b): *Pugh Chart comparing battery types (7-11)*

Battery Type					
	Lithium-Ion	**Lithium-Ion-Polymer**	**Silver Zinc**	**Zinc Bromide**	**Zinc-Carbon**
Safety (x10)	90	95	80	75	75
Size (x7)	90	100	80	80	80
Energy Density (x5)	95	100	92	90	65
Power (x3)	95	100	50	65	70
Efficiency (x3)	85	95	75	80	77
Discharge Rate (x3)	75	35	60	65	40
Cycles (x3)	75	65	75	40	30
Life (x1)	25	20	75	70	65
Voltage (x1)	85	90	75	80	90
Totals	3105	3145	2790	2660	2441

Safety is weighted the highest because it is the most important aspect of the battery. The safety multiplication factor is 10 based on three factors: the toxicity of the chemical components, the reactivity with other biological materials, and the side effects due to exposure.

Size has a multiplication factor of 7 because the design specifications call for the device to be as small as possible. The sizes are based on the average size of the battery on the market. Since the BCI Telemeter is smaller than most other devices, if a battery with a larger size in the table were used, it would be configured into a smaller version.

Energy density has a multiplication factor of 5. This measurement reflects the amount of energy delivered per volume of material. This becomes an important characteristic when working on smaller scales.

Efficiency, cycles/life and discharge rates are weighted equally at x3. These values correspond to effective use of power. Maximizing these qualities allows the battery to last longer between charges.

Life and voltage are given no multiplication factor. The life of the battery depends on how it is used. Since the BCI Telemeter runs continuously, the battery life will be different than that for the average device. The voltage is a characteristic that can be manipulated to fit the design specification.

The scores in the Pugh chart above show that Lithium-Ion-polymer system would be the most suitable battery for the BCI Telemeter. The scores between the lithium-ion and lithium-ion-polymers systems are the two highest. This is primarily due to the fact that safety is such a critical factor. Even though many batteries score well in power and energy categories, they are not suitable for implantation in the body. Lead-Acid, Ni-Cadmium, and Zinc-Carbon are not feasible because they are toxic, even in small quantities, in the body. Alkaline, NiMH and Ni-Zn might be good options as they are typically used in AA and AAA batteries, but they still pose a risk if any components leak or the external casing corrodes. Although zinc is an essential requirement for good health, excessive amounts of zinc can be harmful to the body. The amount of zinc that is contained in a typical dry-cell zinc battery is too much for applicable use. The other nickel-based products can result in nickel poising with symptoms like nausea, headaches, insomnia, irritability and vomiting. These should be used with caution for the protection of the patient. Lithium batteries are the safest on the list because of their low toxicity, but they are not entirely safe. Lithium batteries have the potential to overheat and they contain some flammable active ingredients, so protective measures must be taken when using this type of battery.

In addition, the energy density of lithium type batteries is about twice as high as many of the nickel batteries. This is primarily due to the size of the lithium-ion in comparison to the metals used in the nickel batteries. As a result, the two lithium battery types score the highest because of their relative safety, smaller size, and high energy density.

Lithium ion batteries and lithium-ion-polymer batteries have similar characteristics, and thus, similar scores in the Pugh chart above. The main difference between the two systems is the size scores, which is primarily influenced by the difference in the electrolyte used. The lithium-ion-polymer system uses a polymer as an electrolyte, while the lithium-ion system uses a liquid electrolyte gel. The liquid electrolyte of the lithium-ion battery requires secondary packaging to safely contain some flammable active ingredients. As a result, this additional packaging increases the weight and cost and limits the size flexibility. Additional weight and size decreases their energy density scores. Lastly, there is no free liquid electrolyte in lithium-ion-polymer batteries, which increases stability and leaves the components less vulnerable to problems caused by overcharging, damage, or leakage. The lithium-ion-polymer battery scores slightly higher in the safety, size, and energy density categories and is the best choice for the BCI Telemeter.

C.3.1.1 Cathode Material

Tables 13 is a Pugh Chart comparing materials for use as a cathode in the battery. The input values range from 1-100 and are weighted based on the priority of the design specifications.

Table 13: *Pugh Chart comparing cathode materials*

Cathode Material					
	Cobalt - Oxide	**NiCo - Oxide**	**Mn - Oxide**	**Iron - Phosphate**	**Lithium - Sulfide**
Capacity (x5)	65	80	75	70	90
Voltage vs. Li (x4)	85	80	90	70	60
Safety (x3)	50	75	90	90	50
Cycle Life (x2)	75	75	80	80	60
Toxicity (x2)	75	75	90	90	90
Cost (x1)	50	65	90	90	90
Totals	1080	1230	1345	1260	1170

The Pugh chart for cathode materials shows that magnesium oxide would be the best material for the cathode electrode. Its high score is due to its voltage vs. lithium, safety, and toxicity scores. It is relatively safe because it uses oxygen instead of sulfur and is not as toxic as the other elements. The high voltage characteristics is what sets magnesium oxide apart from the other oxide metal components; this can be attributed to the relationship that magnesium has with lithium compared to the other metals.

C.3.1.2 Anode Material

Table 14 is a Pugh Chart that compares materials for use as an anode in the battery. The input values range from 1-100 and are weighted based on the priority of the design specifications.

Table 14: *Pugh Chart comparing anode material*

Anode Material				
	Graphite	**Soft Carbon**	**Hard Carbon**	**Silicon**
Safety (x4)	80	80	80	20
Capacity (x3)	70	60	70	100
Irreversible Capacity (x3)	80	70	80	100
Efficiency (x3)	90	70	60	100
Cost (x2)	90	90	90	20
Total	1220	1100	1130	1020

The best anode material is a balance between capacity, energy and efficiency. Hard carbon has the best discharge rate, but is the least efficient when charging. Graphite and soft carbon have similar discharge rates, but graphite is much more efficient when charging and has the highest capacity. Silicon has by far the best capacity and discharge rate because it allows lithium ions to pass in and out of the electrode very quickly, but the expansion and contraction of silicon particles degrades the material. Due to this, silicon has to be ruled out to maintain the safety and integrity of the design and to avoid additional costs. Graphite provides the best anodic material based on its high scores relative to the other carbon materials.

C.3.1.3 Electrolyte

Table 15 is a Pugh Chart that compares electrolyte polymers. The input values range from 1-100 and are weighted based on the priority of the design specifications.

Table 15: *Polyethyleneoxide (PEO) vs. Polyvinylidene Fluoride (PVDF). Compares the type of electrolyte polymer used with* $LiPF_6$.

Polymer Electrolyte		
	PEO	**PVDF**
Diffusivity (x3)	90	70
Voltage (x2)	90	90
Viscosity (x2)	70	90
Cost (x2)	90	60
Safety (x1)	70	90
Totals	840	780

The two choices of polymer electrolytes have close scores; the PEO polymer electrolyte is the better choice primarily because of its high diffusivity score.

C.3.2 Recharging

Table 16 is a Pugh Chart comparing systems for recharging the battery. The input values range from 1-100 and are weighted based on the priority of the design specifications.

Table 16: *Pugh chart with values that compare the Transcutaneous Energy Transfer System and the photovoltaic system.*

Battery Recharging Systems		
	TET	**Photovoltaic**
Safety (x5)	95	75
Conductivity (x4)	80	80
Toxicity (x3)	90	85
Power Conversion Rate (x2)	95	95
Cost (x2)	95	80
Total	1445	1300

The Pugh chart indicates that the TET system is the best rechargeable system. This is primarily due to the differences in safety and toxicity. Since the photovoltaic system has not been fully tested on human subjects, it received a slightly lower safety score. In addition, its cost score incorporates the need for future FDA regulations and any potential cost for approval.

C.4 Casing

The main component of the BCI Telemeter casing is titanium, but design enhancements affect a few of the characteristics such as biocompatibility, safety and strength. The Pugh chart in Table 17 compares casing options. The input values range from 1-100 and are weighted based on the priority of the design specifications.

Table 17: *Comparison between three methods for producing the casing*

Casing Options			
Casing Material	**Pure Titanium**	**Titanium Alloy**	**Titanium Alloy + Hydrogel**
Safety (x5)	80	90	100
Biocompatibility (x4)	90	80	100
Corrosion Resistance (x3)	90	90	100
Strength (x3)	100	90	80
Durability (x3)	100	100	90
Flexibility (x2)	80	100	90
Weight (x2)	80	100	90
Cost (x1)	90	90	70
Total	2040	2100	2140

The Pugh chart shows that the titanium alloy with a hydrogel polymer biolayer is the best design. The hydrogel combines the best elements of the other two designs, but incorporates a component that enhances the biocompatibility of the design. The biolayer increases the resistance to corrosion, which also makes it safer. Since safety is of the utmost concern in the design of the BCI Telemeter, the high score in the safety category is worth the increases in weight and cost.

D. Specific Details of Chosen Design

The final ASIC design includes eight 4:1 analog switches, an instrumentation amplifier at its front end, a 24-bit oversampling ADC, and a MSP430 Microcontroller for digital signal processing. While using a second multiplexer before the analog signal processing block conserves space and money, the potential signal distortion causes this option to be unsuitable for the BCI Telemeter. According to the analysis provided, while an instrumentation amplifier is the most expensive option we are considering for the front end of the analog signal processing block, it provides the necessary input impedance and common mode rejection ratio for high fidelity ECoG recordings. Using a 24-bit oversampling ADC provides the required resolution for accurate processing while avoiding the use of additional amplifiers in the ASP block. The output of the ADC will be processed by DSP software programmed on a microcontroller. The MSP430 addresses the BCI telemeter's power consumption specifications and limited space requirements.

The output of the ADC will be wirelessly transmitted via the TI CC1101 Transceiver and the signal carried using amplitude modulation. The TI CC101 Transceiver supports several types of antennas, and the BCI Telemeter will incorporate a chip antenna due to its small size and good performance.

The BCI Telemeter will be powered by a thin-filmed lithium ion rechargeable battery, chosen for its exceptional safety standards and small size. The battery is recharged through the skin using a transcutaneous energy transfer system.

All components will be enclosed in a biocompatible titanium-alloy case. This case will be hermetically sealed and implanted subcutaneously in the body.

E. Updated Design Schedule

The tasks outlined in this section are to be completed throughout the semester to yield a cohesive final design. In addition to maintaining this schedule, each group member is required to keep a design notebook that will convey logical and chronological evidence of the progress of the design. Also, a weekly report will be submitted each week outlining the progress made during the previous week and goals for the following week.

E.1 LIST OF TASKS TO BE COMPLETED

Task 1: Project Scope - Due September 14

The project scope identifies the problem to be addressed and discusses the basic requirements of the design. It presents an overview of the project and lists foreseen challenges that will need to be addressed during the design process.

Task 2: Preliminary Report and Presentation - Due September 28

The preliminary report focuses on defining the scope of the project. It includes background information about previous technologies and an in-depth analysis of the need for the design. The preliminary report includes detailed project specifications, taking into account both the consumer perspective and the eventual marketing potential.

Task 3: Headstage Circuit Design

The headstage circuit board must retain the ability to amplify and filter ECoG signals and have a low noise floor in order to accommodate extremely small brain signals. The design for this circuit board will be completed using the specifications given by Dr.

Moran. While most of the data processing algorithm is already finished and can be easily programmed onto a chip, the hardware that will make this compatible with multiple channels of ECoG recording needs to be designed.

Task 4: Telemeter Circuit Board

The telemeter circuit board must transmit both raw and processed signals to an external receiver to be used for brain control tasks. Brain control is established in ECoG by using power modulation in the frequency domain, so transmitting the processed signal with the frequency response intact is essential.

Task 5: Case Design

The material that encases the BCI Telemeter circuit board and battery must be biocompatible and must include a section that is transparent to the scanning radio-frequency beam that activates the telemetry chip. This design must be large enough to encase all the necessary hardware and small enough to fit comfortably in the chest.

Task 6: Web Page

The project web page provides a clear representation of our project for public access. It includes an overview of the project, all weekly reports, presentations, design safe outputs, and other relevant information. This website will be used primarily to track progress of the project and will be kept active for a significant length of time to be used on resumes.

Task 7: Progress Report and Presentation - Due October 26

The progress report outlines several possible solutions to the problem presented by our mentor. Each of these solutions will be examined and one will be presented as the best choice based on benefits and trade offs of each option. For this report, preliminary circuit designs will be completed and simulations in PSpice will be prepared for presentation. The information in this report will also be presented to the class in the form of a 12-minute oral presentation.

Task 8: Risk Assessment

The risk assessment evaluates the potential dangers associated with our design and discusses ways to mitigate these risks. During the risk evaluation, the ways in which the design might malfunction as well as possible user errors that could contribute to product failure will be examined. The likelihood of these errors occurring and the significance of each risk will be evaluated. To mitigate these shortcomings of the design, ways to eliminate the cause, lower the probability, or protect against the effect of each risk will be determined. A safety assessment will be completed using DesignSafe software. The output of this evaluation will be posted on the project website.

Task 9: Final Report and Presentation - Due December 7

The final report presents the complete solution and an evaluation of the design process. Circuit simulations for both the headstage circuit board and the telemeter circuit board will be completed and the results, matching the specifications of our mentor, will be presented. The information in this report will also be presented to the class in the form of a 12-minute oral presentation.

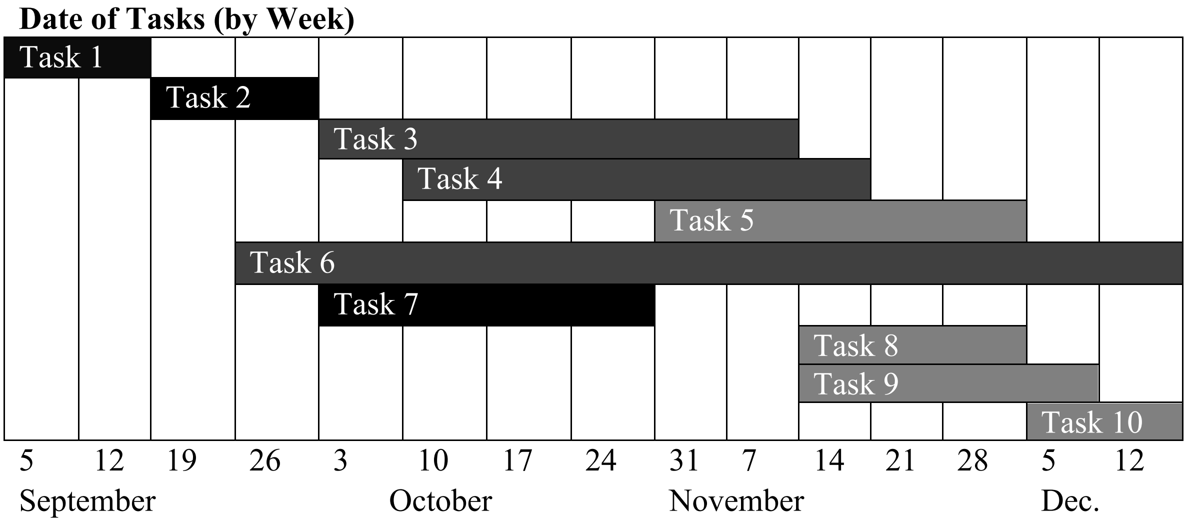
Task 10: Senior Design Poster

The senior design poster presents the final design project in a succinct manner to be displayed to other students and faculty at the Undergraduate Research Symposium.

E.2 Design Schedule

In order to complete this project in the allotted 16 weeks, a strict schedule was developed and has been maintained. The cells that are in black have been completed and the cells in darker grey have been started.

Table 18: *Updated Design Schedule*



E. ORGANIZATION OF TASKS AND TEAM MEMBERS

Tasks will be assigned to team members based on particular strengths. The table below outlines the specific work needed to be done to complete each task.

Table 19: *Organization of Tasks*

Tasks	**Report**	**Presentation**	**Multisim**	**CAD**	**Web Design**	**DesignSafe**
Task 1	☒					
Task 2	☒	☒				
Task 3			☒			
Task 4			☒			
Task 5				☒		
Task 6					☒	☒
Task 7	☒	☒				
Task 8						☒
Task 9	☒	☒				
Task 10			☒	☒		

Table 20: *Distribution of Tasks*

Lindsey	**Suyi**	**Jessi**	**Group Tasks**
Preliminary Presentation	Progress Presentation	Final Presentation	Project Scope
Web Page Design	CAD Drawings	Circuit Design	All written reports
Design Safe Analysis	SolidWorks Drawings	Primary contact with mentor	

G. Abbreviations

ADC – Analog to digital converter
AM – Amplitude Modulation
ASIC – Application Specific Integrated Circuit
ASK – Amplitude-Shift Keying
ASP – Analog Signal Processing
BCI – Brain-Computer Interface
BOM – Bill of Materials
CNS – Central Nervous System
CMRR – Common Mode Rejection Ratio
DSP – Digital Signal Processing
ECoG – Electrocorticography
EEG – Electroencephalography
FDM – Frequency-Division Multiplexing
FM – Frequency Modulation
FSK – Frequency-Shift Keying
IC – Integrated Circuit
ISM – Industrial, Scientific and Medical
LSB - Least Significant Bit
MCU – Microcontroller Unit
MUX – Multiplexer
Op-Amp – Operational Amplifier
PCB – Printed Circuit Board
PEO – Polyehtyleneoxide
PM – Phase-Shift Modulation
PVDF – Polyvinylidene Fluoride
RF – Radio Frequency
SNR – Signal-to-Noise Ratio
SU – Single-Unit
TDM - Time-Division Multiplexing
TET – Transcutaneous Energy Transfer
TI – Texas Instruments

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