I/O System Design for the PSYONIC Advanced Bionic Hand

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1 Introduction

1.1 Objective

There are 11.4 million hand amputees in the world, and over 80% are in developing nations [1]. Less than 3% of these amputees have access to the rehabilitation necessary to rebuild the functionality they lost by losing a limb [2]. The high cost of existing prosthetics makes them unaffordable to amputees in developing nations. Most low-cost designs for prosthetic hands focus on the mechanical design of the hand, not on the design of an integrated system that is a viable product for amputees [3].

PSYONIC is a startup on campus that is working to fix these issues by developing a low-cost prosthetic hand for use on amputees worldwide, in both developed and developing nations. They are working alongside clinicians and amputees to ensure that the hand will meet the needs of amputees. With features such as control by electromyographic (EMG) pattern recognition and tactile feedback through use of electrotactile stimulation, the PSYONIC Advanced Bionic Hand will be a serious competitor to existing prosthetic hands on the market today [4].

1.2 Background

PSYONIC is a startup at the University of Illinois that is developing an affordable prosthetic hand for people with upper-limb amputations worldwide. Their prototypes have reached a high level of functionality, and they are now moving the design towards production hardware [5]. While the core functionality of the hand is well-integrated, auxiliary functionality such as battery charging and external I/O are either nonexistent or require specialized hardware to be used.

We plan to design a new system for PSYONIC's prosthetic hand, to be known as the I/O system. This system will integrate all the external I/O necessary for the prosthetic arm. It will contain two external interfaces, namely USB type-C and Bluetooth. USB type-C allows for rapid battery charging and wired data communications. Bluetooth enables the hand to be capable of wireless data transfer. These interfaces will let us build an API that will let us, and more importantly, clinicians perform a variety of remote control and configuration tasks. This includes the ability to query and write values that control various aspects of the hand's operation, such as the finger speed sensitivity or the battery charge level. While there are COTS solutions for individual aspects of this problem, there is no commercially available solution that can perform all the required functionality, let alone in the space constraints the project requires.

1.3 High-Level Requirements List [6]

- The I/O System shall be capable of powering the prosthetic hand from both an external power source and an internal battery
- The I/O System shall be capable of communicating with external devices using Bluetooth or USB
- The I/O System shall be capable of sending commands to the EMG board

2 Design

The I/O System consists of two physical modules, the I/O Board and a 2.2Ah lithium-ion battery and performs three functions. It supplies power to the prosthetic hand, communicates with external devices through a wired USB connection or a wireless Bluetooth connection, and sends commands to the hand via the EMG board. The power supply powers the prosthetic hand, taking power from a USB type-C connector and storing it in a battery. The communications interfaces communicate with external Bluetooth and USB devices, sending commands and data to the hand through the EMG Board. Lastly, the radiofrequency (RF) front end contains an antenna and matching network required for the I/O Board to communicate wireless over Bluetooth.

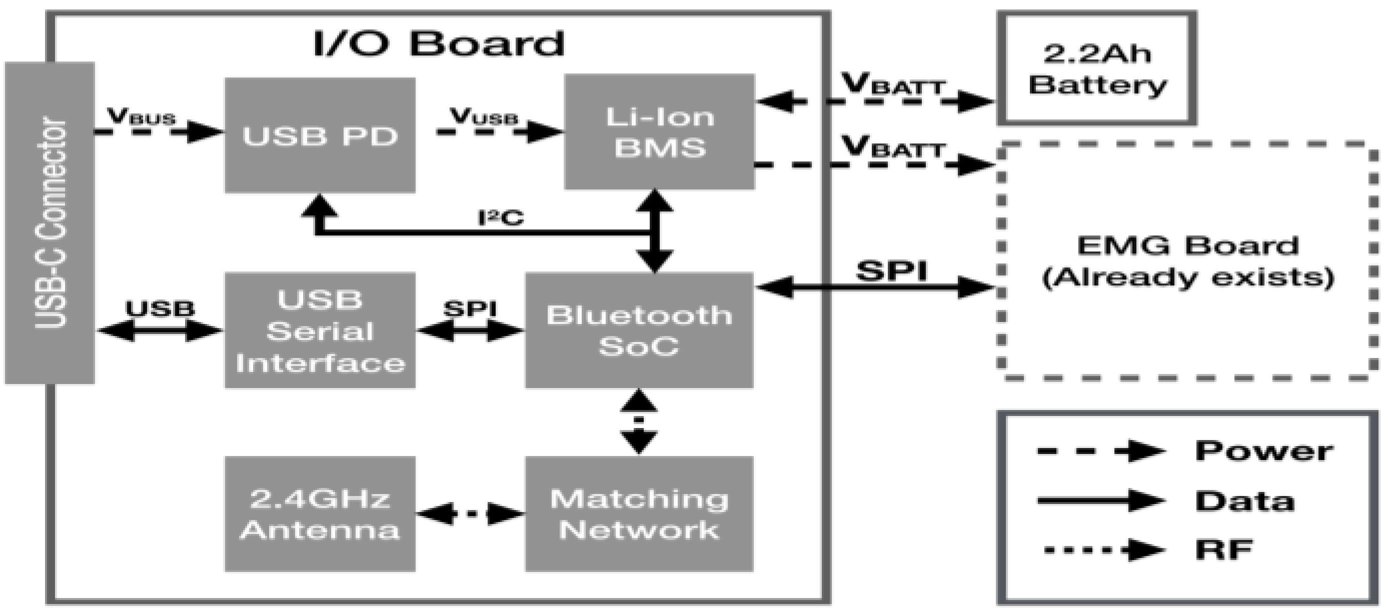

Figure 1: System Block Diagram

- SPI stands for Serial Peripheral Interface Bus, it’s a common bus for Embedded system to exchange large amount of data.
- I2C stands for Inter-Integrated Circuit Bus, it’s another common bus for Embedded system for changing small quantity of data.
- BMS stands for Battery management system, which charges and monitors battery to ensure safe use of Lithium battery.
- USB PD stands for power delivery, it’s the newest power protocol for USB-C devices to support high wattage of power transfer.

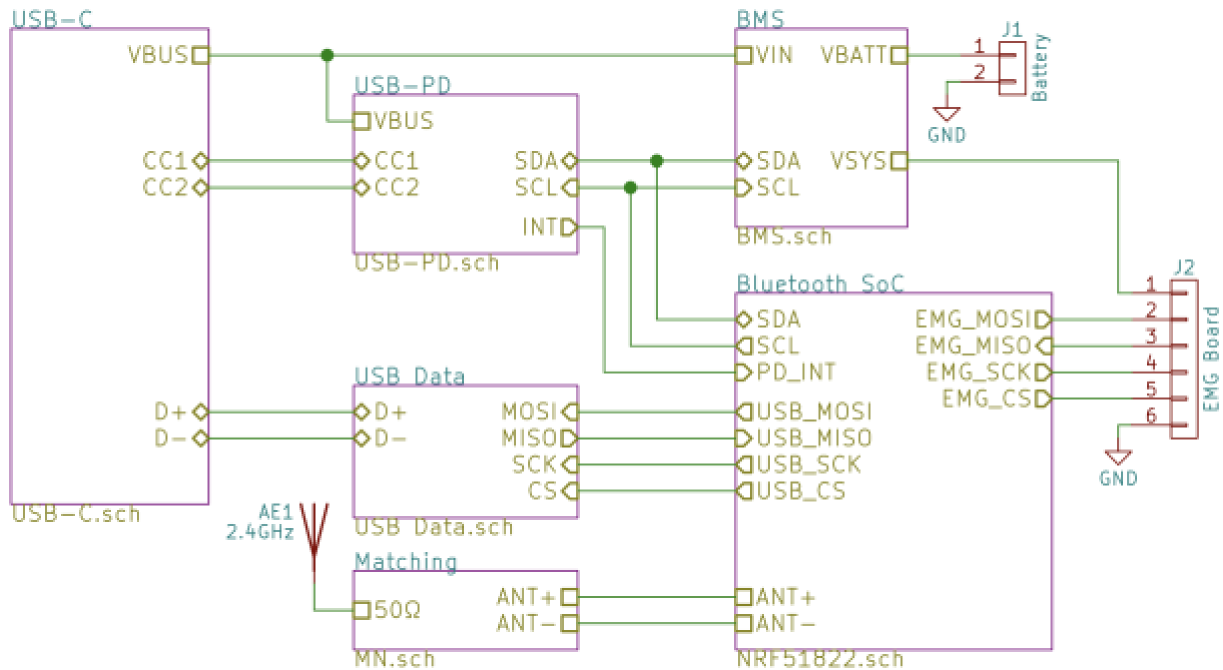

Figure 2: Top-Level Schematic

2.1 PCB Layout

With the exception of the battery, all the circuitry for the I/O System exists on one Printed Circuit Board (PCB), known as the I/O Board. To reduce the cost of the I/O Board, a 2-layer stackup was selected. The top layer will be used as a signal layer, and the bottom layer will be primarily a ground plane. Each layer has a copper thickness of 1oz, a minimum feature size of 6mil, and a Electroless Nickel Immersion Gold (ENIG) surface finish. The board thickness will be 1.6mm with an FR-4 substrate.

The I/O Board will contain switching regulators, medium-speed digital signals, and RF. Proper layout practices are absolutely necessary for a successful design that provides a stable hardware platform for the project's software. Additionally, this design is intended for use in a commercial product and will need to pass RF emissions testing as mandated by the Federal Communications Commission (FCC). As an intentional radiator, the I/O Board will need to meet the more stringent requirements of Title 47 Part 15C [6]. Nodes with a high dI/dt, commonly found in switching regulators, will be routed so that they are as small as possible, minimizing inductance between pins and capacitance to ground. Return current paths will be designed to minimize the loop area, reducing radiated emissions due to the current loop acting as a loop antenna. Any traces traces on the same layer as the ground plane will be routed so that they do not increase the return current path length. Proper decoupling of the power rails will reduce the amount of RF on the power rails as well. To reduce interference between circuit blocks, the power supply, communication interfaces, and RF front end will be routed in separate areas of the PCB.

Design for Manufacture (DFM) issues will be taken into consideration as well. Traces will be routed to avoid acid traps—areas where etching acid can accumulate during board manufacture. Minimum feature size, annular ring size, via aspect ratio, and other board geometry parameters were selected for ease of manufacture.

Lastly, the I/O Board will be designed to maximize flexibility, reducing the need for a second revision of the PCB. This is achieved by adding additional components marked as "Do Not Place" and by adding plenty of zero ohm resistors, enabling circuit blocks to be reconfigured by adding and removing components. The board silkscreen will be taken into consideration as well, ensuring that the

2.2 Power Supply

2.2.1 USB-PD Controller

The USB Power Delivery (USB-PD) protocol allows for USB devices to request more power than the 2.5W available over standard USB. It is separate from the USB data protocol, and is designed to be run in parallel with the USB protocol. As shown in Figure 3, the USB type-C connector contains separate pins for both the USB-PD and USB protocols [7]. There are a variety of commercially available USB-PD chargers on the market today, and compliance with the USB-PD standard will be required to ensure compatibility with all of them.

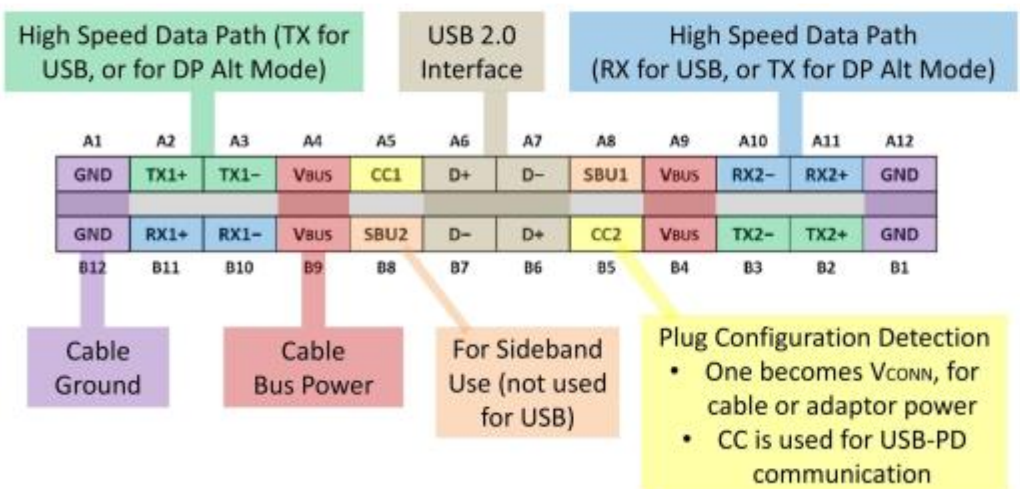

Figure 3: USB Type-C Connector Pinout

The USB-PD negotiator implements the majority of the USB-PD specification, allowing the hand to accept more power than the 2.5W available through standard USB from a wide variety of commercially available wall chargers. Our implementation will select the power supply output with the highest available power, with a preference for higher voltages. This minimizes charging times and increases the charging efficiency.

The FUSB302 USB-PD negotiator was selected for this task for its easy to implement I^2C interface, small package size, few required external components, and low cost. It abstracts almost all of the USB-PD protocol layers shown in Figure 4, allowing us to focus on the firmware for the power policy manager, also known as the Device Policy Manager [8].

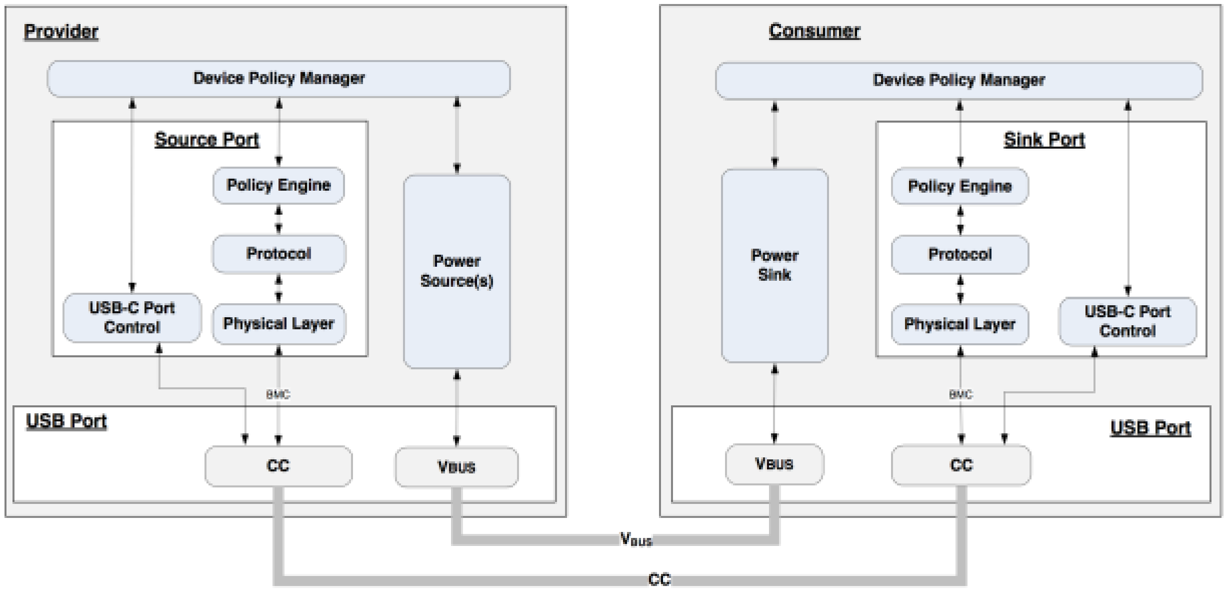

Figure 4: USB-PD Protocol Layers [9]

Requirement and Verification for USB-PD [10 points]

Requirement	Verification
The USB-PD Controller shall select the output voltage with the maximum available power or voltage to provide highest efficiency and remain compatible with variety of chargers on the market	1. Attach a power adapter to the I/O Board 2. Verify that the output voltage is 5V 3. Instruct the USB-PD negotiator to select the optimal output configuration 4. Apply the maximum load to the power output 5. Verify that the VBUS voltage is what was reported by the adapter 6. Repeat this procedure with power adapters from well-known companies such as Apple, Samsung, and Google

2.2.2 Lithium-Ion Battery Management System

The Lithium-Ion Battery Management System (BMS) charges the battery and regulates its output. It contains a switch-mode constant-current/constant-voltage (CC-CV) voltage regulator, which charges the batteries [10]. The BQ25700 was selected due to our experience implementing it in similar designs, as well as its wide feature set available. It is capable of powering downstream system while charging the battery at the same time. It also contains hardware to monitor the battery's state, and keep it in a safe operating state at all times.

The EMG board has an onboard voltage regulator, and it is capable of handling the full range of battery voltages, making an onboard voltage regulator not necessary for the I/O Board.

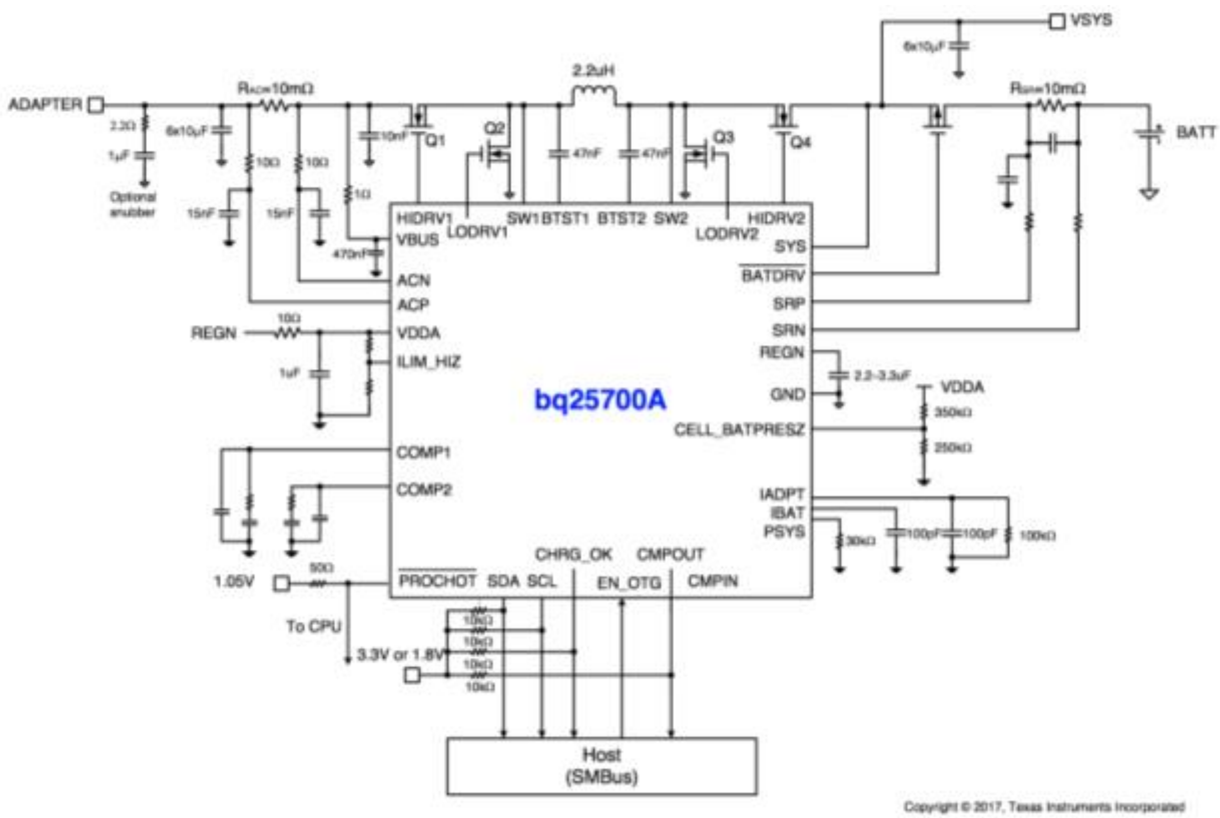

Figure 5: BQ25700 Application Diagram

Requirement and Verification for Battery Management System [15 points]

Requirement	Verification
The BMS shall change the battery from an input voltage range of 5V to 20V, inclusive	1. Attach a power supply to the BMS input 2. Attach a load in place of the battery 3. Sweep the input voltage from 5V to 20V 4. For each input voltage, verify that the BMS battery output voltage is correct
The BMS shall charge the battery with a maximum charge current of at least 750mA, with a preferred value of 1.1A	1. Attach a power supply to the BMS input 2. Attach a load in place of the battery 3. Measure the load current
The BMS shall not charge the battery when the pack voltage is greater than 4.4V or less than 5.4V	1. Attach a voltage source to the battery voltage sense pins 2. Sweep the voltage source from 2.5V to 4.5V 3. Verify that the BMS only attempts to charge the battery when the cell voltage is within the specified range

The BMS shall disconnect the battery if the output is shorted to ground	1. Attach a voltage source in place of the battery 2. Check that the BMS outputs the battery voltage 3. Short the output to ground 4. Verify that there is no current in the short

2.3 Communications Interfaces

2.3.1 USB Serial Interface

The USB Serial Interface allows the hand to communicate with USB devices. It receives serial data from the microcontroller, as it does not have a USB interface built in. The FT2232H was selected due to its ease of implementation and wide variety of supported protocols.

Requirement and Verification for USB communication [5 points]

Requirement	Verification
The USB Serial Interface shall support a baud rate of at least 115200	1. Connect the I/O Board to a computer using a USB cable 2. Transmit known data to the I/O Board 3. Use an oscilloscope to determine the baud rate 4. Verify that the received data is the same as the transmitted data 5. Repeat the above procedure while transmitting data from the I/O Board

2.3.2 Bluetooth System-on-a-Chip

The Bluetooth System-on-a-Chip (SoC) controls all the other blocks on the I/O Board. It communicates with external Bluetooth or USB devices and sends commands to the EMG Board over an external SPI bus and monitors the state of the BMS and USB-PD negotiator through an internal 400kHz I^2C bus. The NRF51822 was selected for its strong support resources and its wide variety of I/O peripherals. Figure 6 contains the example application schematic [9], which we plan to follow when implementing the NRF51822. [10]

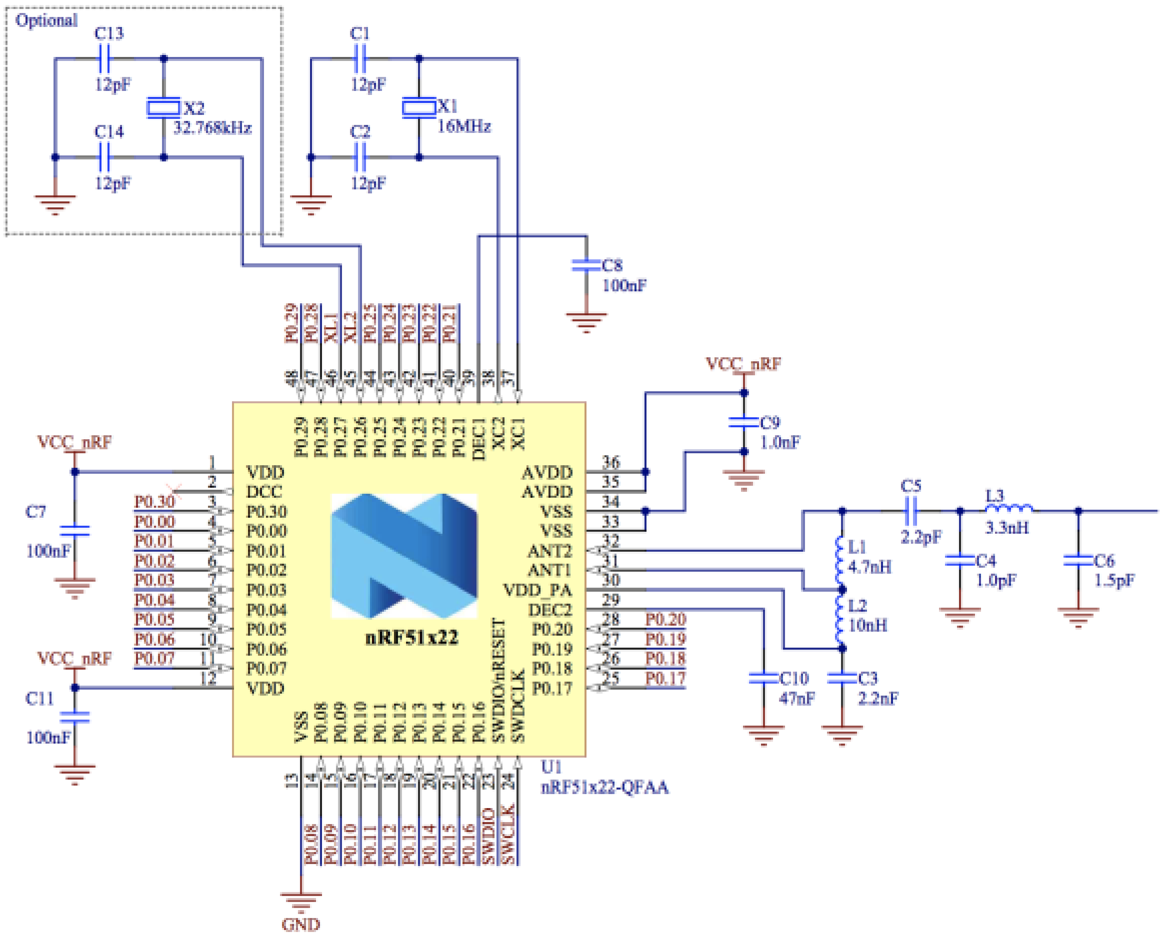

Figure 6: Application Schematic for NRF51822

Requirement and Verification for BLE I/O System [15 points]

Requirement	Verification
The Bluetooth SoC shall support Bluetooth Low Energy (BLE) 4.0 with a 5kbps transfer rate	1. Pair the I/O Board with a BLE transceiver 2. Transmit a known amount of data to the Bluetooth SoC 3. Measure the transfer time to determine the transfer rate 4. Verify that the received data is the same as the transmitted data 5. Repeat the above procedure with the Bluetooth SoC transmitting

The Bluetooth SoC shall be capable of communicating with the EMG Board at speeds of at least 1Mbps	1. Connect the I/O Board to the EMG Board 2. Transmit a known amount of data to the I/O Board 3. Measure the transmit time to determine the transfer rate 4. Verify that the received data is the same as the transmitted data 5. Repeat the above procedure while transmitting data to the EMG Board

2.4 RF Front End

2.4.1 2.4GHz Antenna

The 2.4GHz antenna transmits and receives Bluetooth data. We decided to use a PCB trace antenna due to its small form factor and low cost. To simplify the design procedure, we will follow the recommended design from Nordic Semiconductor

Requirement and Verification for BLE Antenna [2 points]

Requirement	Verification
The antenna shall have an input impedance of 50Ω +/- 5% at frequencies between 2400MHz and 2483.5MHz	1. Attach a network analyzer to the matching network 2. Measure the reflection coefficient of the antenna at Bluetooth frequencies

2.4.2 Antenna Matching Network

The 2.4GHz antenna will need a matching network to impedance match the 50Ω antenna to the 15-j85Ω differential input impedance of the Bluetooth SoC. The matching network will follow the recommended design from Nordic Semiconductor.

Requirement and Verification for Antenna Matching Network [3 points]

Requirement	Verification
The matching network shall have an input impedance of 50Ω +/- 5% at between 2400MHz and 2483.5MHz on the antenna side	1. Attach a network analyzer to the matching network 2. Measure the s-parameters of the network at Bluetooth frequencies 3. Calculate the input impedance from the reflection coefficient
The matching network shall have an input impedance of 15+j85Ω +/- 5% at between 2400MHz and 2483.5MHz on the Bluetooth SoC	1. Attach a network analyzer to the matching network 2. Measure the s-parameters of the network

side	at Bluetooth frequencies 3. Calculate the input impedance from the reflection coefficient
The matching network shall have an insertion loss of less than 2dB	1. Attach a network analyzer to the matching network 2. Measure the s-parameters of the network at 2.4GHz 3. Verify that the insertion loss is less than 2dB

2.5 Bluetooth Firmware

We will use the Software Development Kit and BLE stack provided by Nordic Semiconductor to develop the firmware for the I/O Board. The Nordic BLE stack implements all the controller and host software, letting us focus on designing the communications protocol for the I/O System [9]. Additionally, the BLE stack handles the encryption and security of the connection, which is essential to ensuring patient privacy.

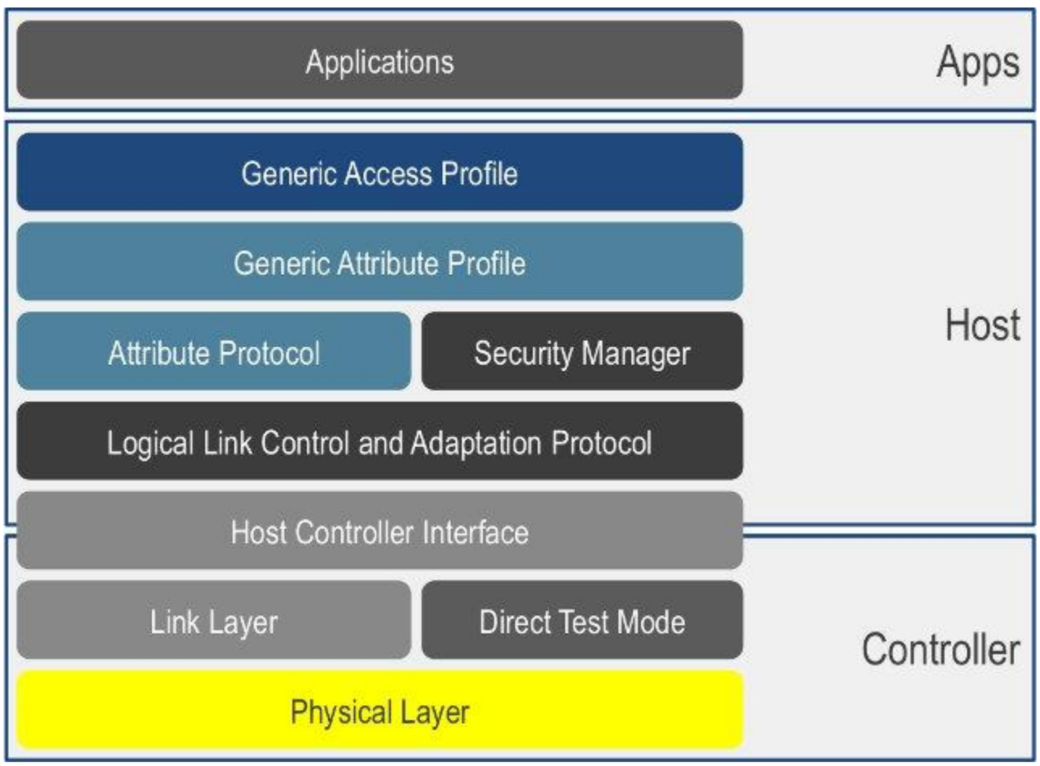

Figure 7: Bluetooth Low Energy Software Stack

2.6 Microstrip Tolerance Analysis

For the feedline of our antenna, microstrip transmission line will be used. This is an RF structure, and the characteristic impedance should be 50Ω to minimize reflections and maximize power transfer. The characteristic impedance is the square root of the ratio between unit length inductance and capacitance.

$$Z_0 = \sqrt{\frac{\mathcal{L}}{\mathcal{C}}}$$

For this project, we will be using microstrip transmission lines. They are simple to construct in a 2-layer PCB stackup and are very widely used in industry. While there is no closed-form expression for the characteristic impedance of microstrip, numerical methods can be used to estimate the characteristic impedance to a high degree of accuracy.

However, the characteristics of the PCB substrate can affect the characteristic impedance. We will be using a low-cost FR4 substrate. One of the disadvantages of such a substrate is that its properties are poorly defined. The relative permittivity of FR4 typically ranges from 4.35 to 4.8, with an average value of 4.7. Using the PCB layer stackup described in section 2.1 and a relative permittivity of 4.7, a transmission line width of 2.88mm is necessary to achieve a characteristic impedance of 50Ω. Over the full range of relative permittivities described earlier, the characteristic impedance will range from 49.53Ω to 51.76Ω; this is sufficient to meet the antenna input impedance requirement. Next, we can calculate the reflection between the section of microstrip and a 50Ω port impedance as shown.

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{50\ \Omega - Z_0}{50\ \Omega + Z_0}$$

This gives us a reflection coefficient ranging between -17.62dB and -7.44dB, with it falling to zero at 50Ω, demonstrating that the return loss is low enough to be negligible at the frequencies of interest.

3 Cost and Schedule

3.1 Cost Analysis

Our development costs are estimated with an hourly rate of $45/hour, 12 hours/week per person. The project is 14 weeks long, and we are a team of two people. This brings the total development costs to $37,800.

Name	Hourly Rate	Hours	Total	Total x 2.5
Wenjun Steven Sun	$45	168	$7560	$18900
Hopps, Byron Bradford	$45	168	$7560	$18900

Table 8. Labor Cost

$$2\ people * \frac{\$45}{hr} * \frac{12\ hr}{wk} * 14\ wk * 2.5 = \$37{,}800$$

Part costs are estimated for a prototype run of 10 units and a production run of 1000 units

Part	Unit Cost (qty. 10)	Unit Cost (qty. 1000)
Bluetooth SoC (NRF51822)	$5.91	$3.93
Lithium-Ion Battery	$17.23	$11.72
Battery Management System Control IC (BQ25700)	$6.95	$5.69
Battery Management System FETs	$2.50	$1.64
USB Serial Interface Controller (FT2232H)	$7.00	$5.80
USB-PD Negotiator (FUSB302)	$1.11	$0.59
USB Type-C Connector	$1.59	$1.33
Various 0402 passives	$9	$3
PCBs	$3 [7]	$1
Total	**$54.29**	**$35.70**

Table 9: Component costs

This project is for prototype hands, so parts will be bought to assemble 10 boards. Due to the in-progress nature of the project, spares will be assembled so that damage to the board will not result in irrecoverable timeline slippage.

3.2 Schedule

Week	Steven	Byron
Oct. 2, 2017	Prepare for Design Review	Write Design Document
Oct. 9, 2017	Present Design in Design Review	Present Design in Design Review
Oct. 16, 2017	First firmware test on dev board for BLE communication	Return from World Solar Challenge, begin schematic capture
Oct. 23, 2017	Test first version firmware for BMS chip	Schematic capture in Altium Designer
Oct. 30, 2017	Test first version firmware for USB-C PD protocol	Component placement and routing (PCB layout)

Nov. 6, 2017	Test iOS software with BLE firmware	Layout RF front end and PCB trace antenna
Nov. 13, 2017	Test fully functional individual firmware with individual hardware components	Send out gerber files, begin writing test plans
Nov. 20, 2017	Test firmware on actual PCB	Receive PCB, begin verification and characterization
Nov. 27, 2017	Test firmware on actual I/O board with full hand system	Finish characterization, prepare for demonstration
Dec. 4, 2017	Writing final report	Begin writing final report
Dec. 11, 2017	Final Presentation	Final Presentation

Table 10: Project Schedule and Task

4 Ethics and Safety

The main safety hazard with our project is the lithium-ion battery used to power the hand. If not properly managed, it has the potential to outgas and catch fire. The only way to put out a lithium-ion battery fire is to wait until it burns out. Battery fires can be avoided by keeping the battery within the safe operating area, as defined by the manufacturer. This generally entails keeping the battery voltage above 2.7V and below 4.2V, as well as keeping the cell temperature between -40ºC and 60ºC [11]. A series of requirements have been written to verify that our BMS keeps the battery within its safe operating area, and the verification procedures do not use an actual battery, to prevent a battery fire in case the BMS does not meet our requirements. This is in accordance with #1 and #9 from the IEEE code of ethics [12], as an improperly designed battery management system has the potential to cause serious harm.

Another aspect of our project is that it is intended for use as part of a medical device. This gives our project a greater potential to do harm to people. As a medical device, our project will be regulated by the Food and Drug Administration (FDA), which means that our project will need to meet strict testing requirements. We will be documenting all the tests we do on the I/O System to support the FDA approval process to help PSYONIC gain FDA approval for the PSYONIC Advanced Prosthetic Hand. Of course, we will follow #3 from the IEEE code of ethics when documenting the tests that we perform, as falsifying test data is a serious ethical violation [12].

Our project will add the capability to configure the hand remotely. This raises the possibility of an unauthorized individual gaining access and doing things against the wishes of the user. This possibility is mitigated by the encryption of the Bluetooth protocol and the access model of the Bluetooth pairing process. Even then, we will be careful to only implement features that will not result in sudden and unexpected changes to the hand’s behavior.

Lastly, our project will include an intentional emitter of electromagnetic radiatio [8]n in the form of a Bluetooth radio module. It will also contain moderately high-speed digital busses and multiple switch-mode circuits. All of these circuits have the potential to cause unintentional emissions. The electromagnetic spectrum is a shared resource by all of humanity, and the noise floor has been steadily increasing due to the proliferation of circuitry which have not been designed with EMI concerns in mind. In the USA, the Federal Communications Commission (FCC) requires that all products sold in the USA pass unintentional emissions testing. We will keep EMI considerations throughout the design process, especially during PCB layout, to ensure that our design meets FCC regulations.

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