BIO-Helmet

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Group 3

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***Abstract* — BIO-Helmet is a wearable helmet device for use in professional football which measures the amount of g-force applied to the helmet through the use of an accelerometer. This device also contains an EEG sensor array which measures and records an athlete's brain waves. The data from both sensors is sent to a local server where it can be analyzed and reported in graphical form. A major goal of this project is to provide a portable monitoring tool for identifying possible concussions in athletes.**

***Index Terms* — Accelerometer, EEG, filters, amplifiers, IEEE 802.11.**

I. Introduction

This project is designed with the goal to make the game of football, and other contact sports, safer for the participating athletes. The motivation of this project primarily stems from the NFL Players Association (NFLPA) suing the National Football League over players who have suffered concussions and thus debilitation mental issues later in life. The BIO-Helmet is designed to track and accurately measure the amount of the g-force that is received to a player's helmet during a typical football tackle or hit. An array of accelerometer sensors placed throughout a regulation size NFL helmet will be used to track the amount of g-force the player experiences as well as the direction of the applied force. The BIO-Helmet is also designed to use an EEG sensor array to measure the brain waves of the player. Both accelerometer and EEG sensor data is processed by a TI Tiva C microcontroller. This microcontroller poles the sensors for data and communicates this data over Wi-Fi to a local server. The server then applies additional processing the incoming data and enters it into a database. A medical professional can view the sensor data in a customized MATLAB environment for analysis. This data can then be used by a neurologist, either during the course of a football game or for additional diagnosis after a game, to determine if the player is showing any biological signs of a concussion. The availability of both the accelerometer and neurological data should allow the heavy g-force hit to be related to the brain data and a more rapid diagnosis and treatment recommendation be provided to the player.

In order to make this project a reality we will need massive amounts of research into not only the realistic applications of this project but also the hardware possibilities. There are many parts that we may choose from and there are pros and cons for each and every single one. There are also design aspects that we must choose over each other in order to maximize reliability and safety for the players.

Research from many other papers and similar studies is incorporated into this project. Most notably, a similar study performed by the National Football League in 2012 is used as a basis for the project inspiration and implementation goals. This study focused on the accelerometer data alone and without a real time tracking or accurate historical approach. This project seeks to expand this study by also measuring brain waves and relating these waves to the accelerometer data. Various other research into the technical details and implementation of this project was also conducted. Several impacting standards, from multiple bodies, were researched and adhered to, or used components which include adherence to relevant standards, as part of this project. Various IEEE and ISO standards are referenced in the context of this project both for the electrical and power system designs as well as the communications aspect of this project.

II. Hardware Design Details

The following subsections describe the hardware design details of the BIO-Helmet and are intended to be a detailed description of each hardware component, design parameters associated with the component, and how the components fit into the overall design of the BIO-Helmet. A high level hardware block diagram is included below in Fig. 1. This block diagram includes the system layout for the components designed in the following subsections.

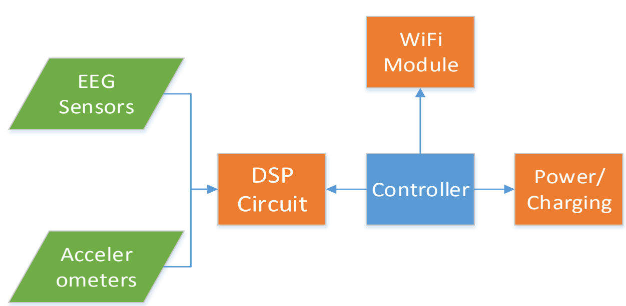


Fig. 1. A high level block diagram describing the hardware system layout of the BIO-Helmet.

A. EEG Sensor Array

The EEG sensor array contains several stages of amplification and filtering to provide quality brain wave data with a high reduction in noise. Several of the filtering and amplification stages mentioned in Fig. 2 are discussed in this section.

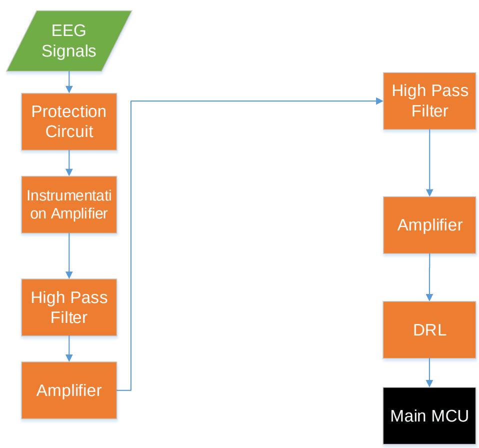


Fig. 2. A block diagram representing the final EEG sensor array block diagram.

The first part of the design to discuss is the protection circuit. This circuit will serve as a safety measure to protect the rest of the hardware design from electrostatic discharge and it should prevent failed circuitry [1]. This will be composed of capacitors, resistors and transistors. The schematic of this circuit is included below within Fig. 3.

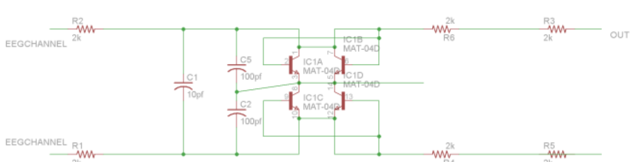


Fig. 3. Circuit schematic of the BIO-Helmet EEG Protection Circuit.

The amplification coming from the electrode signal will begin by going through an instrumentation amplifier. The main reason behind using this type of amplifier is because it lowers impedance of the signal, making it less sensitive to noise [1]. This type of amplifier provides also a high CMRR (common mode rejection ratio), which allows the output value to be near perfect. The BIO-Helmet project uses the INA114 amplifier from Texas Instruments. This will provide a gain of about 16 times the initial signal size. The circuit schematic is included in Fig. 4 below.

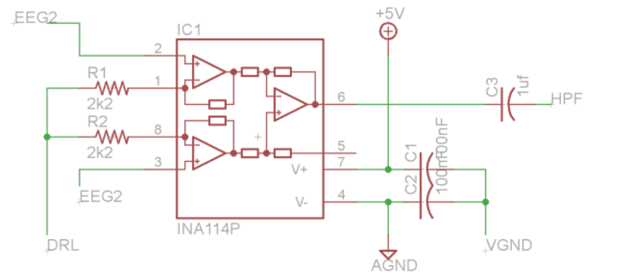


Fig. 4. Circuit schematic describing the instrumentation amplifier.

The gain for the amplifier is measured by (1).

$$G = 5 + \frac{50k\Omega}{R_G} \tag{1}$$

Where R_G will vary to produce the desired gain. The amplifier would need an approximate resistor value of 2.381Ω. The values of the resistors have to be as close as possible; preferably with a margin of error of 1% due to the precision required by this system.

The last major portion of the EEG hardware design consists of a series of filters to clean up the brain wave signals and remove the body's nature hum. This filtering consists of two high pass filters, each with a cutoff frequency of about 0.16 Hz, and a third order low pass filter which is used to amplify the signal with a gain of sixteen. This low pass filter contains the final stage of amplification. Lastly, a notch filter is implemented which helps to remove the human body's nature humming between 50 and 60 Hz. The circuit schematic for the notch filter is included below in Fig. 5.

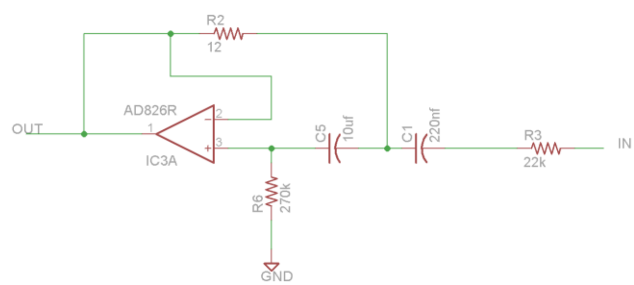


Fig. 5. Circuit schematic of the BIO-Helmet notch filter.

B. Accelerometer Sensor

This section covers the accelerometer subsystem which will be used in the measurement of impacts to the helmet. The BIO-Helmet uses an ADXL377 accelerometer. The decision to use a single accelerometer is based on several factors. Most notably, the GPIO limit on the microprocessor and the accuracy of a completely integrated device. [2] has confirmed that using more than one sensor could potentially skew the accuracy of the data and it is typically better to poll a single accelerometer.

As for the data output, the microcontroller polls data directly from the sensor across three axes. The data is then used to determine the force and direction of the impact on the helmet. From this data, it is then possible to extrapolate the area of impact, which is an important factor in determining the possibility of a concussion.

The mounting of the accelerometer is an important factor in determining the location of impact on the helmet as well as calculating the linear peak acceleration. The accelerator is mounted on its own PCB and wired into the main PCB separately to achieve the mounting location shown in Fig. 6.

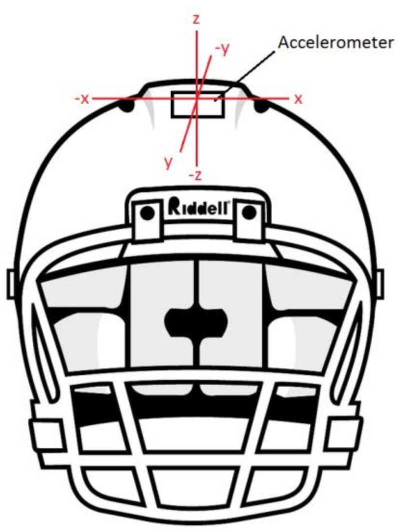


Fig. 6. Figure showing the mounting location of the accelerometer within the BIO-Helmet.

Inherently, there will be some error in determining exact impact force of the brain hitting the skull due to the accelerometer being mounted on the helmet and not directly on the skull. Thanks to the research conducted by [2], it is maintained that any impact to the skull over ten g's in force has the possibility to cause a concussion. This mounting location allows for easy determination of this threshold and report the relevant data back to the user.

The ADXL377 3-Axis High g Analog MEMS Accelerometer, developed by Analog Devices, is the accelerometer used in the BIO-Helmet. It is capable of measurements up to ±200 g's which gives the project plenty of overhead to accurately measure impact force of helmet to helmet contact. The sensor can detect forces on all three axes, both in the positive and negative directions. It is also low powered and only consumes 300 micro amps at 3.3V. A functional block diagram of the ADXL377 is included below in Fig. 7.

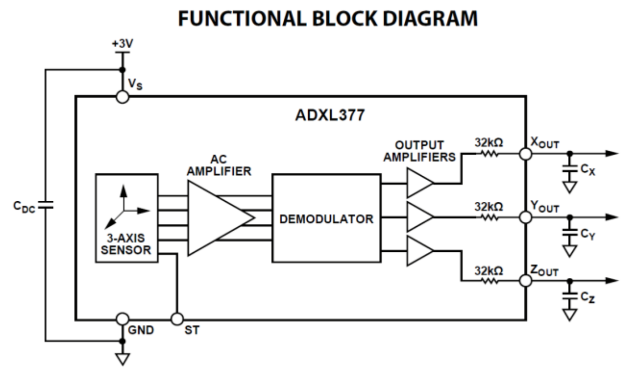


Fig. 7. Functional Block Diagram of the Analog Devices ADXL377 accelerometer.

For the BIO-Helmet, the main pins of interest are the Xout, Yout, and Zout. These pins will output a certain voltage based on the force of an impact to the helmet which can then be used to create an impact force vector. They will each be connected to one of the analog to digital converter inputs on the MCU.

For each axis, the output at 0g is equal to about ½ full-scale. With Vs set to 3.3 V this would give a 0g output voltage of 1.65 V. The ADXL377 is designed to change the output voltage at each axis by ±6.5 mV for every g sensed in the positive or negative direction. With a range of -200 g to +200 g the voltage output range goes from 0.35 V for -200 g to 2.95 V for +200 g. There can be inaccuracies based on temperature and the manufacturing process of the device, as seen in Fig. 8 below.

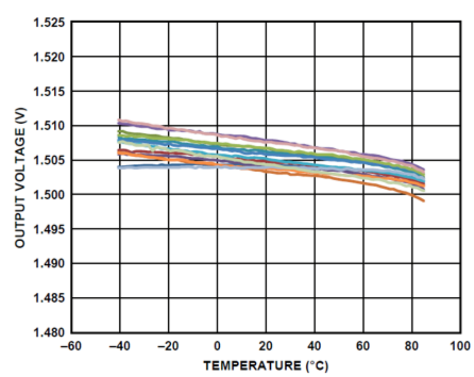


Fig. 8. Graph describing the output voltage variations based on the ambient temperature surrounding the ADXL377.

C. Tiva C Microcontroller: TM4C123GH6PM

The Tiva C was selected as the MCU for this project because of the fact that it was designed for remote monitoring and motion control. The basic needs of this project are to have a microcontroller that can monitor and transmit data in real time from the EEG sensors and accelerometers. The motion control design goals of the TM4C123GH6PM will be especially useful in processing the accelerometer sensor data to calculate impact. Fig. 9 below shows a block diagram and described the features of the Tiva C microcontroller. These features are described in additional detail within Table I.

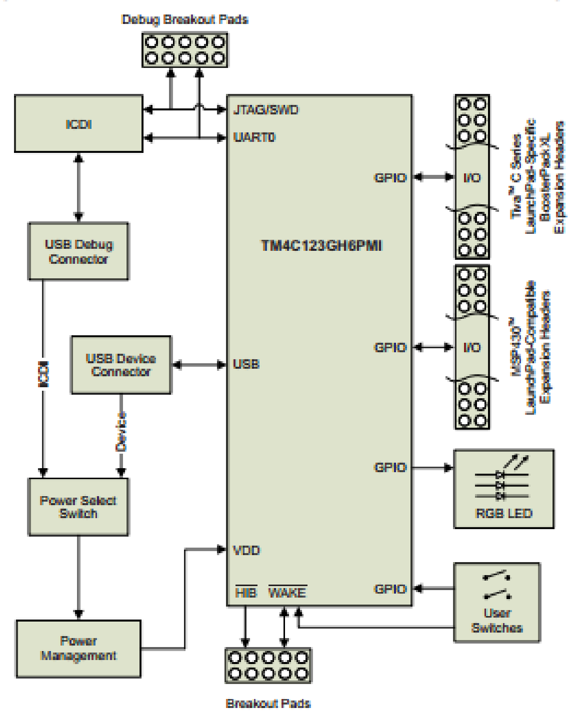


Fig. 9. Block diagram including feature description of the TM4C123GH6PM microcontroller.

A powerful chip that can collect and transmit huge amounts of data was required for this project. The Tiva C is a 32-bit ARM Cortex processor with an on chip memory featuring 256 KB of flash and up to 40 MHz performance benchmark. It has an ARM prime cell 32-channel controller that will allow for very efficient use of the bus bandwidth and the processor. Also, the analog support for this microcontroller is extensive. It features two 12-bit analog to digital converters which will be very useful when reading the analog output from the accelerometers and EEG sensor inputs. The features of the Tiva C are outlined in Table I.

TABLE I
SUMMARY OF TM4C123GH6PM FEATURES

Pin and Package	64LQFP
CPU	ARM Cortex-M4
Flash	256 KB
SRAM	32 KB
Max Speed	80 MHz
Motion PWM Outputs	16
QEI	2
GPIOs	43
Operating Temperature Range	-40 degrees C to 105 degrees C
OTG	Yes
SSI/SPI	4
I2C	4
UART	8
ADC Channels	12
ADC Resolution	12 Bits
CAN MAC	2
SysTick	Yes

D. CC3100 Wi-Fi Module

The CC3100 is a Wi-Fi module designed for low-power wireless transmissions with high levels of data transfers. It includes 802.11 b/g/n radio, baseband, and medium access control capabilities. The major modules within this chip are depicted below in Fig. 10.

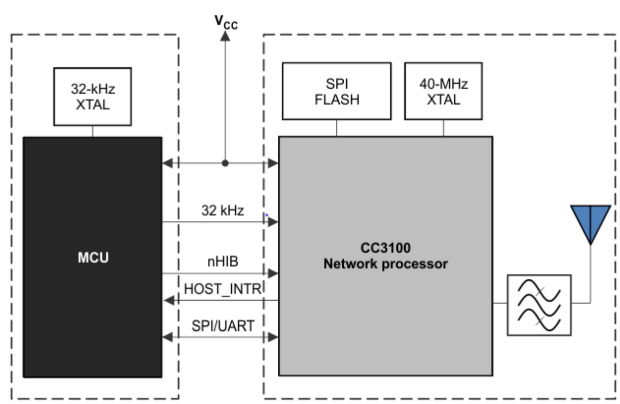


Fig. 10. Block diagram describing the CC3100 Wi-Fi module.

Power consumption is a huge aspect of this project as it is not known how long the device has to be in use for before it can be recharged. Wi-Fi devices typically have a much higher power consumption than other wireless technologies such as Bluetooth. The CC3100 satisfies the range requirements of this project while still using minimal power. The various power consumption metrics of the CC3100 are included in Table II below.

TABLE II
SUMMARY OF CC3100 POWER CONSUMPTION

Wide-Voltage Mode	2.1 to 3.6V
Pre-regulated Mode	1.85 V
Hibernate with RTC	4 nA
Low-Power Deep Sleep	115 nA
RX Traffic (MCU Active)	53mA
TX Traffic (MCU Active)	223mA
Idle Connected	690 nA

E. Power Supply

Lithium ion batteries are implemented in the BIO-Helmet prototype. This decision is due to the fact that the battery can be manipulated to output enough voltage while still staying within the project's budgetary constraints. Lithium ion batteries can be flat and fit within a helmet. Lithium ion batteries are also rechargeable. This allows these batteries to be used throughout testing without the need to continuously replace the batteries. This battery is placed near at the bottom back of the helmets to allow easier access to the charging ports. Placing the battery in this area also for the least chance of direct impact, thus reducing the risk of athletes getting hurt due to the placement of the electronic components.

A PKCELL ICR18650 6600mAh 3.7V 1S3P lithium-ion battery pack is used to power the project. This pack is made up of three 2200mAh cells connected in parallel and spot welded to protection circuitry which prevents over-voltage, under-voltage, and over-current protection. This protection circuitry will prevent the battery from over-heating and exploding which is of the utmost importance in keeping the helmet wearer safe.

The battery pack includes a JST two pin connector which connects to the board and charging circuit through a JST jack. This makes battery replacement simple and adds the ability to charge the battery separately or have a backup in place if need be. The battery pack also has a fairly small form factor that should fit fairly well within a helmet. A size comparison can be seen in Fig. 11 below.

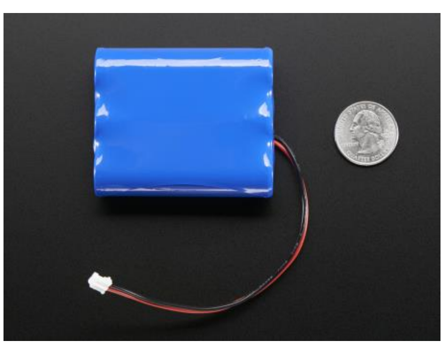


Fig. 11. Size comparison of PKCELL ICR18650 battery.

Considering USB is widely accepted and used form factor, with a multitude of cheap and easily obtainable chargers, this was the specification used for the BIO-Helmet. A micro USB port will be used to connect the charging circuit to a standard USB wall charger and micro USB cable. To ensure that the Lithium Ion battery pack is being properly charged, a specially designed IC manufactured for this purpose will be used. The MCP73833/4 by Microchip fits this need. Fig. 12 and Table III describe the pin layout and function of the MCP73833/4.

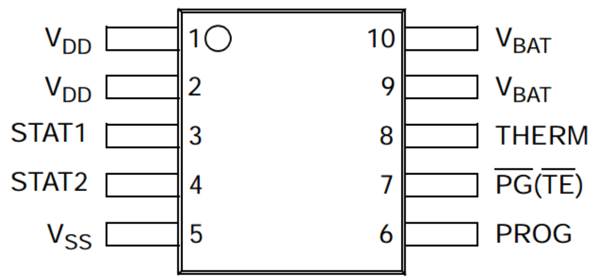


Fig. 12. Pin and package layout of the MCP73833/4.

TABLE III
SUMMARY OF MCP738/4 PIN FUNCTIONS

Pin #	Pin Name	Description	Input / Output
1	V_{DD}	Battery Management Supply	Input
2	V_{DD}	Battery Management Supply	Input
3	STAT1	Charge Status	Output
4	STAT2	Charge Status	Output
5	V_{SS}	Battery Management 0V reference	Input
6	PROG	Current Regulation Set	Input
7	PG	Power Good	Output
8	THERM	Thermistor	Input
9	V_{BAT}	Battery Charge control	Output
10	V_{BAT}	Battery charge control	Output

The MCP73833/4 is designed specifically for use with USB charging applications and can handle a max charge current of 1 amp. It also has built in status updating so that LEDs connected show the status of the charge to the user. Pin 3 lights an LED when the battery is in charging mode. Pin 4 lights an LED when the charging is complete. Pin 7 lights an LED to show that there is power plugged in via the USB port. Respectively, the color of the LEDs are orange, green, and red which should easily indicate to the user the status of the battery and charge.

The layout described in Fig. 13 is implemented on the main board. The JST connector is mounted directly to the board so that the battery can be mounted fairly close to the rest of the electronics to prevent unneeded resistance from long wires. This board was built with the idea that the helmet would not be in use while it is charging. The location of the board and the battery can cause excess heat if the battery were to be charging while the helmet is in operation.

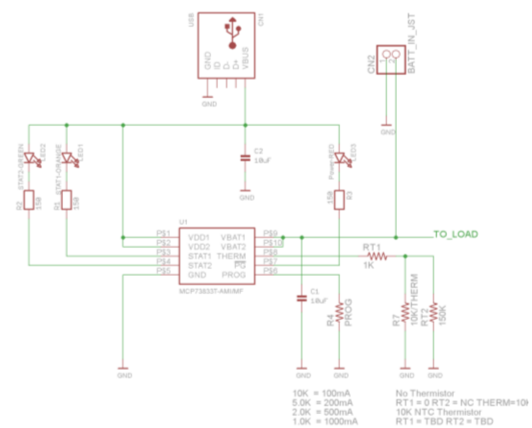


Fig. 13. BIO-Helmet charging circuit schematic.

The TO_LOAD line shown in Fig. 13 will make its way to the microprocessor through a voltage regulator to ensure a constant voltage as the battery drains. The EEG sensors and Accelerometer also make use of the power output of the battery on the load line.

III. Software Design Details

The following subsections describe the software design details of the BIO-Helmet. The software for this project falls into two major categories, embedded software, which runs directly on the ARM Cortex MCU, and server software, which runs on a laptop connected to the BIO-Helmet over Wi-Fi.

A. Embedded Software

This section covers the detailed design aspects of the software running on the Tiva C ARM Cortex microcontroller present within the BIO-Helmet. This piece of software is responsible for polling the accelerometer and EEG sensors, processing the received raw input from the sensors, and outputting this data to the Wi-Fi part for sending to the local server. This software also covers the basic operation of the Tiva C and the Wi-Fi component initializations. This program will consist of a single program, generated from an Energia sketch, running on the ARM Cortex CPU.

The initialization phase of the embedded program will setup various aspects of the ARM Cortex microprocessor, input and output pins, UART, and wireless setup. This phase of the embedded program will always be run first after the BIO-Helmet is powered on. An overall flow and state diagram is included below in Fig. 14**Error! Reference source not found.** that describes the order in which these initializations are performed.

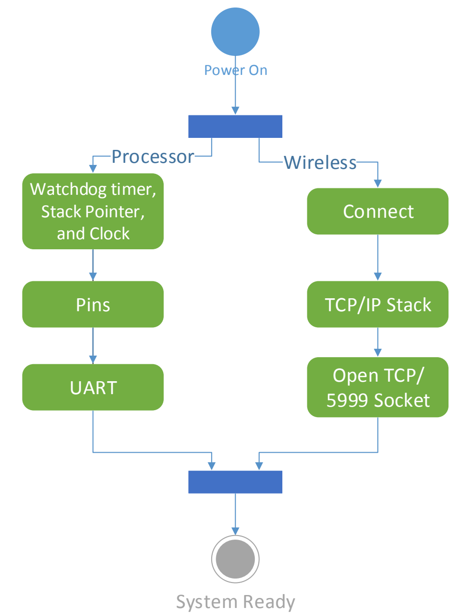


Fig. 14. BIO-Helmet Embedded Software Initialization phase.

The input pins on the Tiva C microcontroller are automatically set to inputs so there are no additional configuration steps needed. The wireless chip will first be initialized to build a wireless direct connection from the CC3100 to the local server over 802.11 wireless. An IP address will be previously statically assigned to the BIO-Helmet and to the local server. The wireless module will then open a TCP socket between the BIO-Helmet and the local server. This TCP socket will be used to transfer data between the BIO-Helmet and the local server. This TCP socket will be opened over port 5999.

Each of the pins connected to a sensor array, both accelerometer and EEG, will be sampled and stored in floating point variables for later processing. Each accelerometer sensor reading includes the velocity in each direction (x, y, and z), thus requiring the embedded program to poll three different pins which are connected to each of the three outputs for the accelerometer. The EEG sensor array will have two pin input channels from several different electrodes placed around the inner cap of the BIO-Helmet. Both the accelerometer and EEG input pins use the analog to digital converter and read in a voltage on the pin.

The next phase of the embedded program will perform normalization tasks on the EEG data, to remove any additional noise, and adjust the accelerometer inputs from volts to milli-g's. Also performed at this phase is the high impact flag check after the accelerometer inputs have been properly mapped to g-force. If the read value exceeds the threshold, then a Boolean value is set in the embedded program which will be referenced in the next phase of the embedded program.

At this stage of the data processing program, there are several pieces of data ready for transfer to the Wi-Fi module for packing and sending. These include: the high impact Boolean flag (true or false) the x, y, and z meters per second averaged values of the accelerometer data inputs, and the brain wave data. These values will be concatenated into a single string, along with the BIO-Helmet ID.

The CC3100 wireless module will make use of the TCP socket opened earlier. This TCP socket ensures data reliability when sent between the BIO-Helmet and the local server. The CC3100 will receive the input as a string from the main MCU. This input string will be packaged into a TCP packet and written to the TCP 5999 socket where the socket API included on the CC3100 will package the string into an IP packet and send it over the wireless direct connection to the local server.

B. Local Server Software

This section covers the detailed design aspects of the backend software used for the BIO-Helmet server. This set of software collects the wireless data received from the BIO-Helmet, processes and prepare that data; and insert this into a database for historical records of all sensor data from the BIO-Helmet. This software is also responsible for preparing a set of files that can be used in a customized MALAB environment to view the sensor data in graphical form. The logical flow of data can be observed in Fig. 15.

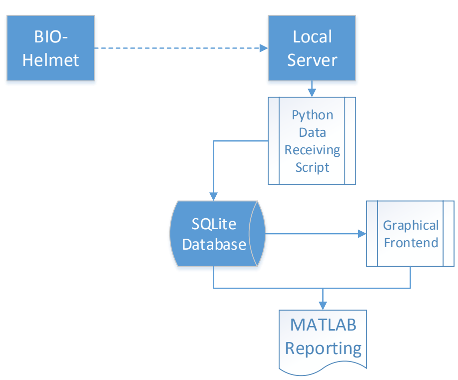


Fig. 15. BIO-Helmet Server Software data flow diagram.

Data is received by the local server from the BIO-Helmet over a Wi-Fi direct connection. The Python data receiving script, accepts and prepares this data and then enters it into a SQLite database. The user is then able to interact with a graphical frontend to display the raw sensor data directly from the database or launch a customized MATLAB environment in which the sensor data can be viewed in graphical form. The graphical user frontend will also alert the user if a high impact event occurs.

The Python program first opens the necessary TCP 5999 port on the localhost. The Python script then listens continually on this socket for a connection from the BIO-Helmet. Once, a connection is received from the BIO-Helmet, the Python data receiving script enters an infinite to loop to listen from string commands sent from the Tiva C microprocessor on the BIO-Helmet. These commands are processed accordingly, receive commands for the accelerometer data, high impact warning message, and EEG sensor data. An activity diagram for the data receiving portion of the Python data receiving script is included below in Fig. 16.

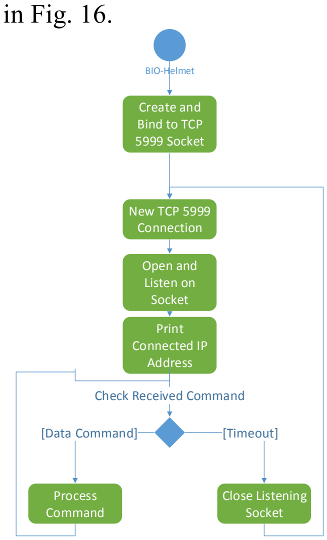


Fig. 16. BIO-Helmet Python receiving script activity diagram.

The BIO-Helmet database is implemented with SQLite and as data is read by the Python data receiving script, it is entered into this SQL database. This database table contains the X, Y, and Z directions of the accelerometer input as well as an overall g-force vector for the helmet. The database contains columns for five brain wave readings, however, for the purposes of this project, only alpha and beta waves are observed. The database also incorporates an integer ID field, for future expansion of multiple BIO-Helmets. This SQLite database can be directly queried for historical data reporting and is used by the graphical user frontend as well as the customized MATLAB environment.

C. Reporting Software

This collection of software includes the user interface and data reporting functionalities for the BIO-Helmet project. The graphical user frontend for the BIO-Helmet reporting software serves as the direct point of interaction between the user monitoring the sensor data and the BIO-Helmet sensor data. Python's Tkinter is used to implement the necessary GUI features of this design. This GUI implements a series of buttons which lead the user into various areas of the reporting software. The user is able to view the raw sensor data in tabular format, directly from the SQLite database. This graphical frontend also alerts the monitoring user if a high impact event has occurred on the athlete wearing the BIO-Helmet.

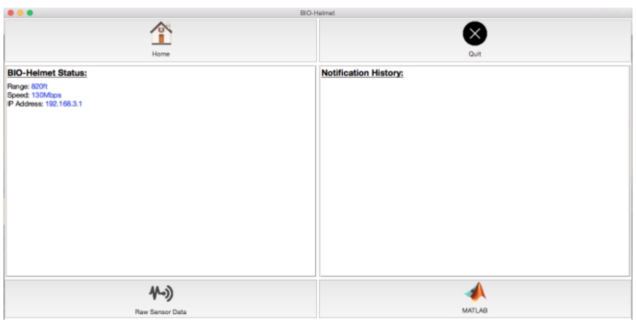


Fig. 17. BIO-Helmet graphical user interface.

MATLAB EEGLAB is an interactive toolbox for utilizing MATLAB with EEG sensors in order to read and compute the data that is coming from the sensors. It is a very powerful toolbox that allows the user to customize and incorporate what they need and allows visual aids in order for the user to easily interpret the data. It has a graphical user interface which will allow the user to easily interpret the data in both independent components analysis and time/frequency analysis.

IV. Conclusion

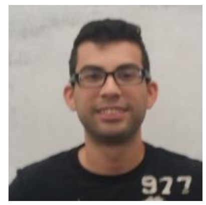
The goal of this project was to develop a sports safety device that can be used to help lessen the dangerous effects of concussions on athletes in contact sports. This project satisfies this goal, specifically with the high impact warning and historical data reporting of force data. Another goal of this project is to conduct additional research into possible correlations between concussions symptoms and observed brain waves. This goal was satisfied by creating a prototype that can present data to a neurological research teach for later analysis and research. Each team member, throughout the completion of this project, was able to use each of their areas of expertise and learn about new interests. This project was concluded with the presentation of a functioning hardware and software BIO-Helmet prototype.

V. The Engineering Team

Frank Alexin – EE

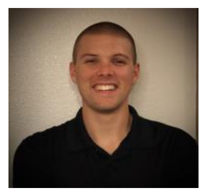
Frank Alexin is a graduating Electrical Engineering student. He hopes to pursue a career in the Orlando area in micro-electronics after graduating. His strengths are in circuit design and programming in regard to embedded systems.

Nicholas Dijkhoffz– EE



Nicholas Dijkhoffz is a graduating Electrical Engineering student. Nicholas has accepted a job offer with Honda Manufacturing of Alabama and will relocate after summer. In the future he would like to work with technology that improves quality of life for people.

Adam Hollifield – CPE



Adam is a graduating Computer Engineering student. His areas of interest include enterprise networking and cyber security. He has accepted a full time position as a Network Engineer at Tech Data Corporation.

Mark Le – EE

Mark Le is a graduating Electrical Engineer. He plans to work as an engineer in the Air Force working on sensory applications on aircrafts and vehicles. He hopes that one day his findings will lead to safer conditions in civilian vehicles.

Acknowledgement

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References

[1] Griffiths, D., Nelo, Peters, J., Robinson, A., Spaar, J., & Vilnai, Y. (2003). The ModularEEG Design. Retrieved April 27, 2015, from http://openeeg.sourceforge.net/doc/modeeg/modeeg_design.html

[2] Cobb, B. (2013). Measuring Head Impact Exposure and Mild Traumatic Brain Injury in Humans. Brain Injuries and Biomechanics. Retrieved April 8, 2015, from https://vtechworks.lib.vt.edu/bitstream/handle/10919/23815/Cobb.pdf?sequence=1