Yonas Yosef Gebreyesus

Hardware Design for Head Impact Assessment in Contact Sports

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Abstract

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Head Impact Injuries have been the most common causes of Concussion in heavy contact sports. Concussion affects the brain, resulting impairment of neurological functions, and is usually underreported or underestimated by standard neuro imaging tools. Therefore, in addition to the clinical methods it has been essential to characterize the kinematics involved in head impact injuries. The objective of this research was to design a hardware that could be mounted inside a helmet, measure the severity level of head impact injuries that could cause concussion and display measurements in real-time to team personnel monitoring the impact levels.

Methods of accelerometry and telemetry were applied in which linear head acceleration (g-force) and rotational head accelerations data would be measured and transferred via wireless communication method. After setting the specifications the design process passed through three phases. In the component selection phase various wireless communication protocols, sensors, system processors, interfaces, power and memory requirements were compared, analyzed and selected. In the second phase, a prototype using breakout boards was developed and tested for operation. After successful implementation of the second phase, the PCB design with IC (Integrated Circuit) components based on ARM Cortex M4 32-bit processor proceeded. PCB schematics and layout of the final prototype design with IC chips was completed and a sample was printed at a milling machine in the school premise.

The designed PCB was small enough to fit inside helmets (with a size of 42mmX31.5mm) and it had ultra-low power consumption as set in the objective. It was able to send real time data of linear and rotational head acceleration via a low energy Bluetooth communication protocol. The hardware testing and software integration of the final device shall proceed at the latter stage of the prototype development.

Keywords	Hardware Design, TBI, Concussion, Head Impact, Accelerometry, BLE, SoC, IoT

Contents

List of Abbreviations

BLE	Low Energy Bluetooth (Bluetooth 5.0)
BOM	Bill Of Materials
CMOS	Complementary Metal Oxide Semiconductor
CS	Chip Select
ED	Emergency Department
GND	Ground
HITS	Head Impact Telemetry System
I^2C	Inter-Integrated Circuit
IC	Integrated Circuit
IOT	Internet of Things
ISM	Industrial, Scientific and Medical license free radio band
LDO	Low Drop Out
LSB	Least Significant Bit
MISO	Master In Slave Out
MOSI	Master Out Slave In
NC	Not Connected
P2P	Pear to Pear
PCB	Printed Circuit Board
PGH	Player Game Hours
QFN	Quad Flat No-leads packages
RF	Radio Frequency
RPM	Revolution per Minute
SCAT	Standardized Concussion Assessment Tool
SCK	Serial Clock signal in SPI
SCL	Serial Clock signal in I^2C
SDA	Serial Data signal in I^2C
SMD	Surface Mount Device
SoC	system on Chip
SPI	Serial Peripheral Interface
SRR-TBIs	Sport and Recreation Related TBIs
SS	Slave Select
TBI	Traumatic Brain Injury
UART	Universal Asynchronous Receiver/Transmitter
UEVB	Universal Evaluation Board
WLCSP	Wafer Level Chip Scale Package

1 Introduction

Concussion is one of the most common injuries that occurs among players in high contact sports such as American football, ice hockey, boxing, etc. It is usually considered as a type of Traumatic Brain Injury (TBI) in which the process of the brain is affected by biomechanical forces causing damage to neurological functions [1]. Such damages are not usually discoverable by standard neuroimaging methods. Therefore, various studies have been required to characterize the kinematics related to head impact injuries.

Head impact assessment is one of the methods several researches have focused on to assist the process of predicting potential concussion or possibility of any other type of brain damage resulting from heavy contact events. Identifying the biomechanics and kinematics behind head impact injuries can also serve as a support tool for clinical personnel by providing real-timed data while game time or during practice [2]. Among the assessment methods Head Impact Telemetry System (HITS) is the most researched and applied method that applies the principle of accelerometry [2].

Most of the head impact assessment studies were performed in American football and fewer in ice hockey sports. As Ice Hockey is the most popular sport in Finland, it was necessary to make a similar system that ice hockey players can also wear inside their helmet that would be helpful in measuring the head impact accelerometry.

The objective of this thesis work is to develop a prototype which applies the method of accelerometry and measure the head impact kinematics that could cause concussion. The linear acceleration (gforce) and rotational acceleration are the main variables of measurement. The software part of the prototype is to be developed by another colleague. This thesis work therefore focuses on the design of the hardware design part.

The design of the prototype has been done in three phases. The first phase was selection of the components, interfaces and communication protocols. The second phase follows with designing the prototype with breakout boards. The final phase focuses on designing the hardware with IC (Integrated Circuit) components. All the phases will be discussed in detail in this thesis.

2 Theoretical Framework

2.1 Traumatic Brain Injury

Traumatic brain injury, also known as TBI, is a type of an injury caused by a violent blow, bump or jolt to the head that affects the functioning of the brain [3]. TBI can also be caused by the penetration of a brain tissue by a foreign object or from broken pieces of an injured skull [2]. The consequence of TBI could be adverse resulting in death, short term injury or lifetime disability, impairment of memory, impairment of vision and/or hearing, emotional malfunctioning, effects on social interactions and several other effects [3].

TBI has been one of the oldest and most common causes of death or disability all over the world. During prehistoric time TBI could be associated with warfare, hunting or dealing with harsh environments. Despite civilization developing, TBI remained a threat to the humankind, contributing to a number of deaths across all ranges of ages [4]. In the United States alone, TBIs contribute to about 30% of all injury deaths; 153 people die per day due to an injury related to TBI or live with a lifetime disability caused by TBI [3]. In China, in 2013, the mortality of TBI was approximately 13 per 100,000 population [5]. In Europe, a meta-analysis on the epidemiology of TBI found that there is an overall incidence of 262 TBI related cases derived per a 100,000 population [6].

TBI mortality depends on the types of activities associated with it and the exposure to it is different among diverse groups of demographics, such as age, gender, activities/sports type, place of residence etc. For instance, the mortality index is higher among urban residents, males, teenagers and elderly people; vehicle crashes and falls take the higher share of TBI related mortality [5].

Sport and Recreation Related TBIs (SRR-TBIs) are also becoming a growing public and socio-economic concern across the population of all ages[5][7]. The number and rate of visits to Emergency Departments (ED) has been increasing continuously over the years. In the United states alone, between 2001 and 2012, there were more than 3 million ED visits related to SRR_TBIs. Most of which occurred in football, cycling, basketball and horse riding among men and between age groups of 0 to 19 years [7].

2.2 Concussion

The severity of a TBI varies from “mild” level TBI (involving temporary change in mental status) to “severe” level TBI (involving bruising, torn brain tissue, bleeding and severe brain damage). And from a brief change in consciousness to a long period of unconsciousness or memory loss. Mild TBI is the most common type of TBI and it is commonly known as Concussion [2,3]. Concussion can be defined as a subsection of TBI that is related to a complex process of affecting the functioning of the brain. And it is induced by biomechanical forces resulting in impairment of neurological functions [1].

Mild traumatic brain injury or concussion may affect brain cells temporarily. The degree of damage can depend on several factors, including the nature of the injury and the force of impact. The most common events resulting in TBIs are, falls, vehicle related collisions, Violence, explosive blasts, combat injuries and sport injuries. Sport related TBIs can occur in all types of sports involving contact and speed such as soccer, American football, boxing, baseball, skate boarding, hockey and in any other types of activities involving high impact or heavy contact.

Usually, the structural injury of concussion might not be readable by using standard neuro-imaging procedures alone. There are various standard clinical tools medical professionals apply in order to assess the mental status after an injury-inducing impact occurred. Even though the assessment of reported head impact injuries indicates a low level of severity, the accumulated effect of repeated head impact over a long a period of time might result in trauma [1].

Reports of concussion related injuries are quite common in heavy contact sports. In Australia 90% TBIs can be classified under mild TBI or concussion, from which 21% of the injuries are related to sport activities [1]. In US, approximately 4 million sport related concussions are reported ever year [1]. A 2012 study in US high schools also found that concussion account for 13.2% of sport related injuries among which up to 67% occurred during competition and 33% concussions during practice [8].

2.3 Head Impact Measurement

Despite the high prevalence or incidence rate of concussion related injuries in high contact sports, they are usually under reported. For instance, a review study on concussions in ice hockey game found out that for an estimate of 6.7 to 8.3 concussion occurrences, only 0.25 to 0.6 concussions per 1000 PGH (player game hours) are reported [9]. Otherwise, if reported, they are either underestimated or there is a delay in starting the diagnosis [1].

Therefore, in addition to the clinical tools available for the thorough diagnosis of concussions, such as SCAT (Standardized Concussion Assessment Tool), it has been found essential to study the biomechanics or kinematics of head impacts that could result in head injury or concussion [1]. In relation to this, several head impact monitoring studies have been done; American football is the most researched sport. Even though the assessments of reported head impacts indicate a low level of severity, the accumulated effect of repeated head impacts over a long period of time might result in trauma [1].

The instrumentation of the movement of the head kinematics has been found the crucial indicator of interest in the assessment of head impact exposure. The instrumentation data can also assist medical personnel in real time assessment of potential head impact injuries during game time or in practice. In addition, in regard to efforts of minimizing or preventing head injuries, instrumentation of head impact assessment will also assist the efforts in improving head protection mechanisms [1].

From review of the literature it is understood that accelerometry is the most common method of Head Impact Monitoring despite differences in hardware and the location where in the body the hardware is attached. Head impact monitoring through accelerometry has been proven to be useful with regard to characterizing the kinematic load associated with concussive head impacts. Most of the instrumentations, in regard to head impact monitoring, can be categorized as helmet and non-helmet-based impact measurement systems. Among the accelerometry based systems, Head Impact Telemetry System (HITS) is the most popular method used by researchers [10].

Whether in HITS or other commercially available devices, the variables of interest specific to the kinematics of head impact injuries are linear acceleration (also known as gforce), rotational (angular) acceleration and impact location; and to some extent head impact density [10]. A meta analytic research based on HITs assessment tools found out that mean peak linear head acceleration associated with a concussive episode can reach up to 99 g and a mean rotational peak head acceleration of 5778 rad/s^2 [1]. Despite the fact that such threshold values are yet to be defined there is a consensus among researches that linear and angular acceleration are quite significant in predicting potential injuries resulting concussion [11].

Some studies have also looked into the relative significance of the two variables for causing damage to the brain. It is discovered that the effect of linear acceleration on helmeted head was significantly lower than non-helmeted head injury, but the damage due to angular acceleration was high in both helmeted and non-helmeted head impact injuries However, in non-helmeted case the amount of the damage due to linear acceleration increases significantly [12]. The combined effect of the linear and angular acceleration to the soft tissue inside the brain is then believed to be responsible for the transient pressure gradients and strain field responses, which could cause injury when they are above threshold values the tissue of the brain can resist/sustain [12].

2.4 Measurement Variables

As illustrated in the literature review above it is important to measure the kinematics related to the biomechanics of head impacts. The physical variables that would cause injury, skull pressure gradients or deformation, due to direct impacts are identified as linear acceleration (usually measured in terms of g-force) and Angular (Rotational) acceleration [12]. Various types of sensors were used to measure these variables. The analysis in regard to processing the sensor data was performed via software programs. This thesis work focused on identifying and designing the right circuit requirements to enable the sensors measure the variables of interest. The next paragraphs will discuss about the physics of linear and rotational accelerations in terms of bio-mechanical forces.

G-Force (Linear Acceleration)

G-force or linear acceleration is related to direct impact causing a pressure gradient inside the skull; and it is considered to account for at least 50% of potential head injuries [12].G-force can be defined as the force of gravity on a unit of mass or a force of acceleration. It is linear acceleration measured in terms of g. 1 g is the amount of gravitational acceleration at the surface of the Earth or known as the measure of the force of gravity which is 9.8 meter per second squared ($9.8 m/s^2$).

In other words, the g-force of an object is the amount of acceleration it experiences relative to gravity. A free-falling object has an acceleration of $9.8 m/s^2$ or 1 g. Any g-force greater than one for a free-falling object will tell the accelerations of an object due to external forces other than gravity. Humans can resist a high amount of g-forces if it is for split seconds. A slap on the face for milli or microsecond may cause up to 100 g but continued g force of above 10 g might cause permanent injury or death. The standard unit for g force is m/s^2. However, for convenience the unit g or G is used quite often.

It is a common mistake to consider g-force as a measure of force, rather it is a measure of acceleration. It is distinct from linear acceleration which is normally a vector quantity. G-force, however, is a scalar quantity and sometimes it is referred as vector acceleration. For example, a cube box on a floor experiences positive g-force at its bottom and negative g-force at its top. G-force is responsible for the mechanical stress on object, whether it is tension or compression, that the box will experience.

Human tolerance of the g-force depends on several factors, such as the magnitude of the g-force, the duration the g-force is experienced, the direction of the g-force (Vertical, Horizontal or a combination), the location of the body the g-force is applied (for example arms feel tensile while our feet feel positive g-force which is compression) and the posture of the body while the g-force is applied.

Accelerometer is the most common method to measure g-forces [13]. An accelerometer in its basic form consists of a spring and a mass. When a load is applied on the mass, the spring deforms and the change in dimensions are measured along one or more axes. For example, an object resting on a horizontal surface or moving with a constant speed will read a g-force of 0 g. However, if the object accelerates suddenly by 4.9 m/s^2 then the g-force will be 0.5 g. In vertical movement, a resting object or an object in a constant speed experiences minimum of 1 g due to gravity.

Three-dimensional accelerometers are quite common in head impact assessment studies. Therefore, the variable of interest in such cases is the resultant linear acceleration. The resultant linear acceleration or g-force is the vector sum magnitude of 3 linear accelerations of the head during the impact across the 3 axes.

Angular Acceleration

Angular acceleration is considered to be one of the causes for potential head impact injuries or cerebral concussion. Studies indicated that angular acceleration is responsible for the sheer strain and tensile strain resulting from the differential motion between skull and brain [12]. It is also claimed angular accelerations account for concussion causing injuries as much or more than linear accelerations (direct impacts) does. However, it is worth to be noted that both angular and linear accelerations are highly correlated.

Angular acceleration, also known as rotational acceleration, is a vector quantity and can be defined as the rate of change in angular velocity of a rotating object per unit time. It has both magnitude and directions. The magnitude is usually expressed in radian per second squared (rad/s^2) or in degree per second squared (deg/s^2). The direction of angular acceleration is perpendicular to the plane of rotation. If a person looks at a clock plane, a clockwise rotation produces an acceleration in the direction of an arrow away from you or the clock plane; anti-clockwise rotation produces an angular acceleration in the direction of an arrow from the clock plane towards you.

For this project we will be using gyroscopes which can measure angular velocities. In order to calculate the angular acceleration, the rate of change of angular velocity for a given time period will be used. The gyroscopes of choice for this project are tri-axial and are able to give three dimensional angular measurements, also known as Euler angles. Euler angles in combination to linear acceleration are quite useful in finding the head impact location. Resultant angular acceleration to the head is determined by the vector sum of the 3 angular accelerations of the three axes across the skull/head.

Impact Location

Impact location as a variable is not a cause for head injury as linear and angular acceleration are. However, it is an important variable for assessment of the impact. Impact location is found by proper integration and differentiation of linear and angular acceleration, velocity and position values. The most common locations where impacts occur are front, front oblique and sides of the head [14].

2.5 Devices

There are two types of devices which are mostly used for head impact measurement, and they are commonly categorized as helmeted devices and non-helmeted devices. They differ in terms of the degrees of freedom for accelerometers and the number and types of sensors they are consisted of.

Helmeted Devices

Impact measurement devices mounted on Helmets usually consist of HITS based systems, which consist of six single axis accelerometers. Others apply six degrees of freedom (DOF) devices which are tailored to various types of sports [15]. In order to take measurement from the device one of the 6 accelerometers should exceed the minimum threshold set by the user. For example, it is quite common to use 10 g as a minimum threshold, but it could go up to 14 g depending on the application. Consequently, impacts below 10 g will be filtered out [15]

The number of single axis accelerometers defines the type of helmet-based devices. In HITS linear acceleration data is collected from six single axis sensors located at different axes of the head. In six DOF based helmet devices 12 single axis accelerometers are placed in pairs at axes tangential to the skull.

An algorithm then converts the raw data into resultant rotational and translational acceleration data, which will be used as an input for injury predicting tools. The head impact kinematics data can then be correlated with clinical or other non-clinical prediction tools such as machine learning, brain finite element methods, logistic regression, etc. [12].

In HITS or six DOF based systems the linear acceleration data is recorded from the 6 single axis accelerometer sensors at a frequency of 1 kHz. Such systems are able to measure Maximum resultant linear acceleration, Resultant angular acceleration (regressed from Linear acceleration data), Head impact locations (bins, azimuth, elevation), Head Injury Criteria, Severity index and Severity profile. The measurement data is collected 8 ms before impact (10 g) and 32 ms after impact data (40 ms time trace).

Non-Helmeted Devices

Non-helmeted devices usually have a three-axis accelerometer and three-axis gyroscope which are either installed inside a mouth guard [14] or attached as a patch behind the ear [16]. The linear acceleration data is recorded at 1 kHz frequency. Meanwhile the angular acceleration data is recorded at 850 Hz frequency which is then interpolated to the time sequence of the linear acceleration[15].

The non-helmeted systems, embedded either in a patch or a mouth guard, are usually designed to give the following outputs: the maximum resultant linear acceleration and its direction, the maximum resultant angular (rotational) acceleration, head Impact location (azimuth, elevation) and head Impact Criteria. The measurement devices collect data every 10 ms before impact (10 g) and 90 ms after impact data (with 100 ms trace).

It could be understood from the list of outputs that non-helmeted devices give a wider pre-impact and postimpact data with a trace of 100 milliseconds, while the helmeted devices only give a 40 milliseconds data (8 ms preimpact and 32 ms post impact data). In non-helmeted devices angular accelerations are usually calculated from direct measurements of angular velocity using gyroscopes. However, in most helmet-based devices angular acceleration is obtained by methods of estimating the regression of linear acceleration data.

In this thesis work a helmet-based prototype was designed and developed, primarily intended for ice hockey helmets, which combined the benefits of both helmet-based and non-helmet-based devices of head impact assessment. The prototype is intended to comprise a 3-axis accelerometer and 3-axis gyroscope. The combination of both sensors will be used to calculate linear acceleration (g-force), Angular acceleration (Rotational acceleration), head impact location and other variables of interest such as severity level. The data collection trace time width will be 100ms, with 10ms before impact and 90ms after impact (this makes the device superior to the previous helmet-based devices which only have 40ms trace time). The other important feature included in this prototype was the latest Low Energy Bluetooth technology (BLE), a wireless communication module, with capability of real time data streaming.

3 Objective of the Study

Objective of this thesis work was to design and develop a helmet-based, small size, wearable and low power consuming hardware prototype which is capable of measuring head impact kinematics primarily in Ice Hockey and other high impact sports. The device was expected to send real time data via wireless communication for team personnel or medical team assessing the levels of head impact injuries on the side lines. The system was required to apply the latest technologies (sensors and processors) and measure the following kinematic variables/parameters known for causing potential head impact injuries that lead to concussion. The two major variables are known as

- Linear head acceleration (in m/s^2) or g-force (in g)
- Angular head acceleration (in rad/sec^2)

The objective of this hardware prototype development project has the following specifications.

- Low power consumption (several months without the need for replacement),
- It should apply a wireless communication protocol (long range, real time),
- It should measure linear head acceleration/impact data (Accelerometry),
- It should measure angular head acceleration data (Gyroscope),
- The size should be as small as possible to fit into helmet (Miniaturized)

4 Scope of the Study

The scope of the study was limited to the design and development of the hardware part of the prototype that is able to convert the head impact kinematics into an electrical signal using a system of accelerometry and telemetry. Further analysis of the signal, for user friendly graphical interface, would be performed by the software development team by converting the collected sensor data into a form that can be used by personnel for diagnosis. This thesis work therefore will not discuss the software part of the prototype and will solely focus on the hardware requirements that will be capable of providing the sensor data according to the prototype specified earlier.

5 Method of the Study

As indicated earlier, the idea of this thesis work was derived by combining the advantages of both non-helmeted and helmet-based systems into the new prototype to be designed. The specified helmet-based device would be made up of a number of units as illustrated below in figure 1. The hardware part consisted of sensors as input, system processor, storage and power units.

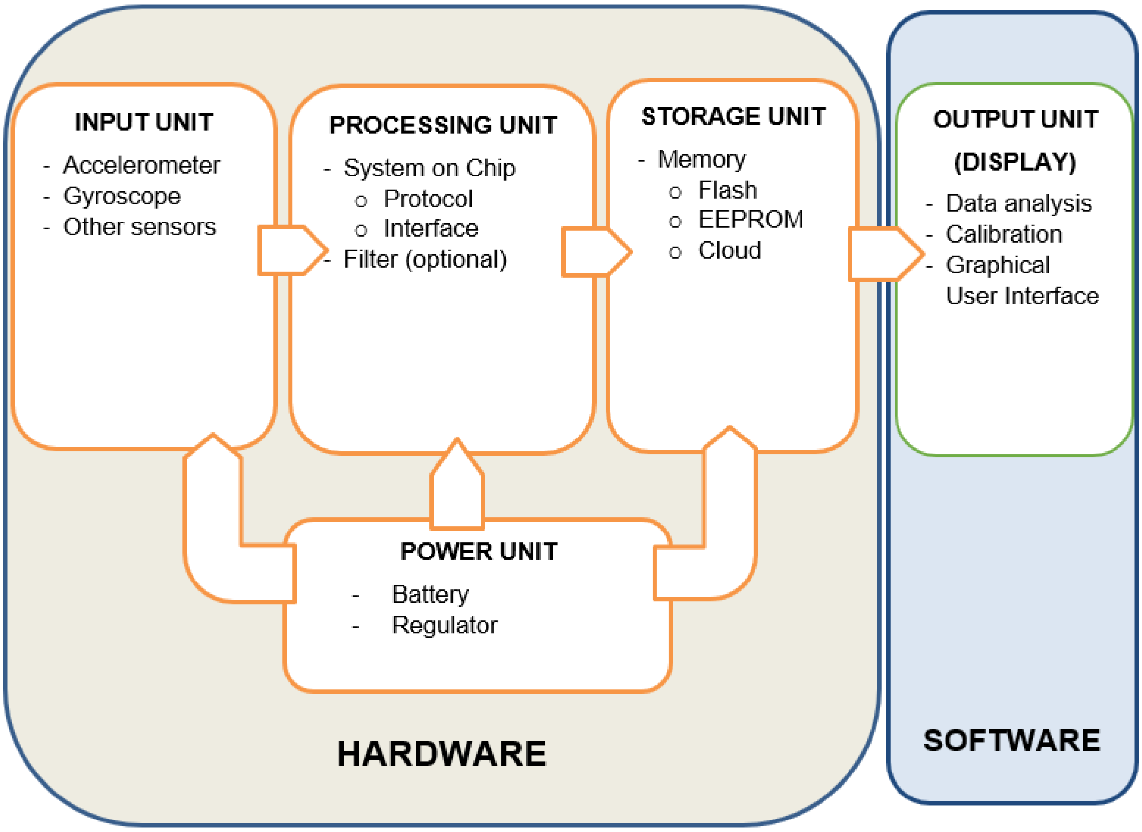

Figure 1. Prototype requirements of the Head Impact Assessment System

6 Hardware Design for Head Impact Assessment

After specifying the scope of the project and identifying the different hardware requirements, the next stage was to set out the product development phase. The product development phase was categorized into three stages, as shown in Figure 2, namely Component Selection phase, Design with breakout boards and Design with IC components.

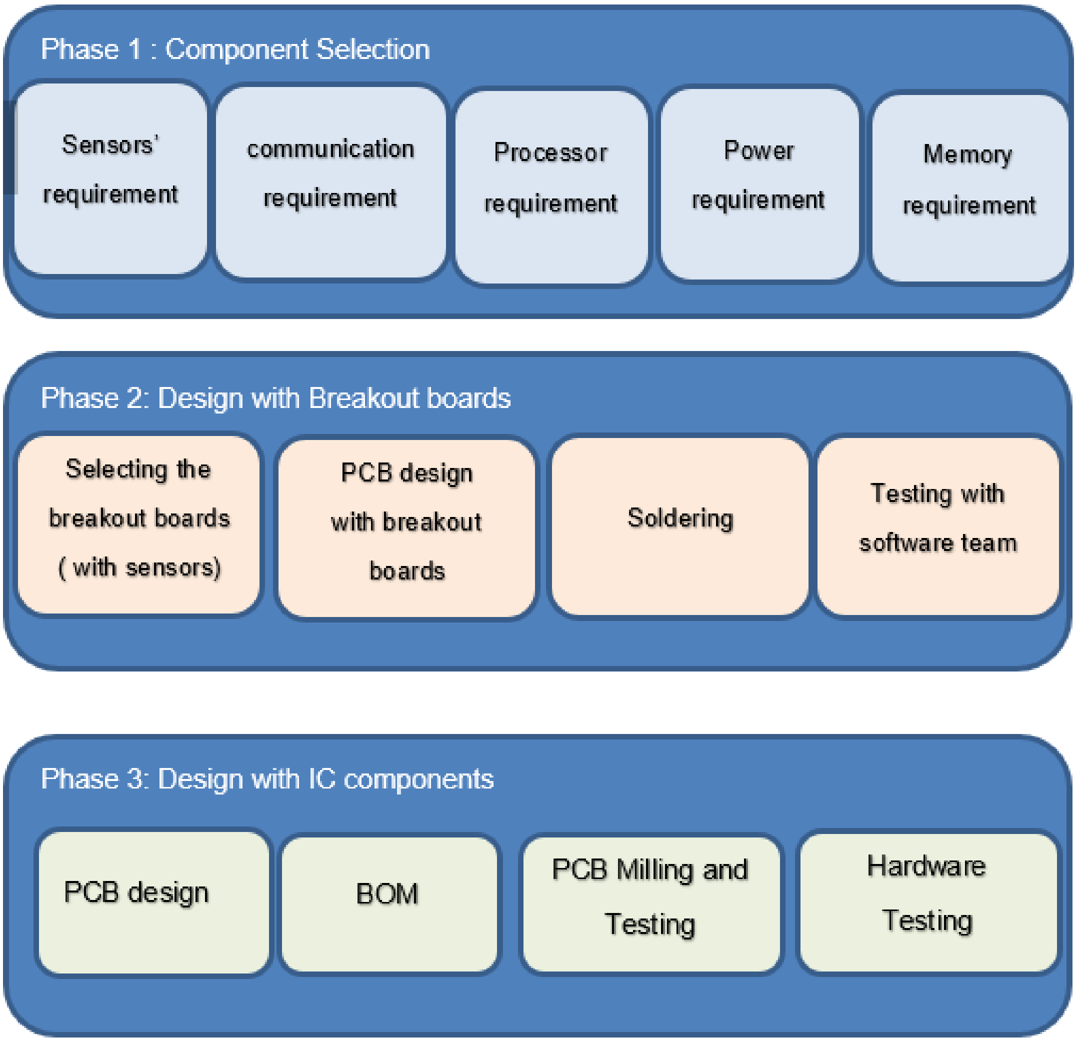

Figure 2. The three phases of the hardware development for the prototype

6.1 Phase 1: Component Selection

According to the hardware requirements specified in the objective, in this phase, the appropriate components, interfaces and protocols relevant for the prototype were listed, compared, analyzed and selected. It was divided into subcategories of selecting the type of wireless communication protocol; selection of sensor to processor interface; selection of sensors; and selection of a system processor that could offer the requirements of the selected communication protocol and sensor to SoC interfaces. Then follows the selection of power supply and memory units for the prototype.

6.1.1 Wireless Communication Requirements

The selection of wireless communication protocol depends on the type of data, its timing and the transmission channel. This was done under the frame of the specification of the prototype, which is low power, real time and long-range data communication. As listed in Table 1, there were a number of options that could be considered for the prototype. Below the technologies are compared with respect to their standard, power consumption, range and security.

Table 1. Comparison of wireless communication technologies [17]

Technology	Standard	Peak Data rate / Power	Range	Security
Wi-Fi	IEEE 802.11	11mbps-1 Gbps/1W	100m	WEP,WPA
Bluetooth	IEEE 802.15.1	1-3 mbps/1watt	100m	8-128bits
BLE	IoT interconnect	1 mbps/10-500mW	100m	128bit AES
Zigbee	IEEE 802.15.4	250 kbps/1mW	10m	128bit
Z-Wave	Z-wave	100 kbps/1mW	30m	Triple DES
RFID	ISO18000/29167/20248	423 kbps/1mW	1m	Available
NFC	ISO/IEC 13157	424 kbps/1mW	0.1m	Available
ANT+	ANT+	1 Mbps/1mW	100m	128bit AES
LTE	3GPP	1000Mbps/1mW	28km	SNOW 3G
EnOcean	ISO/IEC14543-3-10	125kbits/eharvesting	100m	128bit AES

The above technologies were then compared according to the specifications required for the prototypes, i.e. low-power usage, high-speed and reliable communication. Wi-Fi communication, despite its high performance in long range connectivity, it requires high power usage and its cost was found to be relatively high. Zigbee, Z-Wave and classic Bluetooth protocols, despite their low power consumptions, their peak data rate and the range of coverage is below what was required. Similarly, RFID and NFC were not found as suitable for long range application.

LTE and EnOcean are excellent for long range applications. However, they were found to be expensive options for the prototype. They also require additional features such as dedicated 4G mobile network for the former and energy harvesting mechanism for the latter.

Therefore, among the wireless technologies BLE (Low Energy Bluetooth) and ANT+ fulfill the specification requirements for high data rate, low power, long range, low cost and high reliability. Both technologies are suitable for personal-area networks of sensors and are popular in health monitoring and performance applications. Both operate in the 2.4 GHz ISM band (license free frequency band). They use short duty cycle technique and deep sleep mode to ensure low energy consumption.

BLE vs ANT+

As mentioned earlier there are numerous similarities between ANT+ and BLE. Their peculiar differences emanate from the topologies they support, how they transfer data packages and the number of channels that can be connected. Table 2 compares several other features.

From the analysis regarding the two wireless technologies, both are found very competitive and each has a slight edge on the other on different features. From hardware point of view, we selected a System on Chip (SoC) that supports either one or both of ANT+ and BLE. Another aspect of comparison was availability of software and hardware support, with built in features, in windows and android phones. Considering all the features mentioned earlier BLE has been found preferable for the prototype, despite equally excellent ANT+ features.

Table 2. Comparison of BLE and ANT+ wireless network topologies

Technology	ANT+	BLE
Frequency Range	2.4 to 2.483 GHz	2.4 to 2.483 GHz
Frequency	Fixed	FHSS
Band	ISM	ISM
Network Topologies	P2P, star, tree, mesh	P2P, star(Scatternet)
Modulation	GFSK	GFSK
Channel width	1 MHz	1 MHz
Protocol	Simple	Complex
Data rate	1 Mbps	125kbps to 2 Mbps
Range	100m	100 m
Number of Connections	Very high	Up to 20
Effective throughput	Up to 60kbps	Up to 1.4Mbps
Security	64-bit key, 128-bit AES	128-bit AES

In search of SoCs that support these wireless protocols a SoC was found from Nordic Semiconductor that supports both of these communication technologies. This gave the software team a possibility to develop a system that supports either BLE or both ANT+ and BLE. The two wireless communication methods are briefly explained in the following paragraphs.

BLE (Bluetooth Low Energy)

It is a standard wireless communication protocol that can be used for short to Long range applications using low power. The low power feature of BLE enables applications to operate for months with a single coin battery. Bluetooth 5 is the latest standard for BLE with a data rate of up to 2 Mbps, with long range, high sensitivity and improved broadcast capability. The System on Chip (SoC) that will be selected for this project is capable of supporting all the features of Bluetooth 5, including the long-range feature which is the high priority for the prototype as the sensor data is to be sent at least over a distance of an ice hockey rink length. BLE (Bluetooth 5) also provides the option of using four discrete transmission speed choices namely 125 Kbps, 500 Kbps, 1 Mbps and 2 Mbps. The 2 Mbps provides higher throughput capabilities [18].

ANT+

ANT is also an ultra-low power, 2.4 GHz ISM, wireless networking protocol to connect various devices in a robust manner. With the possibilities of a large number of nodes ANT+ enables all types of typologies such as P2P, star and essentially practical mesh in personal area networks that increases the network's flexibility and adaptability. ANT+ has been used in a number of devices in sports, fitness, wellness and home health applications. Because of the reasons mentioned above ANT+ networks are optimized for lower power consumption, cost, latency, robust communication and ease of implementation [19].

6.1.2 Interface Requirements

Sensor to system processor interface is the other major requirement before selecting any hardware for the desired prototype. Interface is quite essential for data transfer between components on the same board. If the proper interface is not selected and wired accordingly, the data that will be exchanged will not be meaningful.

For the prototype, the most common types of sensor to processor interfaces are considered. It is a fact that there are plenty of fast data transfer methods. For example, USB, Ethernet, Wi-Fi etc., However, for this project only the serial data transfer methods are considered. They are found to be fast enough for sensor to processor applications. Besides, their hardware requirements are also less complicated with low power consumption. Serial data transfer interfaces are usually divided into two as asynchronous and synchronous, depending on the availability of a clock line. Asynchronous data communication does not have a clock line, under which UART (Universal Asynchronous Receiver/Transmitter) communication interface was considered. On the other hand, two synchronous data transfer interfaces, I^{2}C (Inter-Integrated Circuit) and SPI (Serial Peripheral Interface), are compared and analyzed. Despite both of the latter interfaces use a clock signal for synchronization, they differ in terms of the wiring, power consumption, data transfer protocol, master-slave relationship, etc. Each interface will be briefly discussed and analyzed.

UART

UART is a type of asynchronous data transfer protocol in which there is no common clock signal between communicating devices. Due to the absence of common clock signal in UART, as depicted in figure 3, the sender and receiver need to agree first on the rate of data transfer. Therefore, an additional synchronization information is to be sent with every byte or frame of data. Compared to synchronous systems the data transfer rate of UART is slower. In addition, UART hardware requirement is more complicated.

Figure 3. Asynchronous UART communication interface

However, in synchronous data transfer, such as in I^{2}C and SPI, a separate clock signal is dedicated for synchronization, which enables higher rate of data transfer. I^{2}C and SPI mainly differ in their master slave configuration.

I^{2}C

The I^{2}C serial communication protocol allows multiple slaves (e.g. sensors) to communicate with one master (e.g. Processor) or more. I^{2}C wiring, in order to transfer data, only needs two wires, as shown in figure 4. One wire for data signal(commonly known as SDA) and another wire for clock signal (commonly known as SCL). I^{2}C supports multi-master system, in which masters take turns on the bus lines, to communicate with slave devices. I^{2}C bus drives are open drain, they can drive the signal line to ‘low’ but not to ‘high’. Meaning if there is no signal coming from the slaves, the signal line remains ‘high’, via the pull up resistors. This minimizes power dissipation by allowing devices to only pull it down when needed, otherwise remaining at ‘high’. The other advantage I^{2}C protocol allows is the communication between devices with different voltage levels without the need for voltage shifting circuitry. This can be achieved just by connecting a pullup resistor to the lower voltage device in the system(e.g. connecting a pullup resistor to a 3.3 V sensor which is exchanging data with a 5 V microcontroller).

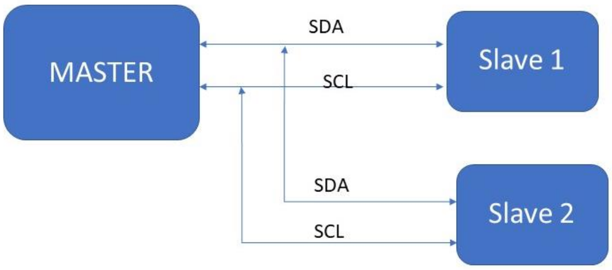

Figure 4. I^{2}C communication interface master-slave wiring

SPI

SPI is also another type of synchronous data transfer bus which comprises two data lines, a dedicated clock line for synchronization and a slave select line. The clock allows synchronizing devices which have different speeds or data rate. As shown in figure 5, the master device generates the serial clock signal (often known as SCK). SPI is a single master system, unlike I^{2}C that allows more than one master. In SPI the data line is divided into two. One data line that is going from the master to the slave, known as MOSI (meaning Master Out Slave In). Another data line is going from slave to the master, known as MISO (meaning Master In Slave Out). The two separate data lines enable SPI bus to send and receive data simultaneously. The slave select line, also known as SS, selects to which slave to send data to or receive data from. SS line is kept high when the device is not used and goes to low when it is needed to send and receive data between master and slave.

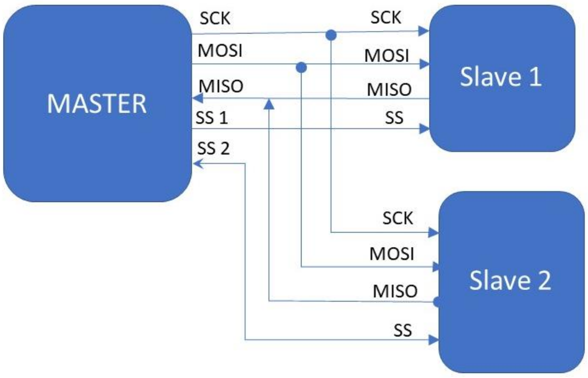

Figure 5. SPI communication interface wiring between master and slaves

SPI vs I^{2}C

In terms of the requirement for the interface between the system processor and the sensors, SPI and I^{2}C were the most suitable ones. The fact that both required less complicated circuitry suits the objective for small size prototype design. In addition, the nature of the head impact measurement data requires a fast data transfer rate as the impacts usually occurs in milli or even microseconds. The sensors that were selected for the prototype also have the flexibility to choose either I^{2}C or SPI communication interface. Even though both methods were tested in the development phase, it was needed to choose the best of the two for the final prototype. Therefore, below in table 3 the two serial communication interfaces were compared for ease of selection.

Table 3. Comparison between synchronous serial communication protocols

	I^{2}C	SPI
Communication	Synchronous	Synchronous
Number of wires	2	4
Signal lines	SDA, SCL	MOSI, MISO, SCLK, SS/CS
Number of masters	Unlimited	One
Number of slaves	1008	Unlimited
Data verification	ACK bit confirmation	No ACK bit confirmation
Addressing system	More complicated	Not complicated
Maximum speed	Up to 5 Mbps (ultra-fast mode)	Up to 10 Mbps
Data streaming	With start and stop condition	Continuous/ No interruption
Data transfer rate	Slower	Faster
Power consumption	Draws more power	Draws less power
Bus lock by a slave	Possible if a slave fails	Not possible
Cost	Cheaper	More expensive

As shown in table 3, both methods have an advantage over the other. The prototype that is to be built will have a microcontroller (i.e. a master) and two sensors (slaves). Therefore, in terms of wiring, I^{2}C will need two wires connected to each sensor. SPI will need four wires going from each sensor. From hardware perspective, the tradeoff will be between the simplicity of the circuitry and the data transfer rate. It also depends on the power consumption. Considering these features, the design proceeded with I^{2}C interface and will be adjusted later to SPI if needed.

6.1.3 Sensor Requirements

The first consideration in selecting the sensors was the amount of acceleration (g-force) they are able to measure. In the literature review [1] it was indicated that the peak linear acceleration related to potential concussive injuries could go up to approximately 100 g and a rotational head acceleration of up to 5800 rad/sec^2 [1]. Therefore, the accelerometers and gyroscope, to be selected for measuring the linear and angular accelerations respectively, should have the capacity to measure at least the peak value or more than that.

Another parameter of interest was the type of axis the accelerometers or the gyroscopes can measure. In regard to the types of axis there were three choices

- 6 single axis accelerometers,
- 3 axis accelerometer and a single axis gyroscope,
- 3 axis accelerometer and 3 axis-gyroscope

The third option is the most applied method in the study of head impact monitoring, especially in non-helmeted applications. With precise proper calibration tri-axis accelerometer and tri-axis gyroscope could be used effectively in helmeted impact measurements as well.

As described in the objective, the other important specifications to be considered for the selection of sensors were low power consumption, high sensitivity and sensor-to-processor interface. With respect to interface, only sensors with serial data transfer options were considered and analyzed in the next sub chapter.

Accelerometer

The selection of accelerometer primarily depended on the peak amount of g-force the prototype was required to measure. It has been described earlier that a peak linear acceleration of up to 100 g could be considered in relation to potential concussive injuries [1]. The fact that the impact occurs in milliseconds also makes the frequency and the sensitivity of the sensor is required to be as high as possible. Therefore, the search for the accelerometer was focused on finding the sensor with the highest possible range of g-force measurement, frequency and sensitivity.

The best accelerometer found on the market that suits the sensor requirement was a high-performance tri-axis accelerometer, consumes low power and it measures in an adjustable range of 100 g to 400 g, with a data rate of up to 1 kHz. It operates between 2.16 and 3.6 Volts. Selected features of the accelerometer extracted from its datasheet are shown in Table 4.

Table 4. General Features of H3LIS33DL accelerometer

Supply voltage	2.16 V to 3.6 V
Low voltage compatible IOs	1.8 V
Power consumption	Ultralow (10µA in low power mode)
Dynamic selectable scale	± 100 g, ± 200 g, ± 400 g
Communication interface	I^2C, SPI
Data output	16-bit
Sensitivity	49 to 195 mg/digit
Shock survivability	Up to 10000g
Package	Small thin plastic
Package	Land Grid Array (LGA)
Dimension	TFLGA 3x3x1.0 mm^3
Weight	20 mg
Operating Temperature	-40 °C to +85 °C

Analyzing the general features of the accelerometer with respect to the desired specification, it is capable of measuring g-force with added high-performance features.

Accelerometer: Pin Description

The accelerometer has 16 pins with LGA footprint. Figure 6 displays the top and bottom side of the sensor, arrows indicating positive directions of detectable accelerations across the X,Y and Z axes. At the bottom view the pin arrangement, in LGA 3 mmx3 mm package, is displayed.

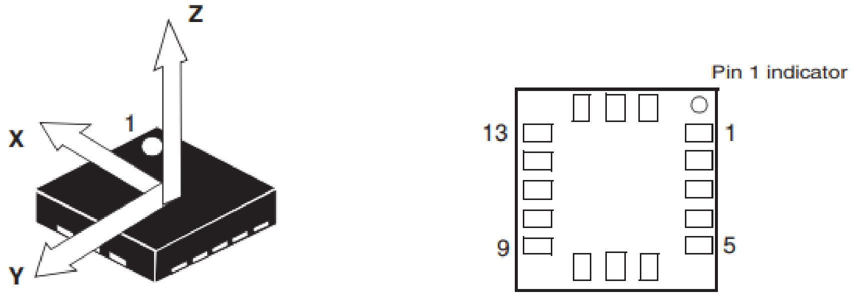

Figure 6. Top and bottom views of accelerometer sensor

Table 5 describes the pins and their function. The functions are illustrated in light of their interface to the system processor which will be elaborated more later.

Table 5. The list of pins in accelerometer and their functions

Pin Number	Pin Name	Function
1	VDD_IO	Power supply for I/O pins
4	SCL	I^2C serial clock
	SPC	SPI serial port clock
6	SDA	I^2C serial data
	SDI	SPI serial data input
7	SA0	I^2C less significant bit of address
	SDO	SPI serial data output
8	CS	I^2C mode: CS set to 1 (HIGH)
	CS	SPI mode: CS set to 0 (LOW)
11,9	INT1, INT2	Interrupt 1, Interrupt 2
5, 10, 12, 13	GND	Ground
2,3	NC	Not connected

Accelerometer: Electrical characteristics

From hardware standpoint the electrical characteristics in table 6 provides the essential information regarding voltage, current, frequency and bandwidth.

Table 6. Electrical Characteristics of accelerometer

Symbol	**Parameter**	**Range of values**
Vdd	Supply voltage	2.16 V to 3.6 V
Vdd_IO	I/O pins supply voltage	1.71 V to Vdd + 0.1 V
Idd	Current consumption in normal mode	300 µA
IddLP	Current consumption in low power mode	10 µA
IddPdn	Current consumption in power-down mode	1 µA
VIH	High-level input voltage	>= 0.8*Vdd_IO
VIL	Low-level input voltage	<= 0.2*Vdd_IO
VOH	High-level output voltage	>= 0.9*Vdd_IO
VOL	Low-level output voltage	<= 0.1*Vdd_IO
ODR	Output data rate in normal mode	50 to 1000Hz
ODR_{LP}	Output data rate in low-power mode	0.5 Hz to 10 Hz
BW	System Bandwidth	ODR/2
Ton	Turn-on time	1/ODR+1 ms
Top	Operating temperature range	-40 to +85 °C

From the electrical characteristics it can easily be seen that the selected accelerometer has a very low power consumption and can be powered by any low voltage power source or regulator. In the prototype a 3.3 V regulator from the microcontroller is used as a supply to the sensor. Therefore, the corresponding parameter values for Vdd_IO will be between 1.7 V to 3.4 V.

Other important parameters such as sensitivity, registers, offsets, etc. will be discussed by another thesis that will focus on the software part of the prototype. The software team also will study on how to convert the electrical signal from the sensor into meaningful variables such as into impact acceleration, impact location, severity level, etc.

Gyroscope

It has already been discussed that angular acceleration is one of the two accelerations that can cause of head impact injury for which using gyroscope is the most common method. Gyroscope sensors mainly measure angular velocity usually in rad/sec or deg/sec and sometimes in RPM. However, the parameter of interest for our prototype is angular acceleration which is obtained by proper differentiation of angular velocity over time.

As discussed earlier sudden rotation of skull during impact, occurs within milliseconds, and can be of very high magnitude resulting in risk of concussive injury. The location of injury is another parameter of interest by medical personnel monitoring the impact. The angular measurement by gyroscopes in combination with the linear measurement by accelerometer will be used to detect impact location. The linear and rotational accelerations are integrated over time to find the positional or location variables which are essential to predict the impact locations. The details of the calculations to derive the impact location or position from the measured acceleration values will be discussed in detail in another thesis focusing on the software part of the prototype. We will therefore focus here on the gyroscope sensor from hardware-requirement perspective.

As was done for the selection of accelerometer, the search for the gyroscope sensor was aimed at finding the one that can measure the highest possible angular velocity, along with low power consumption, high speed data transfer and compatible interface with system processor. One high performance motion sensor, comprising a gyroscope, was then selected from TDK InvenSense. The manufacturer specializes in producing high performance, low power motion sensors. The gyroscope is capable of measuring up to 4000 deg/sec and is mainly made for sports’ and high impact applications.

The chosen motion sensor is different from other regular gyroscopes for the reason that it contains an accelerometer embedded in it that can measure up to 30g force. The accelerometer inside the motion sensor, if not needed, can be disabled. The gyroscope is user programmable and can provide three-axis angular measurement with high level of accuracy. More essential features of the gyroscope are described in Table 7.

Table 7. Essential Features of the gyroscope

FSR range	±4000 dps for gyroscope, ±30g for accelerometer
Gyroscope	3-axis, programmable FSR of ±500 dps, ±100 dps, ±2000 dps, and ±4000 dps
VDD /VDDIO range	1.71 V to 3.6 V
Power	Low power due to Wake-on-motion interrupt feature
Digitizing	16-bit ADCs and Programmable Filters
Interface	7 MHz SPI or 400 kHz I^{2}C
Temperature	−40°C to +85°C
Current (Gyro only)	Operation mode: 1.23 mA to 2.67 mA; sleep mode :8 µA (NB: Accelerometer disabled)
Package	3x3x0.9 mm 24-pin QFN
Application	Wearable fitness solutions, impact analysis in contact sports

Pin configuration

The gyroscope, with an optional accelerometer embedded in it, has 24 pins among which 10 pins are not-connected(NC) pins and the rest 14 shall be used. The pin numbering, pin names and their function is illustrated in Figure 7 and Table 8.

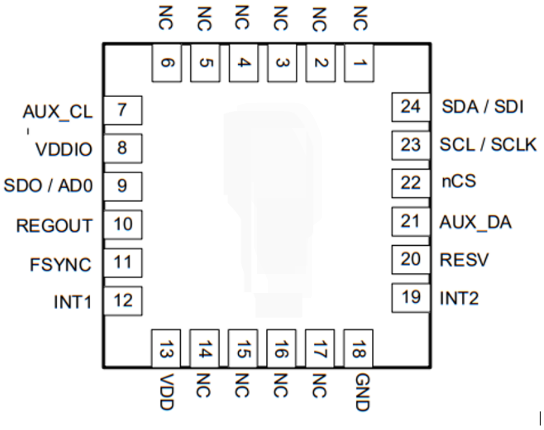

Figure 7. Pin out Diagram for gyroscope (3.0x3.0x0.9 mm QFN package)

Table 8. Table: Description of the pins of ICM-20649 (extracted from the datasheet)

Pin number	Pin name	Pin Function
7	AUX_CL	I^{2}C Master serial clock, for connecting to sensors.
8	VDDIO	Digital I/O supply voltage
9	AD0/SDO	I^{2}C slave Address; SPI serial data output (SDO)
10	REGOUT	Regulator filter capacitor connection
11	FSYNC	Frame synchronization digital input./ GND if unused.
12	INT1	Interrupt 1
13	VDD	Power supply voltage
18	GND	Power supply ground
19	INT2	Interrupt 2
20	RESV	Reserved. Connect to GND
21	AUX_DA	I^{2}C master serial data, for connecting to sensors
22	nCS	Chip select (SPI mode only)
23	SCL/SCLK	I^{2}C serial clock (SCL); SPI serial clock (SCLK).
24	SDA/SDI	I^{2}C serial data (SDA); SPI serial data input (SDI).

NB: Pins 1 to 6 and 14 to 17 are NC (Not connect) pins.

6.1.4 System Processor Requirements

The selection of system processor focused on finding the one with the latest technologies integrating the protocols and interfaces we have already chosen for the prototype. The major factor of selection was finding a SoC (system on chip) with long range wireless communication protocols. The reasons for these protocols were elaborated under the subsection of wireless communication requirements. And the other selection factor for the SoC is that must support high speed sensor to SoC interfaces. Low power consumption is also an equally deciding factor for selection.

System on Chip (SoC)

After analyzing a number of options, the SoC manufactured by Nordic Semiconductor,nRFxxxxx, was found to be an excellent fit to our objective requirements of the prototype. The selected SoC is an ultra-low power IC with a 2.4 GHz transceiver with the latest ARM Cortex -M4F processor. It has been the ultimate choice in regard to long range wireless area networks for sensor or IOT applications. The SoC supports both BLE and ANT+ communication protocols. In addition, it supports all types of serial interfaces we have considered for the prototype, mainly I^2C and SPI. The SoC has more than 60 pins with hundreds of features. The important features and pins that will be required for the prototype are identified and discussed here. From hardware perspective, the main task was also selecting the pins that suit the needs of both the hardware and software requirements; and then develop the PCB (Printed Circuit Board) with the right connections to other units of the prototype, such as power unit, sensors, memories, and others.

It is not in the scope of this thesis to discuss the multitudes of features for the selected SoC; therefore, this thesis will focus on the main features of interest as per the objective. Those features are extracted and summarized in Table 9. The other more important factor in regard to the requirement for the system processor's wireless communication is antenna design. In this regard, the manufacturer recommended readymade modules with its SoC and integrated antenna. Those modules will be compared in the next section.

It should be noted that within the scope of the hardware requirements, the relevant pins are identified and selected before proceeding to the PCB design. The main goal was how to transfer the data from the sensor through the I^2C/SPI pins with the required voltage level. The SoC is manufactured in two types of packages as shown in figure 8. In this project the third-party module, which will be discussed in the next subsection, uses the SoC with the QFN package.

Figure 8. Top and bottom view of QFN and WLCSP packages of the nRFxxxxx SoC.

As shown above the SoC is very small in size (7 mmx7 mm) but with high performance features that makes it suitable for wearable health monitoring applications.

Table 9. Essential electrical features of the nRFxxxxx SoC relevant to the prototype

Bluetooth version	Bluetooth 5 / BLE (Bluetooth low energy)
Transceiver	2.4 GHz
Sensitivity	95 dBm in 1 Mbps;103 dBm in 125 kbps
Data rates	2 Mbps, 1 Mbps, 500 kbps, and 125 kbps long range
Antenna	Single-ended antenna output
Current	4.8 mA peak current in TX, 4.6 mA peak current in RX
Processor	ARM Cortex M4 32-bit processor, 64 MHz oscillator, 52 µA/MHz running, Serial wire debug (SWD)
Memory	1 MB flash and 256 kB RAM
Interfaces	48 general purpose I/O pins 4x SPI master/3x SPI slave 2x I^{2}C compatible 2-wire master/slave 2x UART
Power management	
Supply range	1.7 V to 5.5 V LDO or DC/DC
Regulation	1.8 V to 3.3 V with low current modes
Wake up	Fast using 64MHz oscillator
OFF mode	0.4 µA at 3 V
ON mode	1.5 µA at 3 V
Applications	Health monitoring/ fitness wearables/IOT/gaming
Packaging	7x7 mm aQFN73 with 48 GPIOs 3.5x3.6 mm WLCSP93 with 48 GPIOs

SoC_Antenna Module

As indicated earlier, there are third party modules that integrate the RF (Radio frequency) or antenna design of the SoC and simplify the design process. Therefore, in this thesis work the modules from RAYTAC were selected, which are quite popular in the design of different breakout boards in the IOT market. In this module the RF design, tuning of the antenna and matching network design is taken care of. The antenna module, as shown in Table 10, has three versions short, medium and long range which have their own type of specific antenna requirements. They will be compared in Table 10 and the most suitable one will be selected for the PCB design.

Table 10. Comparison between modules integrating the SoC and an Antenna

	Module 1	**Module 2**	**Module 3**
Package	QFN	QFN	QFN
Antenna	Chip	PCB	UFL
Size	10.5 mm x 15.5 mm x 2.2 mm	10.5 mm x 15.5 mm x 2.0 mm	10.5 mm x15.5 mm x 2.0 mm
Memory	256k RAM, 1 MB flash	256k RAM, 1 MB flash	256k RAM, 1 MB flash
GPIO	48	48	48
Connectivity	Excellent	Good	Long range

Even though the module 3 series have excellent long-range feature, it needs external antenna connection that would make the prototype bigger than the desired size. Therefore, the Module 1 version with Chip antenna, which also has the desired long range and excellent connectivity features, was chosen for the prototype in this project.

6.1.5 Power Unit Requirements

The selection of the power unit is based on the current and voltage requirements of the system components. The main components in this case are the SoC_ Antenna module, the sensors and other peripheral components, such as regulator and external memory.

Battery

From the specification requirement of the prototype, using a coin cell battery has been found to be preferable by minimizing the additional charging circuitry that could have made the device bigger. It also indirectly supports the miniaturization of the device as well. It is also quite common to use 3V coin cell batteries for wearable ,small size, fitness and health monitoring applications.

The two most common types of coin cell batteries are CR2032 and CR2025. Both are thin, flat and round batteries, supply 3 V, have the same diameter of 20 mm but CR2032 has 3.2 mm thickness while CR 2025 has 2.5 mm thickness. In terms of storage capacity CR2025 holds a capacity of 160-165 mAh, while CR2032 holds up to 225 mAh. Their main difference is that CR2032 is thicker and lasts longer than CR2025. The CR2032 coin cell battery, shown in Figure 9, was chosen for its storage capacity and small size.

Figure 9. CR2032 coin cell battery (20 mm diameter x 3.2mm thickness)

The outer surface of the cell is the positive side, the middle/inner part of the cell is the negative or the ground. The cell battery can be put either in a battery holder usually soldered to PCB boards or a special 3D case can be designed to hold the battery in.

Regulator

Under the power unit requirement, the voltage to the system processor, sensors and other peripherals can be supplied from the regulator with a standard 3.3 V voltage output. The selected accelerometers and gyroscopes for the prototype require a 3.3 V supply. The AP2112, a CMOS LDO(low drop output), regulator was chosen for this project. AP2112 has enable function and delivers a 600mA continuous load current with fixed output voltages of 1.2 V, 1.8 V, 2.5 V, 2.6 V, or 3.3 V. This regulator is known for low power consumption. It is made in different packages; in our design the SOT-23-5 package was used, its top view is depicted in the figure 10.

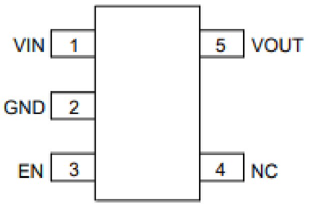

Figure 10. Top view of AP212 LDO regulator (SOT-23-5 package)

6.1.6 External Memory Requirement

In the design phase of the prototype it was discussed what precautions could be taken, if somehow the wireless connection fails to work. For this adding an external memory to the design was suggested. In regard to memory two possibilities were considered namely EEPROM and Flash memory. Two products with high memory size are compared in Table 11 across a set of parameters.

Table 11. Comparison of memory specifications: EEPROM vs Flash

	EEPROM (M95M02-A125)	Flash (SST26VF032)
Memory size	2 Mbit	32 Mbit
Organization	256 k x 8	4 M x 8
Max clock frequency	10MHz	80 MHz (faster)
Interface	Serial, 4-Wire, SDI, SPI	SPI
Max Supply current	5 mA	12 mA
Supply voltage	2.5 V to 5.5 V	2.7 V to 3.6 V
Package	SO-8	SOIC-8
How Data is erased	can erase any byte of memory at any time	can only erase an entire chunk/block of memory at a time
Usually needed for	small amounts of memory	Large amounts of memory

This is an optional requirement which may challenge the low power requirement of the prototype as the writing to memory needs a considerable amount of power. However, considering the importance of a backup just in case the wireless data transfer stopped working it was found to be essential. Therefore, flash memory was chosen for its higher speed and larger memory size capability.

6.1.7 Summary of Product Selection Phase

In the product selection phase, the aim was to select the right components for the prototype as specified in the objective. Even though there were a multitude of options under each category of requirements, they were filtered out through the frame of the objective specifications. Below the summary of the selections is listed.

Requirement 1: Wireless communication protocol

- under this category both ANT+ and BLE (Bluetooth Low Energy, Bluetooth 5) were found to be suitable for the design. BLE was selected as the primary choice as a greater number of devices and operating systems support BLE.

Requirement 2: Interface requirement

- For the interface between sensors and system processor, I^2C and SPI are the most suitable choices. It was decided to develop the first prototype with I^2C interface. Design with SPI will be done later, for this thesis the design with I^2C proceeded.

Requirement 3: Sensor requirement

- For the prototype two sensors were selected to be used a three-axis accelerometer that can measure up to 400 g and a three-axis gyroscope that can measure up to 4000deg/sec.

Requirement 4: System processor requirement (SoC)

- The nRF52X SoC from Nordic Semiconductor was selected, for its high performance and low power consumption. A SoC_Antenna module that integrates the SoC and a chip antenna was selected for its long range and excellent connectivity.

Requirement 5: Power supply requirement

- A 3 V CR2032 coin cell battery was selected for its size, storage and durability. And AP2112 low drop output regulator was selected to be used for a stable 3.3 V voltage supply.

Requirement 6: External Memory

- A 32 Mbit flash memory has been selected for it is speed and large storage capability.

6.2 Phase 2: Design with Breakout Boards

After selecting the components, the next phase of the project was to design the prototype with breakout boards. It was important to design with breakout boards for the reason that the IC components such as the accelerometer, gyroscope and processor have very small sized SMD (surface mount) pads that cannot be placed and tested on solder-free breadboards. In order to work with the sensors and the processor, breakout boards make the pins accessible. There are a number of manufacturers that extend the pads of small sized ICs into header pins on breakout boards, which could easily be mounted and tested on breadboards or custom-made PCB boards.

6.2.1 Selection of the Breakout Boards

In the previous phase of the project, three ICs were selected, such as the accelerometer, gyroscopes, SoC_Antenna module. Even though these ICs were to be used in the final prototype design, it was necessary to test the components and their wiring with breakout boards. The search for the breakout boards to the sensors was not difficult because there were only few options to choose from in the market.

Relatively, there were several breakout board options to choose from for the SoC (microcontroller). However, they were found to be more or less similar except in size, pin arrangement and antenna choice. After some analyzing two good breakout boards were then selected: one with PCB antenna (Sparkfun) and another with chip antenna (Adafruit). The design started with the Sparkfun board. However, in the later phase of the project Adafruit’s feather board was used. The feather makes debugging pins easily accessible; its chip antenna is also better than the PCB antenna in terms of long-range bluetooth connectivity.

The pin configurations and the electronic connections between the boards will be discussed in the coming sections. It should be noted that the choice of wiring between the breakout boards of the sensors and the microcontroller was based on I^2C interface. Therefore, connections mainly included data line and clock line. In addition, power line and sensor’s address lines were connected . After assuring the functionality of the wiring, further analysis proceeded as will be discussed in section 6.2.2.

Accelerometer Breakout Board

The breakout board by Sparkfun was selected, it comprises eight pins, as shown in figure 11, breaking out from the IC in the middle of the board. The features of the accelerometer IC have already been discussed in the component selection phase (section 6.1.3). The board gives access to the electrical features of the IC to be able to use them on breadboard. The breakout board provides serial interfacing options of I^{2}C and SPI.

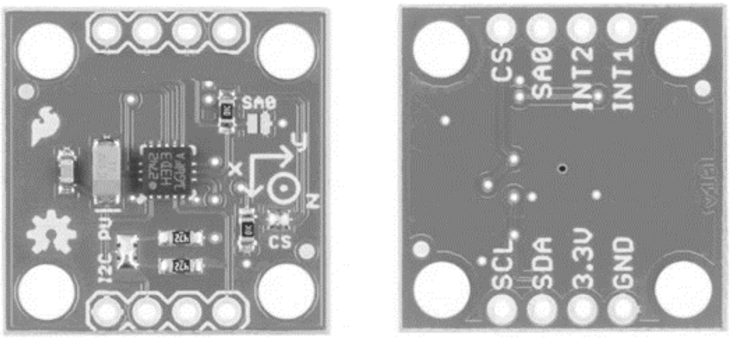

Figure 11. Top and bottom side of the accelerometer breakout board

For I^{2}C interface direct connection from SCL and SDA pins to a microcontroller can be used along with the 3.3 V and GND pins. There exist also two pullup resistors soldered to the board attaching SCL and SDA pins to the 3.3 V supply. If necessary it is possible to isolate the pull up resistors by removing the jumpers above the resistors.

There is an open jumper attached to the SA0 pin, which can be used to change the address of the sensor. This pin is essential to identify sensors when there are more than one sensor (slave) attached to the I2C bus on the microcontroller (master). The jumper can be closed, to set it from low to high, to change the address of the accelerometer.

For SPI data transfer four pins, other than the 3.3 V and GND, need to be connected. The SCL pin is used as a clock line (SCK), the SDA pin is used as Master out Slave in (MOSI), the SA0 pin is used as Master in Slave out (MISO) and The CS pin is used as Chip selector or Slave select (SS). As described earlier, the design with SPI connection would be done after the successful implementation of the prototype with I^{2}C design. However, SPI wiring was not implemented in the scope of this thesis work.

Gyroscope Breakout Board

It was a challenge to find a breakout board for the gyroscope that was chosen at the component selection phase (section 6.1.3). Even though it was not possible to find a separate breakout board for the gyroscope, the manufacturer of the sensor provides a universal evaluation board (UEVB) that includes the gyroscope. The board, in addition to the gyroscope, comprises magnetometers and accelerometers. The gyroscope on the UEVB, shown in Figure 12, is user-programmable, and three-axis gyroscope.

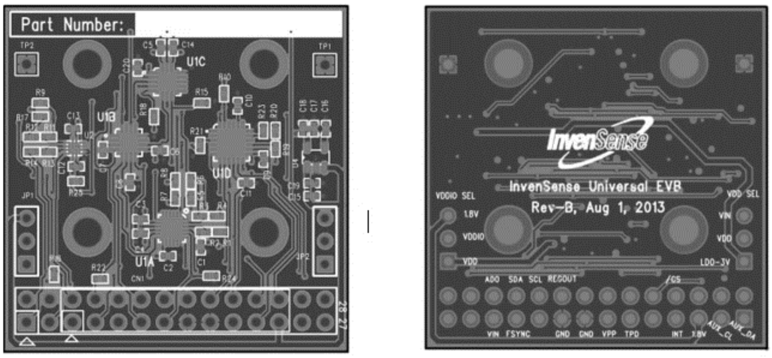

Figure 12. Top and Bottom side of UEVB evaluation board (38.1 mm x 38.1 mm x 1.6 mm)

The universal evaluation board is consisted of 28 pins. In addition, on the sides, it has pins that can easily be shunted to select from voltage supply options to the sensors on the board. The shunts can be adjusted depending on whether to use a voltage output from the regulator on the evaluation board or a voltage from an external 3.3 V supply (e.g. microcontroller).

During the calibration of the sensors, it was noticed that the UEVB was too large to fit in to the calibration equipment (centrifuge), when it was put together with the accelerometer breakout board and a microcontroller. Therefore, another custom-made, small sized, breakout board for the gyroscope alone was designed and printed as shown on Figure 13. This would be used while calibrating the accelerometer and gyroscope together.

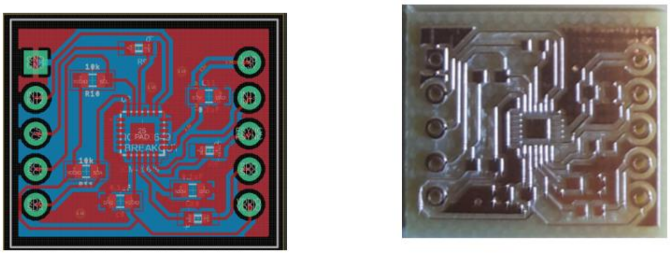

Figure 13. Custom-made breakout board for gyroscope (20 mm X 17 mm)

SoC Breakout Board (Microcontroller)

While searching for a breakout board for the SoC (nRFxxxxx), that was chosen in the component selection phase (see section 6.1.4), a board from Adafruit was selected. Other than the fact that this feather board comprises the chosen SoC, it made the I^2C pins and debugging pins easily accessible. In addition, the reason that it contains the chip antenna module of the SoC made it comparatively the better choice over other types of microcontrollers. The chip antenna module of nRFxxxxx SoC has been proven for excellent and long-range connectivity as stated in the component selection phase.

The SoC breakout board, by Adafruit, is named as ‘feather’. The term feather is an equivalent of breakout board commonly used by the manufacturer for its boards. Adafruit’s feather, as shown in figure 14, comprises several GPIO pins, analog inputs, PWM, timers, USB interface, LiPo battery connector, a regulator, switches, reset button, LEDs, QSPI flash and SWD connector.

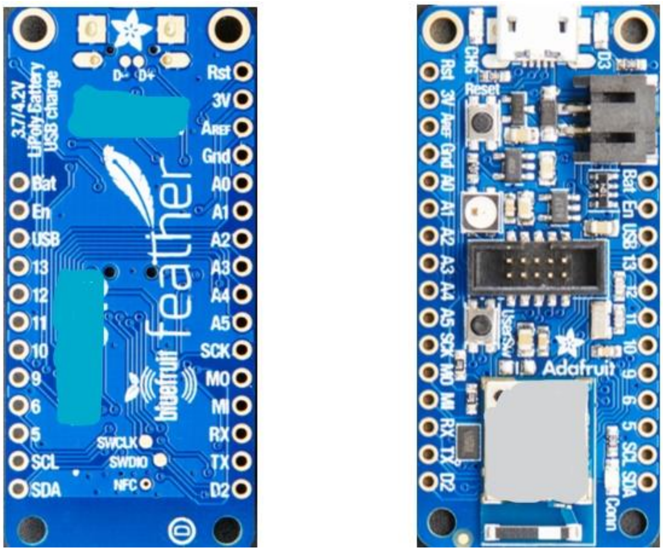

Figure 14. Top and bottom side of Adafruit’s SoC_Antenna module feather

Summary

In the phase of breakout board selection, the following are selected: An accelerometer breakout board from Sparkfun; UEVB evaluation board from TDKInvensense, a custom-made gyroscope breakout board and a SoC feather board from Adafruit.

6.2.2 PCB Design with Breakout Boards

PCB design with the breakout boards, after connecting the sensors on the bread board, was needed to test if the circuits are working as intended and to be able to calibrate the sensors. The calibration process was performed by the software development team using a centrifuge machine where the PCB boards were mounted and calibrated by supplying different values of RPM (Revolution per Minute) and corresponding g-force values.

The first stage of the PCB design process started by learning the Autodesk EAGLE software, for the reason that in the company where the thesis work was done it is customary to use the EAGLE software. In addition, it is easier to find readymade libraries in EAGLE's format for footprints of commonly used components.

As indicated earlier, this PCB design stage was synchronized with the need of testing the connections, the codes and calibrating the sensors. Therefore, the PCB design (Schematics and Layout) was performed also along with the following needs of the software team

- PCB design with breakout boards of SoC and accelerometer
- PCB design with breakout boards of SoC and gyroscope
- PCB design with breakout boards of SoC, accelerometer and gyroscope

The procedure that was followed in each of the above stages was similar. Initially footprints or packages for the breakout boards (see Appendix 1) were designed using the dimensions and the pin configurations depicted in their respective datasheets. Then appropriate symbol, which looks like the physical appearance of the boards, was designed. The footprints and the symbols were then connected together, according to their pin arrangement, to form a device that will be saved and archived in the library file(.lbr file) on EAGLE software. The created devices were then added from the library to be used in the schematics and layouts, as discussed in the next section, where the circuit connection of different devices was designed, printed and tested.

PCB design with Breakout Boards of SoC and Accelerometer

The PCB design of the prototype with the boards started by initially designing their footprint (packages) on EAGLE. After the design of the footprints, the PCB schematics and layout with I^{2}C wiring between the breakout boards of SoC and accelerometer was initially performed. as illustrated in Figures 15 and 16. Then the header pins were soldered to the printed circuit board for testing and calibration.

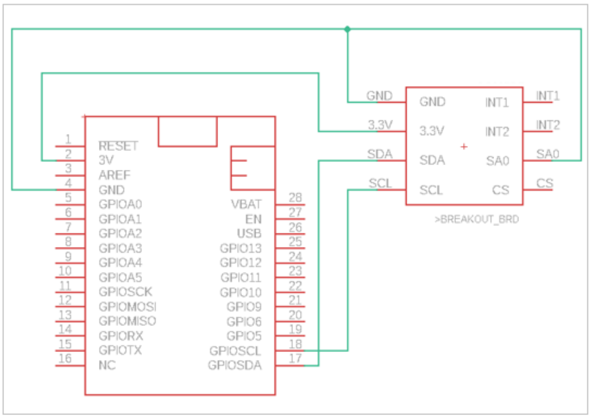

Figure 15. PCB schematics with breakout boards of SoC and accelerometer (I^{2}C wiring)

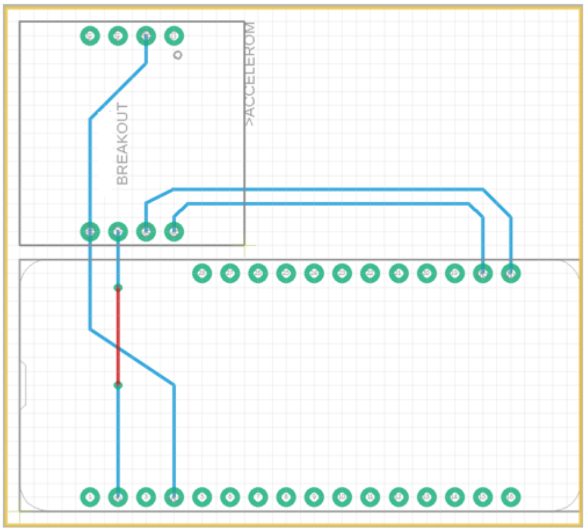

Figure 16. PCB Layout with breakout boards of SoC and accelerometer (I^{2}C wiring)

After soldering and printing, the breakout boards fit in the PCB precisely. The connections were working as expected after compiling and uploading the software codes on the processor.

PCB design with Breakout Boards of SoC and Gyroscope

Unlike the accelerometer, there was a slight difficulty faced related to designing the footprint of UEVB board (gyroscope). The UEVB is intentionally prepared to fit it into a development kit produced by the same manufacturer. The 28 pins were already soldered in double layers with horizontal right angled pin arrangement. To solve this problem a PCB footprint design with a double layer of 28 pins was required. Figure 17 and 18 illusutrates the schematics and layout of the Adafruit’s feather connected to the the evaluation board for gyroscope (UEVB). The wiring was done according I^2C interface. The figures for the footprint design of the UEVB and printed version of the PCB are shown in the Appenix 1..

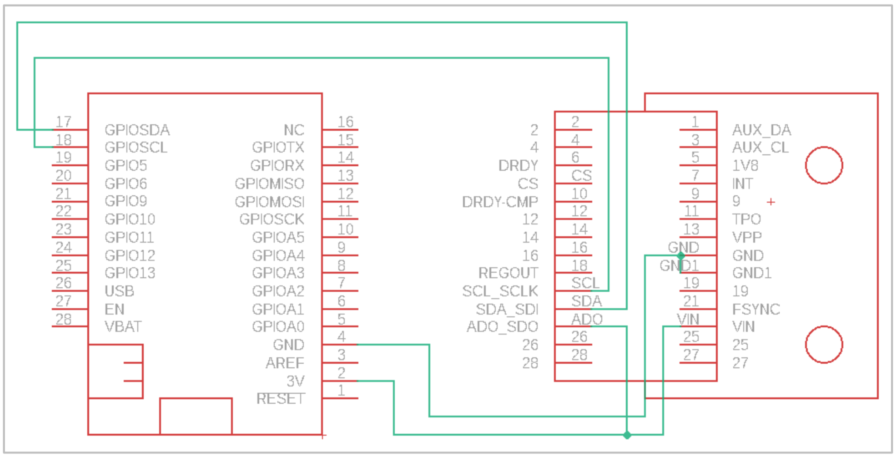

Figure 17. PCB schematics with breakout boards of SoC and gyroscope/UEVB (I2C wiring)

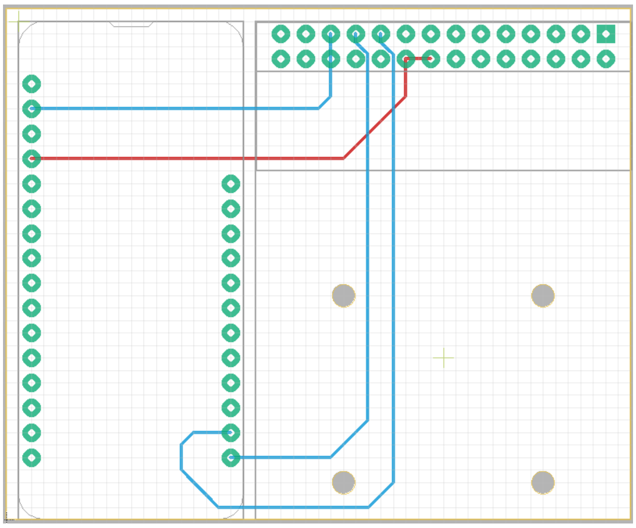

Figure 18. PCB Layout with breakout boards of SoC and gyroscope/UEVB (I2C wiring)

PCB design with Breakout Boards of SoC, Gyroscope and Accelerometer

In this design, as shown in Figure 19, the breakout boards for the system processor, gyroscope (UEVB) and accelerometer were combined and wired together using I^{2}C wiring interface. Due to the large size of the UEVB (38.1 mm x 38.1 mm) it was difficult to minimize the size of the board to be able to fit it into the calibration equipment. The printed circuit board can be seen in the Appendix.

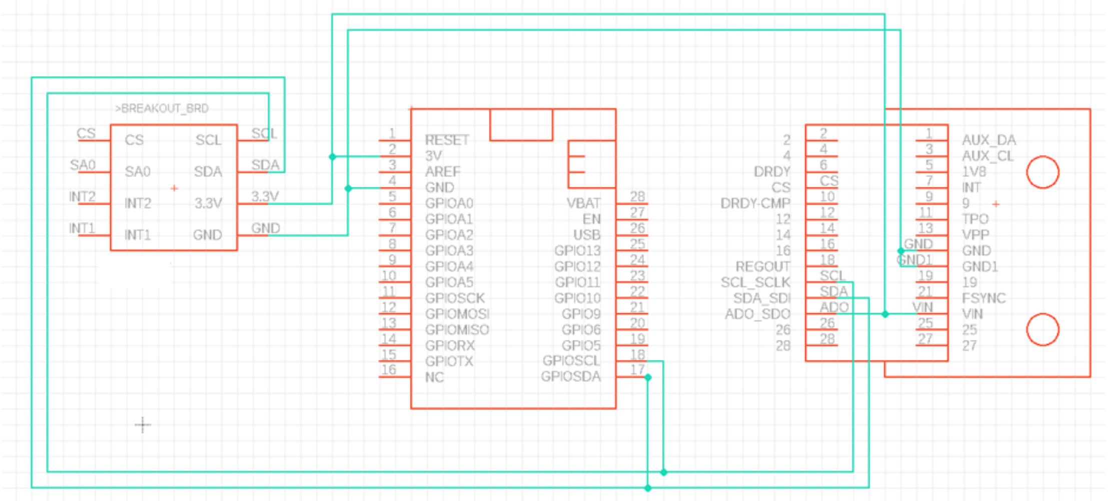

Figure 19. PCB schematics with breakout boards of SoC, gyroscope and accelerometer

In order to make the PCB layout and routing, small width trace lines are used in an effort to minimize the size of the board to a minimum. Some corners and edges of the borderlines were also removed for the same purpose.

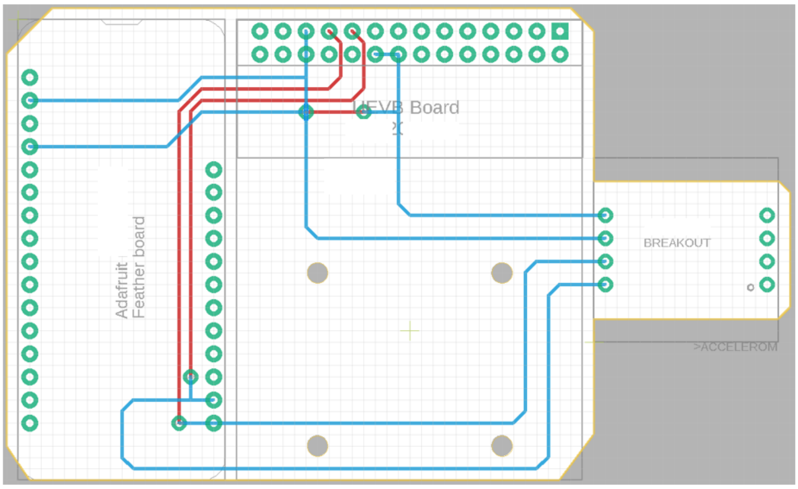

Figure 20. PCB layout with breakout boards of SoC, gyroscope and accelerometer

6.2.3 PCB Milling, Soldering and Calibration

Milling and Soldering

All the above PCB designs with break out boards were printed on FR-4 Copper board using a milling machine at Metropolia UAS, Myyrmäki campus. The CAM files were first processed on the Autodesk EAGLE software. On CIRCUITCAM the LMD files were prepared and exported to the BOARDMASTER application that controls the milling machine. After further settings, such as drills, boarders and isolations were configured, the milling machine manufactured the PCB boards. After milling the soldering of the header pins were done on which the breakout boards were mounted and made ready for testing.

Testing and Calibration

Connectivity test was then done for if there was undesired short circuits or open circuits. The voltage levels were checked at every terminal before supplying power to the sensors for voltage more than their maximum ratings will damage the sensors and the circuit might not function properly as intended. After doing connectivity and voltage level testing, the breakouts of the devices were assembled and mounted on the header pins. The program codes, written by the software team, were then uploaded and compiled on the assembled prototype for testing its functionality. The team then successfully performed calibration of the sensors for measurement precision. An example of calibration process of the SoC_accelerometer breakout board is illustrated in Fig 21.

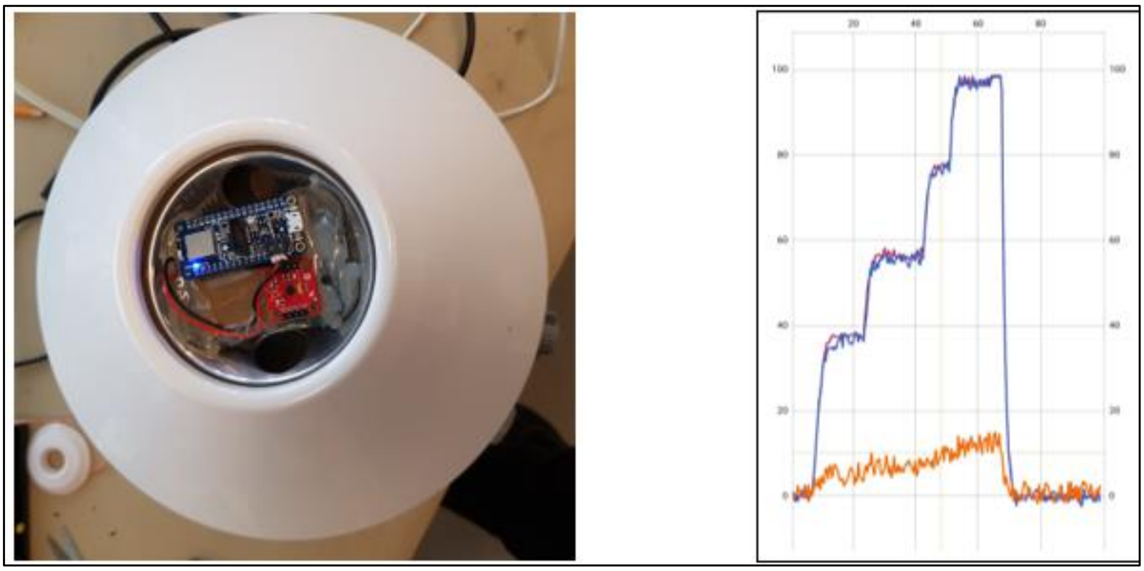

Figure 21. Calibration of the SoC_accelerometer breakout board on a centrifuge machine

6.3 Phase 3: PCB Design with IC components

The PCB design with IC (Integrated Circuit) chips was made be based on the list of components, interfaces and communication protocols which were analyzed during the selection phase, (section 6.1). In addition, it was based on the functionality of the connections that was implemented and tested with the implementation of designs with breakout boards (Section 6.2).

The PCB requirements for the final PCB design was described while specifying the objective of the prototype (Section 3). Accordingly, the PCB design with ICs was focused on how to bring all the components together on one board and make the size as small as possible without compromising the functionalities. In addition to the size the sensor too SoC interface was decided to be I^2C for the advantages stated earlier (section 6.1.2).

Within the framework of this thesis work, the PCB design phase was focused on preparing the schematics, the layout and the CAM files necessary for manufacturing the PCB. However, it should be noted that the prototype development would proceed after the thesis as well with the next stages of the prototype development , such as PCB printing, soldering, testing, etc. .

Autodesk EAGLE was the software that was used for designing PCB schematics and PCB layout. It was mentioned earlier that the software is chosen for the reason that there might be open source libraries for the most common components. The libraries for the footprints of some of the components were found online. For others, whose footprint was not found, new footprints were designed and archived in custom made library.

The number of layers to be used for the PCB was another factor to be considered. Due to the limitation of the student version of EAGLE it was not possible to consider more than 2-layer PCB design. Despite so, a 4-layer design, with two separate layers for ground and power, would have been a better choice..

6.3.1 PCB Design Sketch with IC Components

The ideal final device was expected to be as small as possible and wearable inside helmets. It is also customary in the wearable sport products' market to make a round shaped devices. Even though that is the final objective of the prototype, a rectangular shape PCB prototype was designed during this thesis work. However, if necessary it can easily be rearranged to make it round or design a round case in which the PCB will be put in. Before starting the PCB design process, the prototype requirements listed in section 5, were put on a sketch as shown in Figure 22. The sketch provides a visual illustration of the physical components of the final prototype for which the footprints would be put in place and get connected according to the electrical requirements.

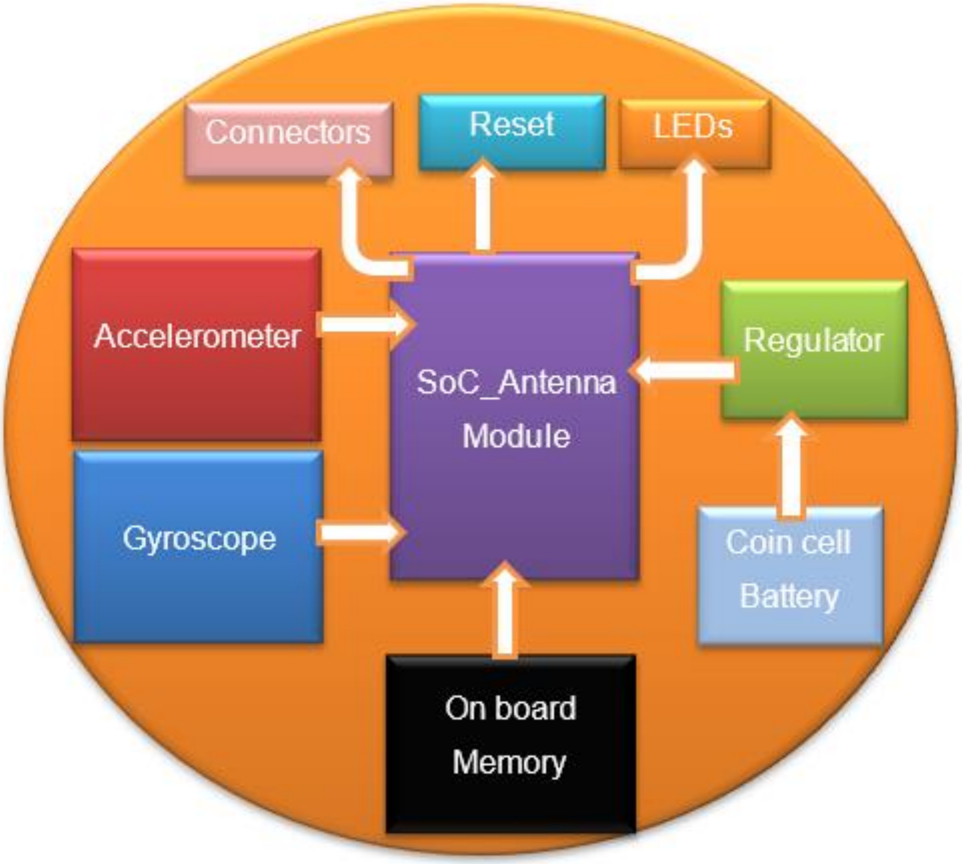

Figure 22. The sketch of the PCB design with IC components

6.3.2 PCB Schematics with IC Components

After the sketching arrangement, the schematics was designed as shown in Figure 23. Readymade footprints were used for most components and custom-made footprints were used for rare components. The sensors were setup for I^{2}C connection .

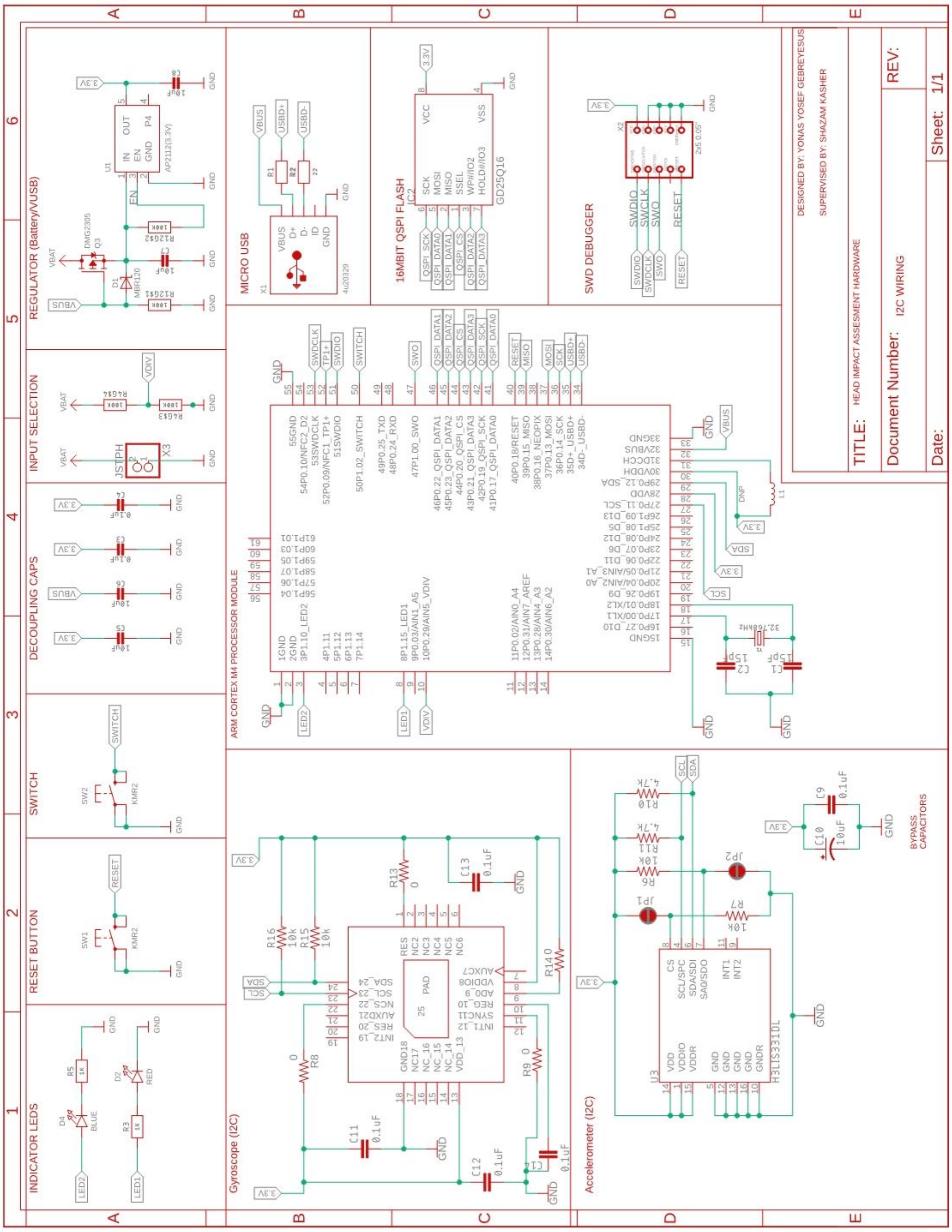

Figure 23. PCB Schematics designed with IC components of the final prototype

6.3.3 PCB Layout with IC Components

The layout and routing process continued with the consideration of keeping the size as small as possible. The components were placed close to one another with a standard clearance between them and the the routing was also done accordingly. The layout made some of the essential pins, required by the software team accessible, as shown on Figure 24. For this, there are two connectors on the right side with Micro- USB and Debuging pins put at accessible positions. However these connector options might not be required at the later stage of the product development, which was not included in the scope of this thesis work.

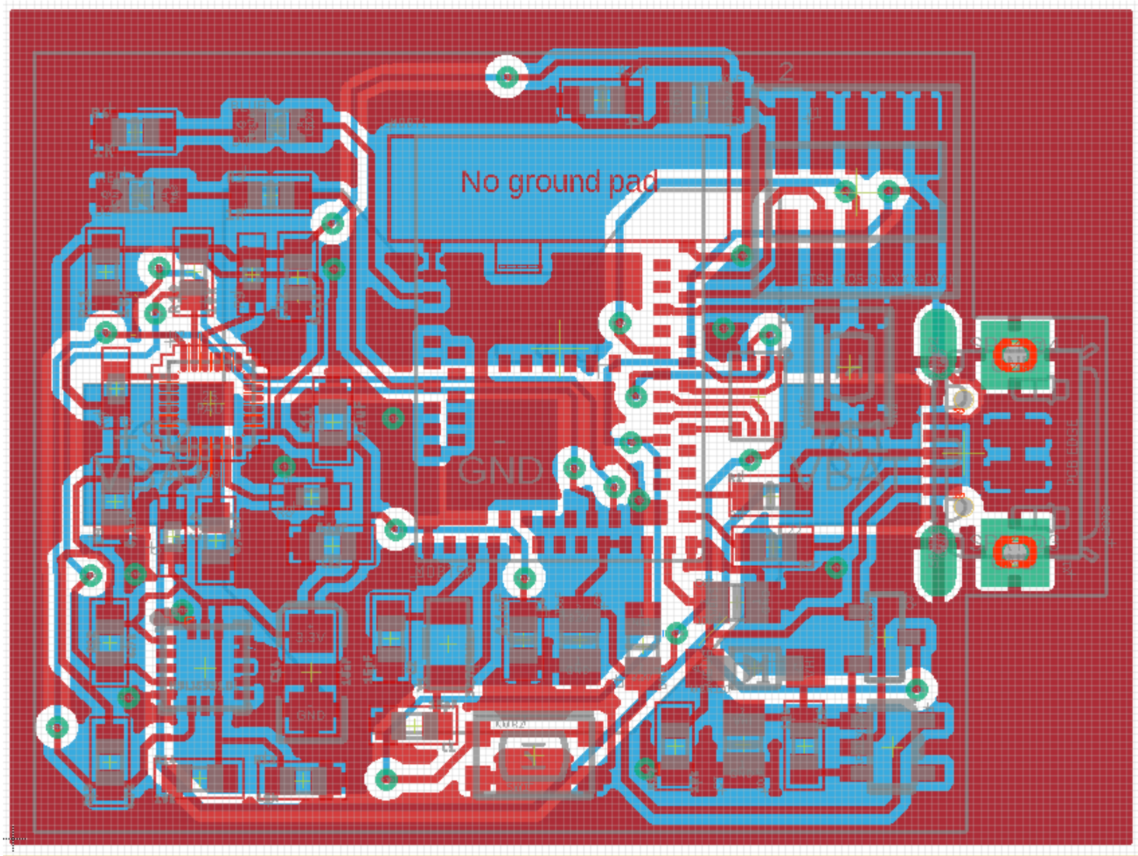

Figure 24. PCB layout of the final prototype design with micro USB and Debugging pins

In order to avoid excess wiring a copper ground plane was used while preparing the layout and routing. Appropriate polygon width, isolation and spacing was used and the result can be seen from figure 25 and 26.

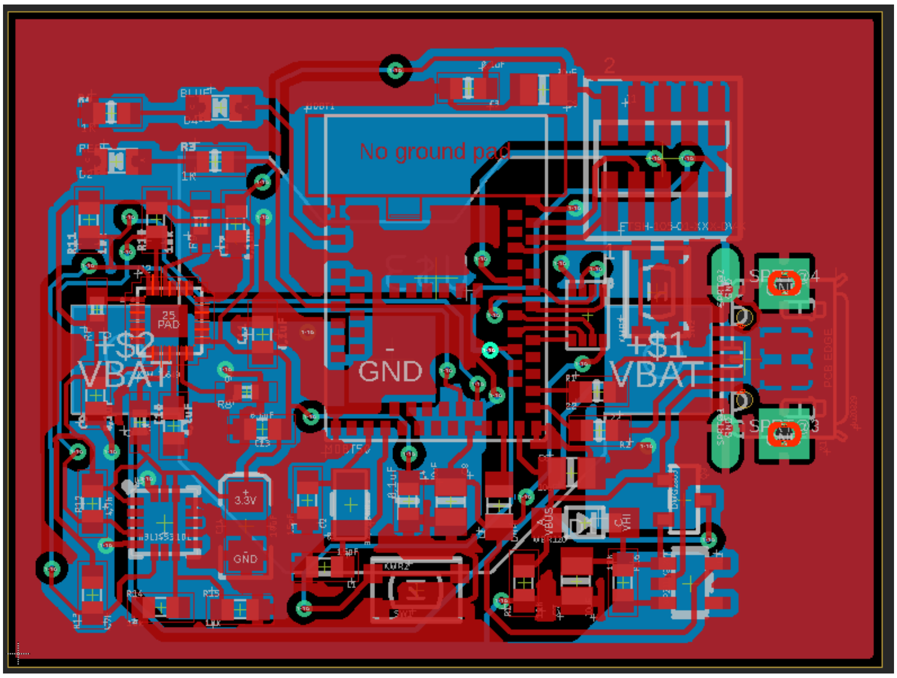

Figure 25. Top side of the PCB layout with ground plane

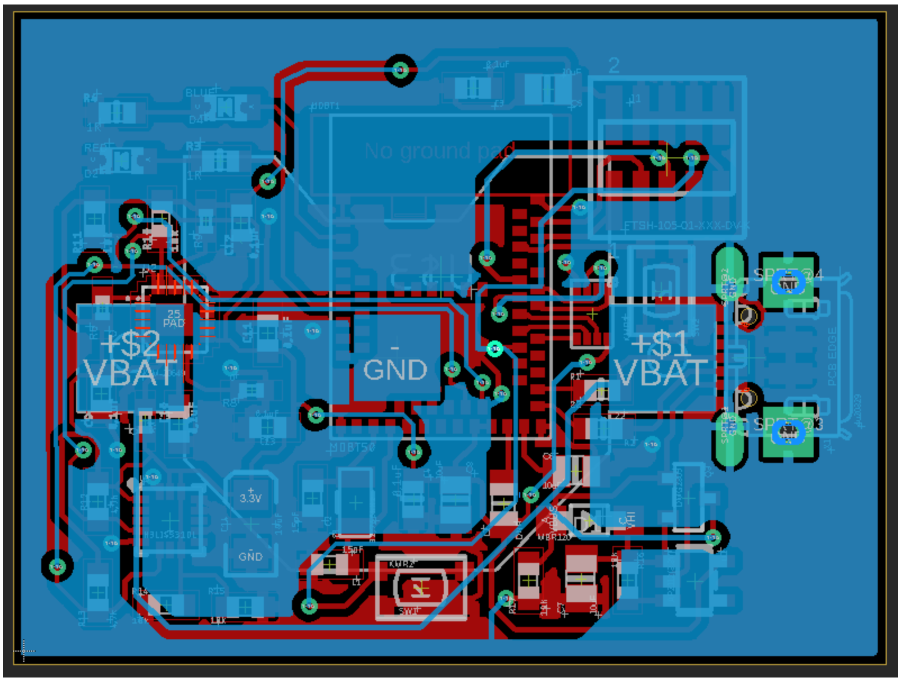

Figure 26. Bottom side of the PCB layout

6.3.4 PCB Printing, Assembly and Testing

With in the scope of this thesis work the final task of the prototype design ended with preparing the CAM files. These files would be used to print the PCB on which the IC components will be soldered. For an overview of the size of the PCB board a sample was printed at the school premise where existed a general-purpose PCB milling machine. However, the machine did not have the drills to make the small sized pads, footprints and routes. The size of the printed sample PCB was 42mmX31.5mm which was as small as the desired specification. The sample print of the PCB is as shown in Appendix 1.

The final PCB version could even be smaller after removing the micro USB and debugging connectors, as they would not be required at the later stage. However, for the prototype development phase those connectors would be essential to configure the system processor and the sensors.

The PCB manufacturing was outsourced to a company abroad, where it would be printed, and components would be soldered. While the writing of these report the ordering was on process.

After the PCB assembly, the next stage of the prototype development would be hardware testing. It would be tested for its current requirements and electro magnetic compatibility. after testing the integration of the hardware and software would follow. From hardware point of view the final stage would be the casing of the hardware and proceed to other product development phases.

It should be noted that this thesis work was part of a prototype development process for a company. The thesis solely focused on the PCB design of the prototype. Other parts of the prototype development would follow according to the schedule set by the company, such as the PCB manufacturing, components assembly, hardware testing, software integration, casing design and product certification would be done in the later stages.

Conclusion

The initial goal was designing a hardware that would be able to measure the head impacts that could cause concussion in high contact sports. Then specifications were for the hardware such that it should be able to provide real time linear and rotational head acceleration data, small sized and low power consuming.

The design process then proceeded with three phases.. During the component selection phase, a number of components, interfaces and communication protocols were compared and analyzed. The best possible options were then chosen based on the specification set in the objective. Then the design with breakout boards proceeded; a number of PCB footprints were then designed, printed, soldered and tested for their functionality. In the last phase schematics and layout of the final PCB with IC components were desinged. A sample PCB board was printed, despite poor quality of PCB due to an old milling machine and low copper quality. The PCB manufacturing and assembly was then outsourced to a professional company for better quality of the prototype.

The prototype was designed successfully to be able to measure head accelerations. In terms of size it was small enough to fit inside a helmet, 42mmX31.5mm. Its power consumption was very low due to BLE (Low Energy Bluetooth) technology. It consisted of accelerometers and gyroscopes which would provide the required linear and angular acceleration respectively. The interface between the sensor and the system processor was designed with I^{2}C wiring that would be able to provide impact data at 1 kHz frequency.

Further improvement of the design could be done after the hardware testing and software integration which were scheduled at the later stage of the prototype development. For example, a 4-layer board design would have been a better solution instead of the two-layer design with separate planes for ground and power. In terms of versatility of interface, an SPI option could have been integrated in addition to the I^{2}C interface, despite a more complicated wiring.

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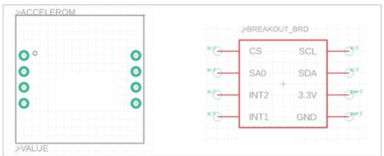
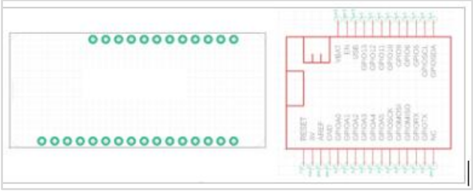
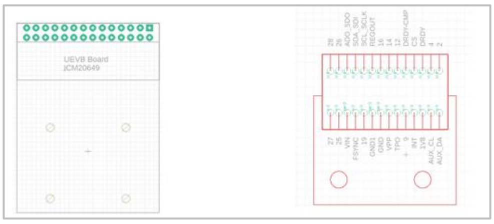
Appendix1



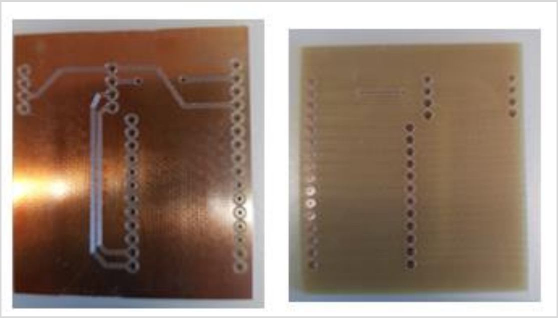
Footprint design for breakout board of accelerometer



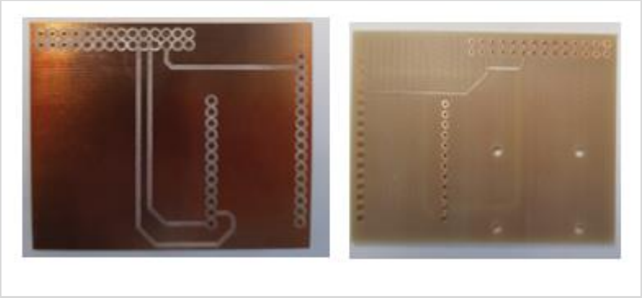
Footprint design for Adafruit’s SoC feather



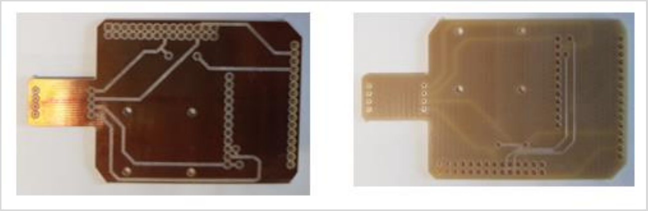
Footprint design for right angle, two row pins of UEVB evaluation board used for gyroscope



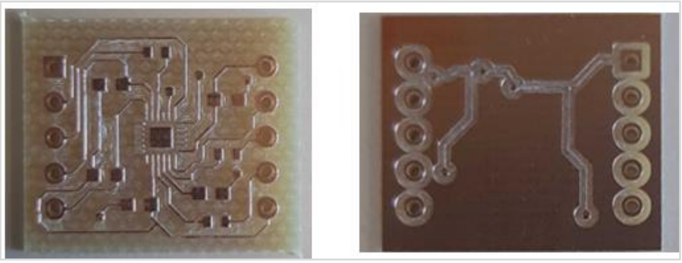
Printed PCB for Adafruit’s feather and breakout board of accelerometer



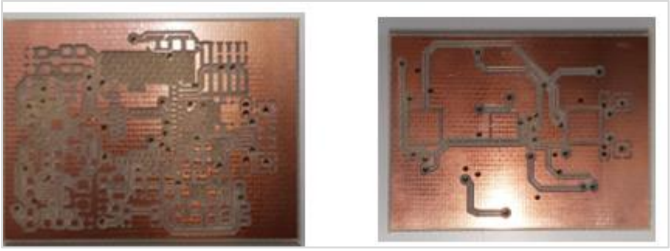
Printed PCB for Adafruit’s feather and breakout board of accelerometer



PCB print for Adafruit's SoC feather and breakout boards of accelerometer and gyroscope (UEVB)



PCB print of sample custom-made breakout board for gyroscope (not implemented due to soldering limitation for the small sized IC)



Sample of low-quality print of the PCB with IC components. (Therefore, the PCB manufacturing was outsourced)