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Adding an IoT Wi-Fi Board to the Head Impact Assessment Prototype in Contact Sports

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Head injuries are considered one of serious and worrying injuries for players and doctors due to the difficulty of examining the injured player at the time of injury and also the difficulty of following up the condition of the player's head during the period of exercise.
Head Impact Prototype is a device that follows player's head status instantaneously, as it is fixed in player's helmet, which helps the specialist and doctor in early detection of traumatic brain injury and concussion.

The goal of the project is to find a cheap and convenient transmission technology that able to transfer the Head Impact Prototype data and display it on smart devices such as portable smartphones or computers in order to be examined and followed up by health staff, doctors,.. etc. Internet of Things (IoT) system has been chosen as a suitable solution for this project, since the technology connects the device to the Internet, which allows specialists to control and display the received data from distance, due to the wide prevalence of internet networks.

Thereupon, Particle Photon has been chosen to represent an IoT device, since it is considered one of the cheapest microcontrollers that support this technology, as well as small in size, low power consumption, high performance and was available in Metropolia University lab. A Particle Photon has been added to Head Impact Prototype by connecting to Adafruit Feather nRF52840 Express microcontroller over one of data transfer protocols UART. The function of Photon is to receive the transferred data by Adafruit and send it to the Particle Cloud. The transferred data contains values of Accelerometer and Gyroscope which are considered the evaluation of brain movement. This data is stored in Particle Cloud temporary until it is sent again to a platform, where data can be viewed graphically. The graph can be monitored by a specialist or doctor to assess the player's situation.

Keywords	IoT, Wi-Fi, Particle Photon, UART, Platform

Contents

List of Abbreviations

$	United States Dollar
ACK/NACK	Acknowledged/Not Acknowledged
ADC	Analogue to Digital Converter
AES	Advanced Encryption Standard
BLE	Bluetooth Low Energy
CAN	Controller Area Network
CPU	Central Processing Unit
csv	Comma separated values
CT	Computerized tomography
dBm	Decibel miliwatts
DC	Direct Current
dps	Degrees per second
ECU	Engine Control Unit
EEG	Electroencephalogram
FCC	Federal Communications Commission
FIFO	First in first out
FSR	File Select Register
g	G-force/ gravity

GB	Gigabyte
GCS	Glasgow Coma Scale
GHz	Gigahertz
GPIO	General Purpose Input/ Output
GPS	Global Position System
HDMI	High Definition Multimedia Interface
HITS	Head Impact Telemetry System
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
I^2C	Inter Integrated Circuit
I^2S	Inter IC Sound
IaaS	Infrastructure as a Service
IC	Industry Canada
IEEE	Institute of Electrical and Electronics Engineering
iOS	iPhone operation system
IoT	Internet of Things
IP	Internet Protocol
ISM	Industrial, scientific and medical
JSON	JavaScript Object Notation

KB	Kilobyte
kbps	Kilobit Per Second
KiB	Kilo Binary Byte
Km	Kilometer
LED	Light Emitting Diode
m/s^2	Meter per second squared
MB	Megabyte
Mbps	Megabit per second
MDS	Medical device consulting and services
MEMS	Micro-electromechanical system
MHz	Megahertz
MISO	Master in Slave out
MOSI	Master out Slave in
MRI	Magnetic resonance imaging
mTBI	Mild Traumatic Brain Injury
PaaS	Platforms as a Service
PC	Personal Computer
PLL	Phase Locked Loop
PWM	Pulse Width Modulation

$\mathrm{rad/s^2}$	Radian per square meter
RFID	Radio Frequency Identification
RJ45	Registered Jack-45
RoHS	Restriction of Hazardous Substances Directive
RTC	Real time clock
Rx	Receiver
SaaS	Software as a Service
SCK	Synchronous Clock
SCL	Serial Clock
SD	Standard Definition
SDA	Serial Data
SMD	Service Mount Device
SPI	Serial Peripheral Interface
SQL	Structured Query Language
SRAM	Static random access memory
SS	Select Signal
SSL	Select Socket Layer
TBI	Traumatic Brain Injury
TCP	Transmission Control Protocol

TLS	Transportation Layer Security
TV	Television
Tx	Transmitter
UART	Universal Asynchronous Receiver Transmitter
UF2	USB Flashing Format
USB	Universal Serial Bus
VDC	Voltage Direct Current
VDD	Voltage Drain Drain
VM	Virtual Machine
Wi-Fi	Wireless Fidelity
μA	Microampere

1 Introduction

The brain is one of the most important and irreplaceable organs in the human body and exposing to any injury may cause great damage temporarily or permanently. Therefore, everyone is keen to stay healthy, away from any danger to the brain including concussion, which is one of the common injuries among athletes, and the delay in detecting may cause serious complications in the future that are difficult to treat.

Hence, an idea was born to create a device that measures the state of the player's brain periodically during the time of practice, especially in sports most likely vulnerable to a head injury such as direct contact sports, ice hockey, and others. The purpose was to make the prototype able to send the brain data to a longer distance that makes the specialist able to follow the athlete's head health. As such, the prototype works to follow the condition of player's head which is monitored by a healthcare specialist through smartphone or a computer viewing instant data graphically. Once the player is exposed to a concussion, the device records a clear change in the graph proportional directly to the head movement.

The device went through several important stages: the device design stage, the device programming stage, and the third stage which was finding an appropriate means to transfer prototype data to display it in more convenient way.

The Internet of Things was chosen as an effective system for transmitting data and connecting devices together via the Internet. A Particle Photon microcontroller was also chosen to represent the IoT system through taking advantages of the wide spread of the Wi-Fi, moderate power consumption, as well as cost of the system.

The data was successfully transferred by Adafruit microcontroller to the Photon microcontroller using wired transmission technology UART. Then this data was sent again by Photon microcontroller to the cloud, which in turn deliver the data to an appropriate application for display.

Three methods were followed to display the data: one of them using a pre-prepared page to display the data through following intelligent algorithms that analyze the data (Thingspeak). Another method was used a ready-made application that displays data instantly on the mobile phone (Blynk). The last method was created a Webserver that able to display the data in real time via any smart device such as computer, mobile, tablet … etc.

2 Medical Theoretical Background

2.1 Traumatic Brain Injury

A Traumatic Brain Injury (TBI) is a disruption in normal function of brain that can be caused by an external force such a bump, blow, or jolt to the head, or penetrating head injury [1]. It can also be defined as damage that occur to the brain because of external force, for instance rapid acceleration or deceleration, direct impact, shock wave, or penetration by a missile fragment. As such, brain performance is affected temporarily or permanently, and the injury may be assessable or may not be assessable with recent technology. Figure 1 shows types of traumatic brain injury that affect a human head directly.

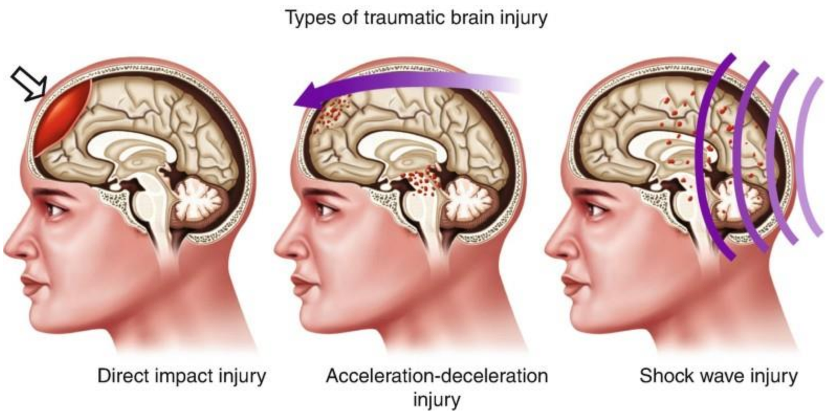

Figure 1. Types of TBI which affect human head directly [2].

Generally, TBI can be assessed by the severity, which can be measured by Glasgow Coma Scale (GCS). A GCS is the level of consciousness that is estimated on a scale of 3-15 by a verbal, motor, and eye opening reactions to stimuli, for the injured person. Based on severity and extent of damage to the brain, brain injury can be classified into three categories [3]:

- Mild: the injury state may result in a slight change in mental state or consciousness. The mild injury has scaled of GCS between 13 - above.

- Moderate: the injury state may result in moderate change in mental state or consciousness. The symptoms are more intense than mild TBI and less than the severe TBI. The moderate injury has scaled of GCS between 9 - 12.

- Severe: the injury state may result in long time of unconsciousness, coma, or even death. The severe injury has scaled of GCS between 8 - below.

2.1.1 Brain Parts

A center of human activity is a human brain, which consists of nerve cells that distributed through directed pathways to the body. Repeated injuries that occur to the head may affect the body's functions, as the body's functions are directly related to the brain. Understanding the function of different parts of brain, helps to evaluate the injury effects on person's abilities and behaviors. Human brain can be divided into six main parts as shown in Figure 2. Also functions of each brain part are mentioned in Table 1.

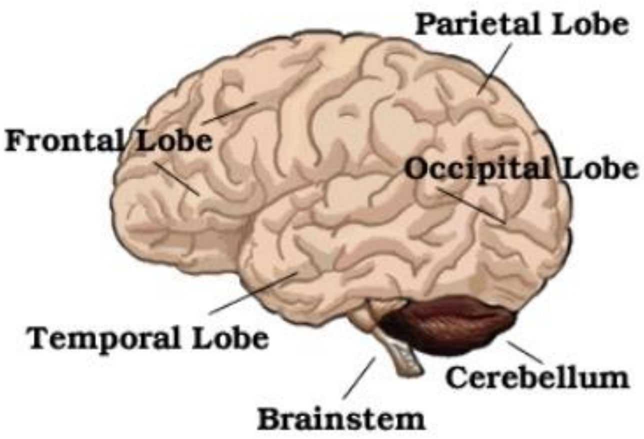

Figure 2. Brain six parts [4].

Table 1. Illustrates six main brain parts and their functions [4][5].

Brain Part	Functions
Brain Stem	• Breathing • Heart Rate • Swallowing • Reflexes for seeing and hearing • Controls sweating, blood pressure, digestion, temperature • Affects level of alertness • Ability to sleep • Sense of balance
Cerebellum	responsible for controlling the coordination of voluntary movement • Coordination of voluntary movement • Balance and equilibrium • Some memory for reflex motor acts
Frontal Lobe	Responsible for behavioral output like social and cognitive behaviors and body movement. • How we know what we are doing within our environment • How we initiate activity in response to our environment • Judgments we make about what occurs in our daily activities • Controls our emotional response • Controls our expressive language • Assigns meaning to the words we choose • Involves word associations • Memory for habits and motor activities • Flexibility of thought, planning and organizing • Understanding abstract concepts • Reasoning and problem solving
Parietal Lobe	Responsible for complex behaviors, including all behavior involving the senses. • Visual attention • Touch perception • Goal directed voluntary movements • Manipulation of objects • Integration of different senses
Occipital Lobe	• Vision
Temporal Lobe	responsible for memory development and learning • Hearing ability • Memory aquisition • Some visual perceptions such as face recognition and object identification • Categorization of objects • Understanding or processing verbal information • Emotion

2.1.2 Brain Injury Symptoms

The appearance of some symptoms of TBI may vary from person to person and may last for days, weeks and even longer. However, once these symptoms appeared on a person, it is advised that the physical activity should be terminated immediately. Here are some of TBI symptoms, which should be evaluated by a health care specialist approved in TBI diagnostic:

- Symptoms may appear early as soon as TBI occurred [5]:

  Headache or a sensation of pressure in the head, nausea or vomiting, altered level of consciousness, slurred speech, delayed response to questions, blurred vision (dilated or uneven pupils are a sign of severe TBI), confusion, dizziness, tinnitus (ringing in the ears), memory loss, and fatigue.

- Symptoms may appear lately after TBI occurred few hours, days or weeks [5]:

  Continued or persistent memory loss, trouble in concentration, irritability, personality changes, sensitivity to light and noise, disorders of taste and smell, sleep problems, mood swings, stress, and anxiety or depression.

2.2 Concussion

Concussion is a type of mild traumatic brain injury (mTBI) that impacts the brain function temporarily [6]. It can happen as a result of sports, car accident, falls and physical altercations. Brain injuries can be affected by a direct blow to the head or by an external force on the body that is transmitted to the head as illustrated in figure 3. Once the brain faces enough force that result to collide in the skull, there may appear some of short term symptoms. Unfortunately, the repetition of concussions can result to a long term consequences, which make the recovery more complicated.

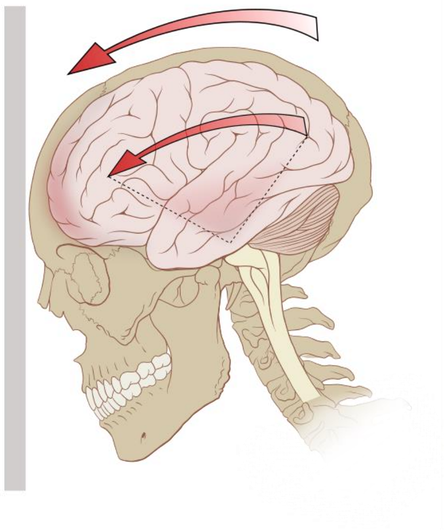

Figure 3. The idea of a concussion [6].

However, having a concussion does not necessarily cause a loss of consciousness. Concussion results a variety of symptoms, which some of them may appear right away, or may delay for several days after the injury. Some symptoms are physical, such as drowsiness, while others are cognitive, like memory loss. The following symptoms considered as the most common signs may appeared on concussed athletes, which help to diagnose the injury: drowsiness feel, memory loss and difficulty in remember something, irritability and anger, headache, vomiting and nausea , indecision and confusion, imbalance, dizziness, loss of consciousness, difficulty in speaking, depression, and changes in sleep habits [7].

2.3 Concussion in Sport

There is no doubt that every sport player is exposed to a blow on head directly or to a blow to the body indirectly, which pushes the head to rotate quickly. Therefore, concussion is considered one of a major concern in contact sport duo to the serious consequences that may occur to the athlete, especially, who exposes to similar incidents frequently. As such, in some sports have more probability of contact as instant rugby, football, ice hockey, ... etc.

However, most of concussed athletes can recover within 7 to 10 days in case the right process of prevention has been followed. As such, once athletes have suspected in concussion, they should terminate the sport immediately and try to have a plenty of rest time as the brain injuries need enough time to recover, and straining it can delay the recovery time that makes brain healthy [8].

The young athlete exposes more to concussion and needs longer time to recover, because the brain during this period is still growing until the age of 25. Therefore, concussions can result greater damage among collegiate athletes and may increase the danger to cognitive impairment [7].

Medically, the injured athlete submitted to a neurological exam to be assessed generally. Essential procedure is to pass through a test for balance, coordination, vision, hearing and reflexes. Once the brain injury is proved, it is checked with MRI or CT scan, which provides doctor more details of the skull and brain status, but concussions, cannot be seen on MRI or CT scans, so prevention is important [8].

2.4 Concussion Technically

Concussion can be evaluated by measuring two motion impacts on and athlete's head: linear acceleration and rotational acceleration. Linear concussion can be caused by direct impacts that stops moving the head forward, but the brain continues moving forward until collide to the skull, causing damage to the frontal lobe or occipital lobe or both. Linear motion can be detected by using Accelerometer sensor. While rotational concussion can be caused by side impacts that makes the brain to spin around its axis causing a tear on brain structures. Rotational motion can be detected by using Gyroscope sensor. These two components can estimate the greater impacts of motion in the head, which may reduce injury complications and future risks. Figure 4 shows the idea of linear and rotational acceleration [9].

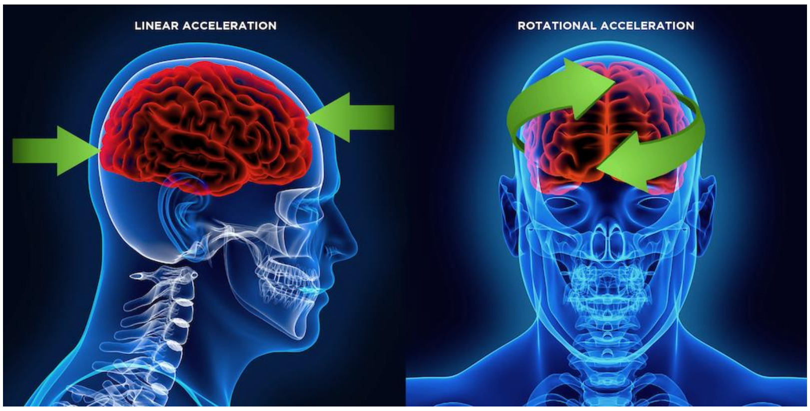

Figure 4. Linear and rotational acceleration [9].

The Sports Legacy Institute has considered 20g or more force as the threshold for such a hit.[7] Another study has been conducted that an average value of the linear accelerations experienced by the head during a concussion is approximately 40.62 g, and an average value of rotational acceleration is approximately 3388 rad/s^2 [10].

3 Modern Devices Technology

Previously, concussions were determined by CT scan, regular patient questionnaire, patient history data, or a neurological test, which some of them considered inaccurate method. However, with the revolution of technology in healthcare and medical fields recently new methods have appeared to evaluate TBIs including concussions. Some of new technology devices will be covered in this section.

3.1 i-STAT Alinity

Abbott company has invented a device called "i-STAT Alinity" to evaluate suspected mild TBIs and concussions through blood test. The main function of the device is to determine whether the TBI patient needs to have CT scan or not. The test takes 15 minutes to show up the result. The measurement is done by putting a plasma sample on a cartridge, then installs it into the device, which in turns show up the presence of specific proteins negatively or positively. The positive result means the patient suffers from concussion impact [11][12]. Figure 5 shows i-STAT Alinity plasma test device.

Figure 5. i-STAT Alinity plasma test device [12].

3.2 Ahead 300

BrainScope company has invented a device called "Ahead 300", which provides a fast (within minutes) evaluation of mild TBIs, including concussion. Basically, it is a disposable headset consisting of 8 electrodes expanded to 20 electrodes, which functionally collects EEG data from the head, then shows it up on a screen of portable device [13]. The headset is worn when it needs to assess the severity injury of patient whether it has serious affection. As such, Ahead 300 is considered as an early diagnose device and can be used in Emergency Department [14]. Figure 6 shows Ahead 300 device.

Figure 6. Ahead 300 device [13].

3.3 Q-Collar

Q-Collar is a C-shaped device that is used by sport players and worn around the neck during sport activity in order to protect the player from repetition of concussion. Indeed, Q-Collar works by making a pressure on the arteries around the neck causing increase in the volume of blood in the skull. This reduces the movement of the brain inside the skull, which considers a main cause of TBI and concussion in general [15]. Figure 7 shows Q-Collar device.

Figure 7. Q-Collar device [16].

3.4 Head Impact Telemetry System

Head Impact Telemetry System (HITS) is a programmed hardware designed for football players and used to detect whether the player is exposed to a concussion during exercise or not. The device is fixed in football player's helmet and the data can be viewed from a computer. Generally, HITS technically consists 6 linear Accelerometers fixed in specific places, a computer, an alert device and a battery [18]. Figure 8 shows HITS fixed in a Riddell helmet.

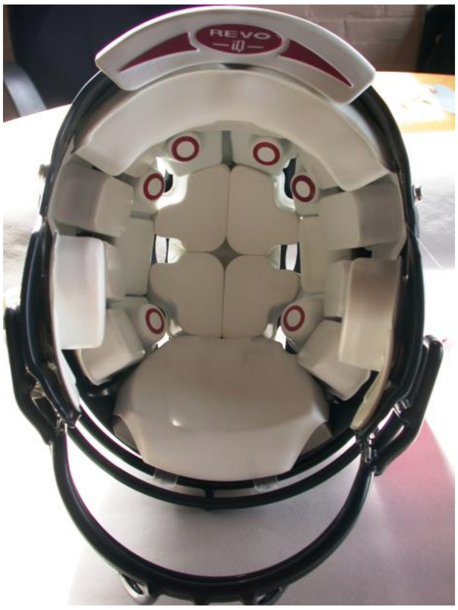

Figure 8. HITS in a Riddell helmet [17].

3.5 X2 Biosystems xPatch Pro

X2 Biosystems is a system that is used to detect TBI and concussion with helping of xPatch Pro sensor, which is used to measure linear and rotation impact, due to it contains Tri-Axis Accelerometer and Tri-Axis Gyroscope as main components [18]. The sensor is mounted on the head skin behind the ear of sport player. Figure 9 shows xPatch Pro sensor taped on the athlete head.

Figure 9. xPatch Pro sensor taped on the athlete head [19].

In fact, this system uses a wireless communication technology, since xPatch sensor transfers data directly to Cloud through a platform where Cloud processes data in order to be stored and monitored on any smartphone using a specific app [20].

3.6 MDS Head Impact

MDS Company aspires to make a device that checks the severity of concussion for athletes to reduce complications that result from direct or indirect attack and help the player to get rid of symptoms that may affect him in future. The device will be covered in more detail in Hardware System section.

4 Embedded Communications Technologies

Embedded device connects to other device by using certain communication technologies and protocols. In this thesis, it is divided into wireless or wired transmission technologies depending on the transmission medium that is used.

4.1 Wireless Communications Technologies

4.1.1 Wi-Fi

The most popular wireless technology based on IEEE 802.11 standard, which developed to replace the wired communication IEEE 802.3 Ethernet standard. Although Wi-Fi operates on 2.4 GHz or 5 GHz ISM Bands, newer versions can also work with other frequency bands. An example of newer version is HaLow, based on 802.11h, uses band 902-928MHz and covers 1km with a suitable antenna [21]. The most popular topology that are used in Wi-Fi: point to point and star topologies.

Many IoT applications use Wi-Fi to build a network that connect between devices. It is commonly used with devices that require higher speed, larger size data, higher bandwidth, and direct connection to the internet. However, it is less used by the applications that depend on low power consumption, and very limited in a device that running on small batteries for long time [22].

4.1.2 Zigbee

Zigbee is one of recommended choices used by IoT application and based on IEEE802.15.4. It is designed to work on 2.4GHz ISM, 902-928MHz and 868 MHz frequency bands [21]. Particularly, Zigbee is characterized by low power consumption and low data rates. It is compatible with IoT application, which uses small data rate and controls devices through internet such as the smart home. The most popular topology that are used in Zigbee: star and star topologies [22].

4.1.3 Bluetooth and BLE

Bluetooth is a wireless technology that works on 2.4 GHz ISM frequency band. Although it transfers data through shorter distance, it is widely used in streaming application, wearable devices and smart home [22].

On other hand, BLE is considered as one of lowest power consumption wireless technologies. The technology can be used to work in various network topologies: point to point, star and mesh. However, in mesh topology all devices can communicate with others directly, which means it can send and receive data freely among the device neglecting the source. This makes the network expand to cover larger area. As an advantage of power consumption BLE is widely used by medical devices, indoor navigation and fitness wearable device [22].

Table 2 compares among Wi-Fi, Zigbee, Bluetooth and BLE and shows the most reasonable technical values, which can help to select a suitable wireless technology that meets the demanding application.

Table 2. Comparative among wireless communication protocols [23].

Wireless Technology	Power Consumption	Transmission Range	Data Rate
Wi-Fi	Medium	100m without (Boosters)	10-100+ Mbps
Zigbee	Low	10-100m	20-250 kbps
Bluetooth	Medium	1-100m	1-3 Mbps
BLE	Lower	100m	125 kbps - 2Mbps

4.2 Wired Transmission Technologies

4.2.1 SPI

Serial Peripheral Interface (SPI) is a high speed serial synchronous data transfer bus which is used commonly in short distance systems, such as embedded. As shown in Figure 10, it consists of four signals: two data signals MISO and MOSI, clock signal (SCK) and slave select signal (SS). The two data signals MISO and MOSI are transferred to direction that referred by their names. MISO refers to Master In Slave Out, whereas MOSI refers to Master Out Slave In. Master device launches the frame for reading and writing data. SCK is produced by the master device to slave in order to synchronize the transferred data to devices. SS is used to determine which slave is going to receive the transferred data. SPI communicate between devices in full duplex mode using single slave. Multiple slaves need separate select signal (SS1, SS2, …etc.) [24].

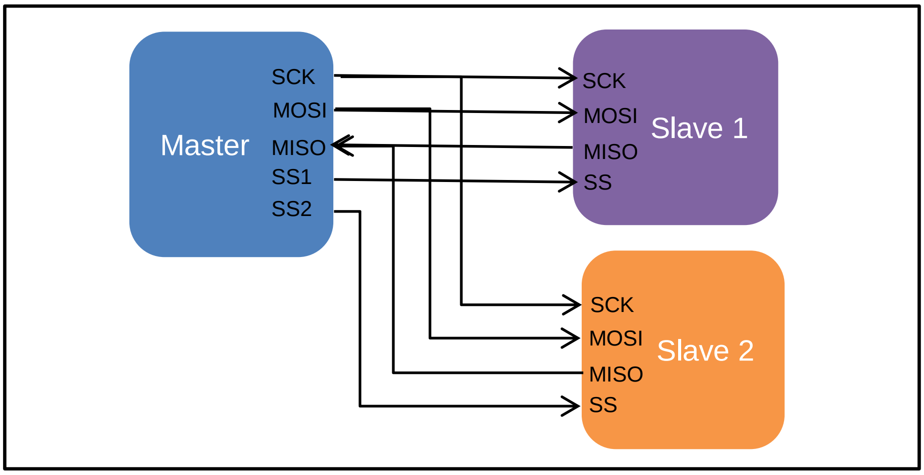

Figure 10. The structure of SPI between master and two slaves.

The master sends data to the slave with the most significant bit first through MOSI line in serial way bit by bit, whereas the slave sends data to the master with the least significant bit first through MISO line in serial.

4.2.2 I^2C

Inter Integrated Circuit (I^2C) is an asynchronous serial communication protocol that allows connecting multiple slaves to a single master or more. It takes the advantages of UART and SPI, so it uses only two wires to transfer and receive data between devices. One wire called Serial Data (SDA) is used as a transmitter and receiver, while the other wire called Serial Clock (SCL) is used to generate a clock signal for synchronization in order to achieve successful communication. Figure 11 shows the connection idea of I^2C communication [25].

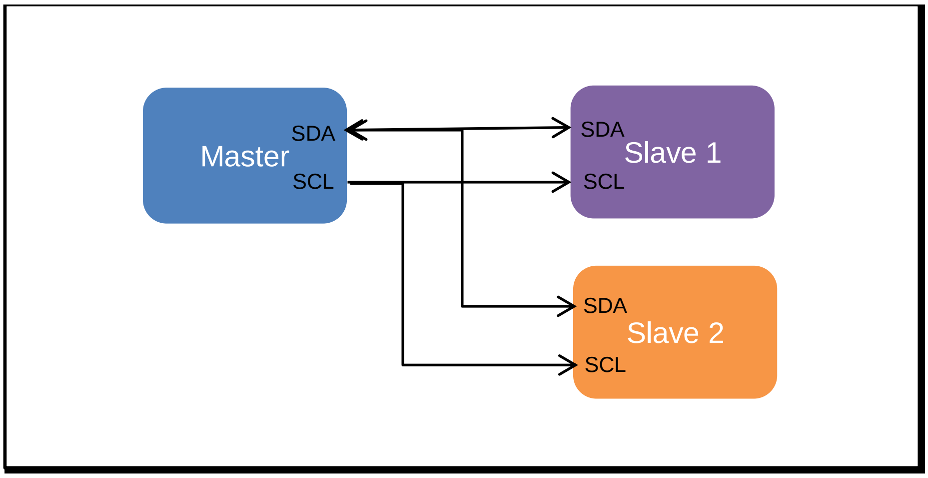

Figure 11. The structure of I^2C between master and two slaves.

With this serial communication, the data is transferred as a message which consists of start, address frame, read write, frames of data separated with ACK/NACK, and stop bits as shown in figure 12.

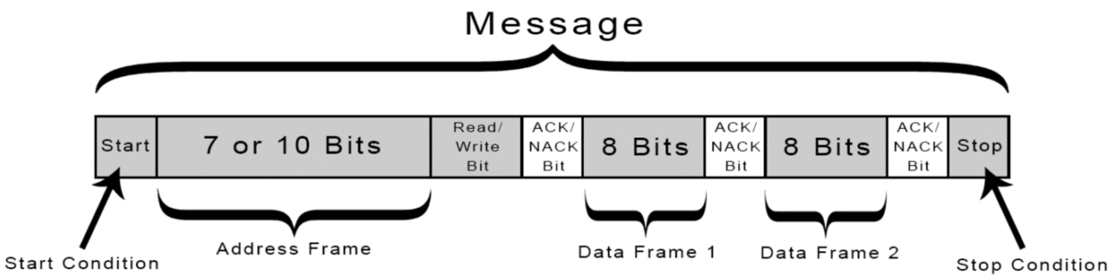

Figure 12. A message of data in I^2C communication technology [25].

4.2.3 UART

Universal Asynchronous Receiver Transmitter (UART) is an asynchronous serial data transfer circuit used to connect between devices, such as microcontrollers. UART circuit consists of two wires: transmitter Tx and receiver Rx. To connect two microcontrollers Tx of first microcontroller is connected to Rx of second microcontroller, while Rx of first microcontroller is connected to Tx of second microcontroller as shown in Figure 13. The transmitter converts the parallel data received from the control device into a serial form, then transmits it in sequence to the receiver, which converts the serial data back into parallel data for the receiver [26].

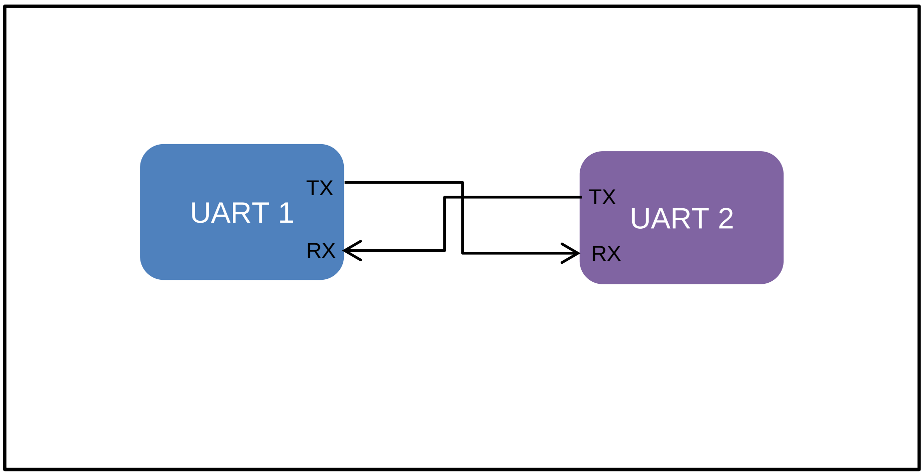

Figure 13. Two UARTs devices connected together.

Basically, UART does not need a clock signal, so data is sent by a transmitter Tx as a packet includes start, data frame, parity and stop bits, which is handled by receiver Rx. Figure 14 shows the packet of data which is used by UART.

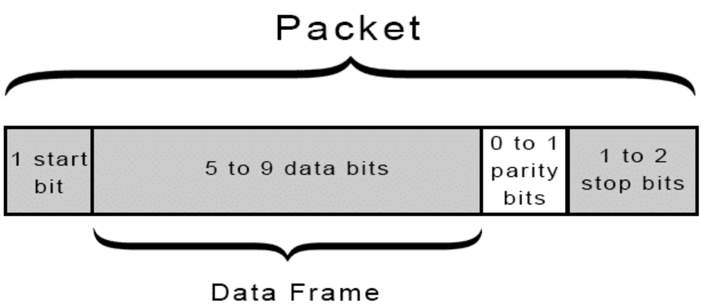

Figure 14. A packet of data in UART communication technology [26].

4.2.4 CAN

Controller Area Network (CAN bus) is a multi-master serial bus that allows devices or different microcontrollers communicate with other's applications without a host computer. CAN bus is commonly used by automobiles, as well as some industrial equipment. This serial communication uses two wires to connect each EDU. Figure 15 illustrates the communication way of CAN bus [27].

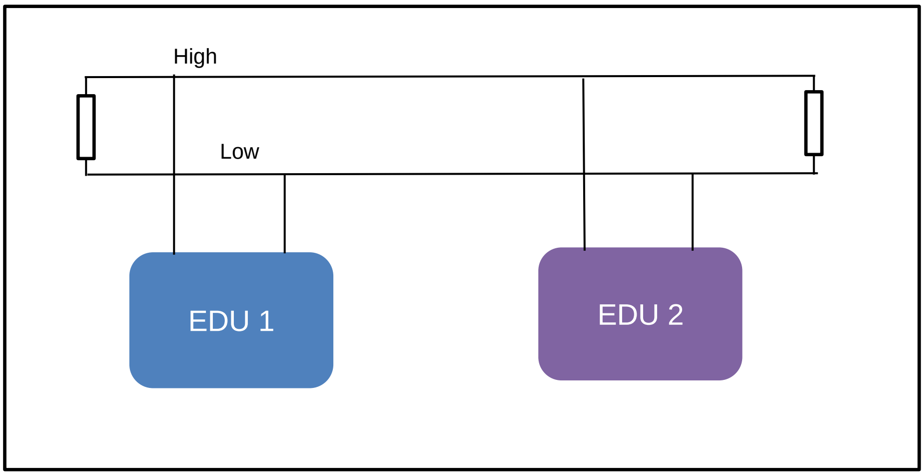

Figure 15. Two EDUs connected together via CAN bus.

5 IoT System

5.1 IoT Overview

Internet of Things (IoT) is a network of devices or "things" that are connected to each other over the internet in order of transferring and receiving data among others. A practical example for IoT is a smart home, which can connect all home appliances such as refrigerator, dish washer, TV … etc, to the internet and share the data with the home-owner via mobile app or web page or any suitable platform.

The term "internet of things" was initially mentioned for first time by a British technology pioneer Kevin Ashton of Procter & Gamble in 1999 while presenting RFID as a basis of Internet of things [28].

Nowadays, IoT system has become one of technologies that are developed rapidly. According to McKinsey Global Institute, specialists expect in 2025 will be more than 60 billion of IoT device owned in worldwide that there will affect to the economic by $11.1 trillion per year [29].

5.2 IoT Architecture

Due to a great variety in implemented technologies of IoT, there is no certain architecture of IoT. However, simple design of IoT system can present the basic idea of IoT work and its architecture. Furthermore, it explains the data transferring from the device to end destination to be viewed. Figure 16 shows the path of transferred data in blocks of IoT system.

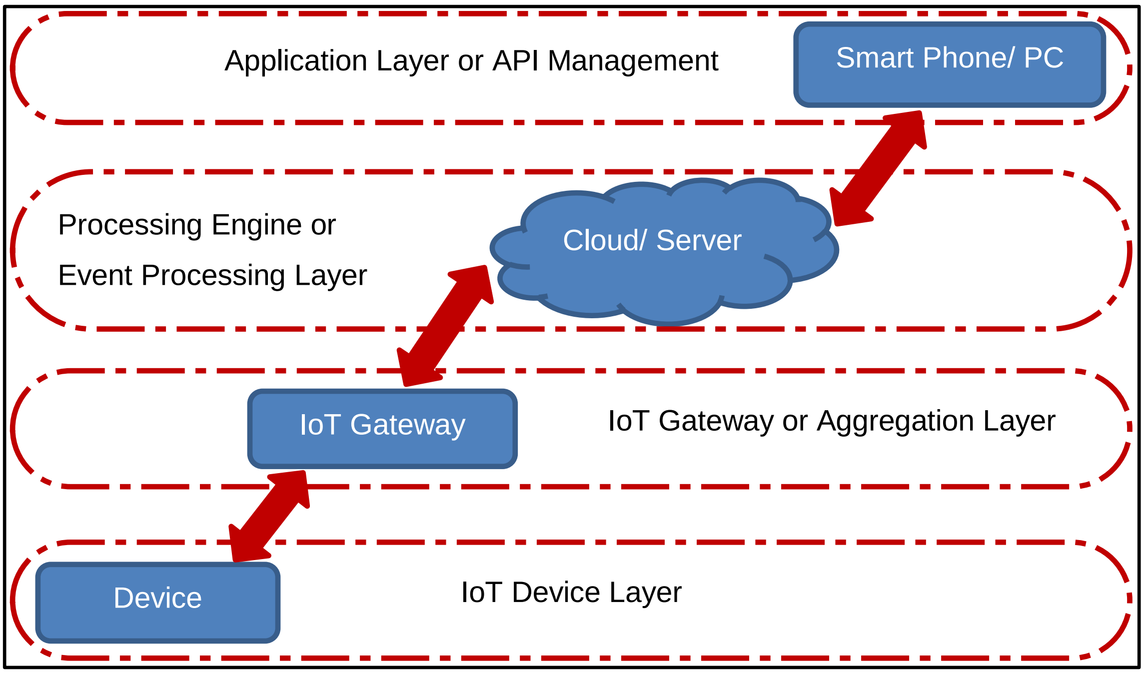

Figure 16. IoT architecture [30].

IoT architecture can be simplified into four main significant layers:

1. IoT Device Layer: includes a sensor or more that collect data from surrounding environment, then send it to gateway.

2. IoT Gateway or Aggregation Layer: convert the received data to digital packets, then send packets to the cloud or data center wirelessly over a medium of communication such as Wi-Fi, BLE, … etc.

3. Processing Engine or Event Processing Layer: include Cloud or Server that used to manage and store the acquired data.

4. Application Layer or API Management: includes Smart Phone or PC which request the stored data, then review it graphically.

5.3 IoT Boards

Many devices can be used for representing IoT system. It can be chosen according to the required performance, such as the number of GPIO pin, cost, and other features.

Table 3 shows the most popular IoT microcontrollers with its most important technical specs.

Table 3. Most important IoT boards [31].

Board Name	Microcontroller	Memory	Interfaces	I/O Pins	Price
Arduino Uno Rev3	ATmega328P	32 KB flash, 1 KB EEPROM, 2 KB SRAM	Wi-Fi, UART, I^2C, SPI	6 PWM, 14 digital, 6 analog, USB, Ethernet RJ45	~23$
ESP32	240MHz, Xtensa 32-bit LX7	2 MB PSRAM, 320 KB SRAM, 16 KB SRAM in RTC	Wi-Fi, Blue-tooth, BLE, UART, I^2C, I^2S, SPI	46 GPIO, 18 ADC, 2 DAC	~22$
ESP8266	80MHz, L106 32-bit RISC	4 MB flash, 32 KiB instruction, 80 KiB user data	Wi-Fi, BLE, UART, I^2C, I^2S, SPI	16 GIPO, 11 digital, 1 analog	~19$
Particle Photon	120MHz, STM32F205 ARM Cortex M3	1 MB flash, 128 KB RAM	BLE, Wi-Fi, UART, I^2C, SPI	18 GPIO, 8 digital, 6 analog	~19$
Raspberry Pi	1.2 GHz, ARMv8 CPU	1 GB RAM	Bluetooth, BLE, Wi-Fi, UART, I^2C, SPI	40 GIPO, Full HDMI, Micro-SD card slot, 4 USB	~35$
Giant Board	500 MHz, SA-MA5D2 ARM Cortex-A5	128 MB DDR2	Wi-Fi, UART, I^2C, SPI	4x16 bit PWM, 6x12-bit ADC, Mi-cro-SD	~28$

In this project, a Particle Photon is selected as an IoT board that transfer data over Wi-Fi due to its superior characteristics which are represented in low power consumption, small size, and easy to use. Moreover, it was available in the Metropolia University of applied sciences lab.

5.4 Cloud Services

Cloud is a virtual structure that offers some of computing services over the internet, such as servers, data storage, databases process, networking, software, analytics and intelligence as presented in figure 17.

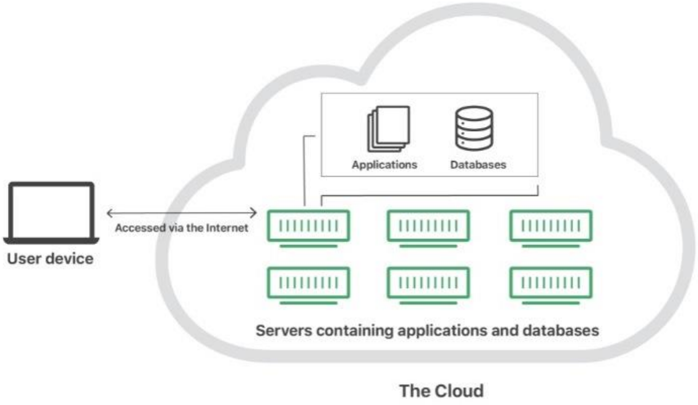

Figure 17. Cloud System [33].

Comparing to other data processing systems, Cloud has superior advantages that makes it on priority selected by IoT system: lower cost, fast enough in processing data, ability to reach it globally, high security, productivity and reliable.

5.4.1 Types of Cloud Hosting

The cloud can be divided into three main types according to the type of hosting: a public cloud, private cloud and hybrid cloud [32].

- Public Cloud: it is owned and managed by a third-party cloud service provider, who provides its own computing services such as servers and online data storage. The user can access to these services and manage its account through a web browser. Microsoft Azure and Google Cloud are examples of a public cloud, where cloud providers own and manage all the hardware, software, and other supporting infrastructure.

- Private Cloud: it is exclusively dedicated by an organization or company. It can actually exist in the organization's data center within the internal network. Also some organizations pay to another companies, like third-party service providers for their cloud hosting. Users are selected within the organization to access into cloud services instead of the general public. The maintenance process of services and infrastructure are being done on a private network.

- Hybrid cloud: it is an integration of public and private clouds, which are linked together in order to allow sharing data and applications between each other. Through merging feature, the hybrid cloud provides more business flexibility, more deployment options and helps improve existing infrastructure, security, and compliance.

5.4.2 Types of Cloud Services

Nowadays, cloud services become increasingly important in the business field. The cloud can be divided into four main categories according to services that are provided to the user [32]:

- Infrastructure as a Service (IaaS): it is considered as the simplest category that can be rented from a cloud service provider. In return, the cloud service provider offers infrastructure servers, virtual machines (VMs), data storage, networks, operating systems depending on a pay as it goes basis. Microsoft Azure, Google Cloud Platform and Amazon Elastic Compute are some examples of IaaS.

- Platforms as a Service (PaaS): provides a demanding environment for developing, testing, delivering, and managing software applications. A PaaS is custom designed for developers to create web or mobile applications easier and faster, without worrying about setting up or managing the underlying infrastructure of servers, data storage, network and database infrastructure which needs to develop continuously. Windows Azure, Blynk and Google App Engine are examples of PaaS.

- Serverless Computing: it is based on Function as a Service (FaaS) which focuses on saving time by allowing cloud platform implement application functionality without caring of managing the servers and infrastructure. The cloud provider is responsible to manage the setup procedure, capacity planning, and server administration. Serverless architectures are highly scalable and event-oriented, using other services only when a specific function or trigger occurs. IBM Cloud Functions is an example of Serverless Computing.

- Software as a Service (SaaS): is a way to access a software application over the Internet on demand, which is usually on a subscription basis. The cloud provider hosts and manages the software application and core infrastructure, and carries out maintenance tasks, such as upgrading on software and patching on security. Users connect to the app via the Internet using a web browser on smart devices such as phone, tablet, or computer. Google Apps, Thingspeak and Cisco WebEx are examples of SaaS.

Figure 18 clarifies graphically the idea of services that is provided by Cloud in different categories.

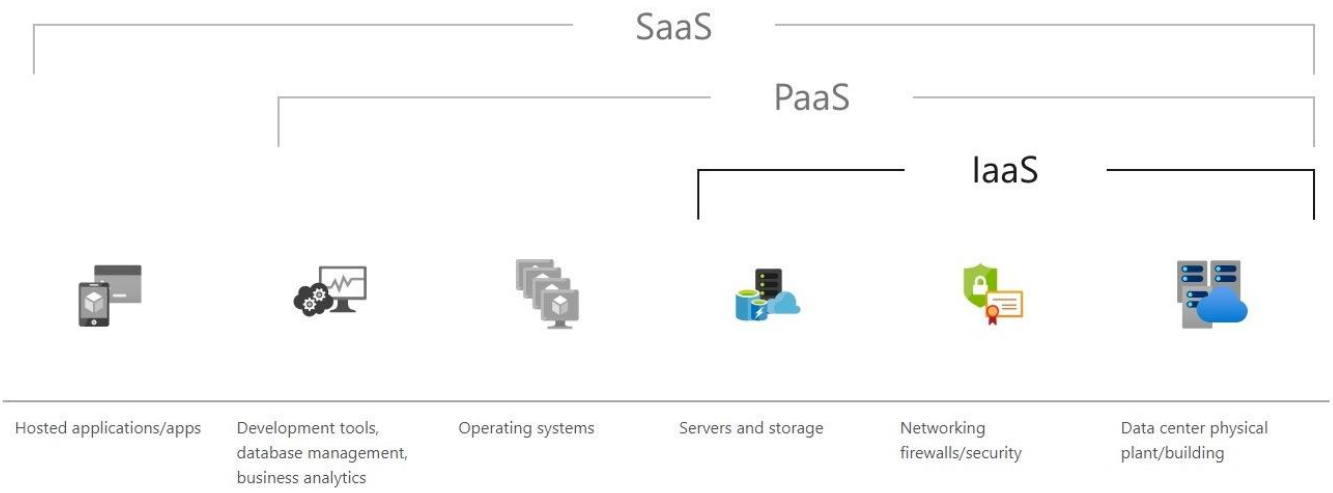

Figure 18. Types of Cloud services [32].

6 Hardware System

The selection of hardware system had been chosen in another thesis by the designer Yonas Gebreyesus which explained in more details the reason of each device [44]. What was added to this section, was only a device that works on transferring data over the internet in order to visualize it in more convenient way. The hardware can be classified into four main devices that were connected to each other: Adafruit Feather nRF52840 Express, Accelerometer H3LIS33DL, Gyroscope ICM20649 and Particle Photon. Figure 19 shows the whole hardware system that was built to represent the prototype of Head Impact device includes IoT Wi-Fi Particle Photon [Appendix 2].

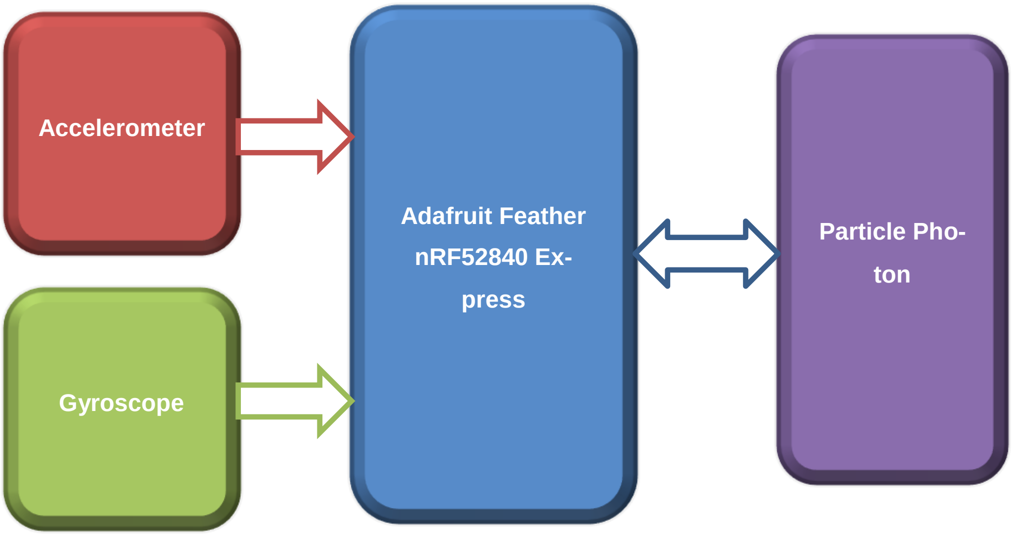

Figure 19. Hardware system of Head Impact with Particle Photon.

6.1 Adafruit Feather nRF52840 Express

This board is a new edition of Feather family that included BLE and supports IoT Bluetooth system. The most common advantage of Adafruit Feather nRF52840 Express is supporting CircuitPython language and Arduino IDE. An Adafruit was used to collect data from the Accelerometer and Gyroscope, then the collected data was sent over BLE to visualize it in Adafruit app "Bluefruit Connect". Figure 20 shows Adafruit Feather nR52840 Express microcontroller.

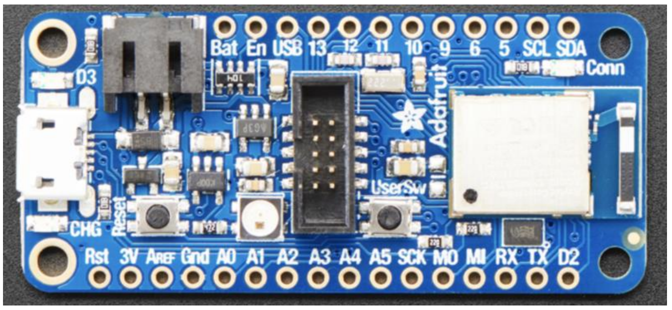

Figure 20. Adafruit Feather nRF52840 Express [35].

The technical features of the Adafruit Feather nRF52840 Express are listed below [34]:

- ARM Cortex M4F running at 64MHz
- 1MB flash and 256KB SRAM
- Native Open Source USB stack - pre-programmed with UF2 bootloader
- Bluetooth Low Energy compatible 2.4GHz radio
- Up to +8dBm output power
- 1.7V to 3.3V operation with internal linear and DC/DC voltage regulators
- 21 GPIO, 6 x 12-bit ADC pins, up to 12 PWM outputs (3 PWM modules with 4 outputs each)
- Pin #3 red LED for general purpose blinking, NeoPixel for colorful feedback
- Power/enable pin
- 4 mounting holes
- Reset button
- SWD connector for debugging
- Works out of the box with all of our Adafruit Feather Wings! (Even the UART-using ones like the GPS FeatherWing)
- FCC / IC / TELEC certified module

6.2 Accelerometer H3LIS33DL

Accelerometer sensor is a device that can measure linear acceleration, linear motion, tilt, and vibration, thus why it fits to use in concussion detection application. H3LIS33DL is a 3-Axis linear accelerometer that means it can detect changes in linear motion in three dimensions x, y and z. The measuring unit can be written in $\mathrm{m/s^2}$ or in G-Forces (g) where the value of 1g on the Earth is equal to gravity $9.8\ \mathrm{m/s^2}$. Figure 21 shows the H3LIS33DL sensor that has used in the project.

Figure 21. Accelerometer H3LIS33DL sensor [36].

The core element of this sensor is a MEMS accelerometer which is typically formed by proof mass and micro-sized capacitive plates internally. Some of these plates are fixed, while others are flexible to move between these plates according to the displacement of mass. Movement of plates occur difference in capacitance or an imbalance in the capacitive half bridge which can be amplified to produce a voltage proportional to the acceleration [37]. Figure 22 shows the structure of MEMS accelerometer and the work basic idea.

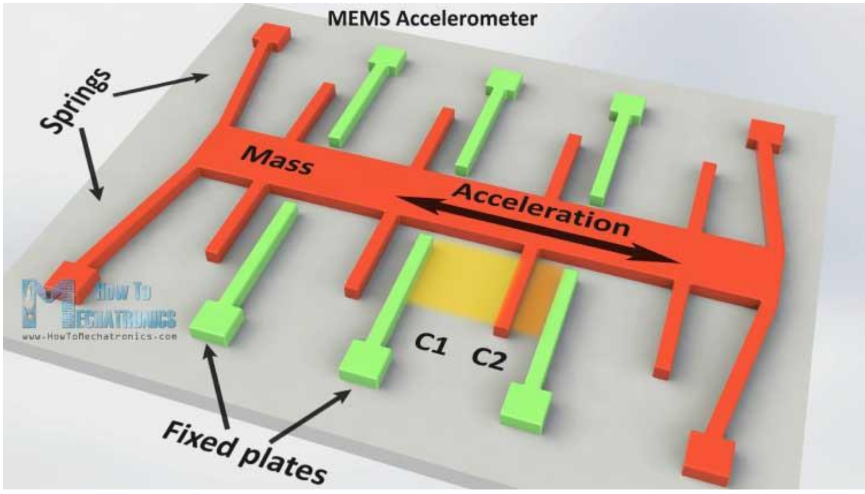

Figure 22. The basic structure of MEMS accelerometer [39].

H3LIS33DL accelerometer sensor has the following features as mentioned in datasheet [37]:

- Voltage Supply 2.16 V - 3.6 V.
- Low-voltage compatible IOs, 1.8 V.
- Ultra-low power consumption down to 10 µA (low-power mode).
- ±100g/±200g/±400g dynamically selectable full scales.

- I^2C/SPI digital output interface.
- 16-bit data output.
- Sleep-to-wakeup function.
- 10000 g high-shock survivability.
- ECOPACK®, RoHS and “Green” compliant.
- Temperature range -40 - +85 °C.

6.3 Gyroscope ICM20649

The ICM20649 consists of three different MEMS gyroscopes, which can detect the rotation of X-, Y-, and Z- Axes. Gyroscope is a device that can measure angular rotation or angular motion by means of Coriolis Effect which generates a force that moves the mass due to changes occur with velocity (V) and external angular rate (Ω). The value of displacement of mass is directly related to angular rotation. That means when gyroscope is rotated in different angular motion, the Coriolis Effect causes a vibration which can be detected by changing in capacitance values. This value can be amplified, demodulated and filtered to produce a voltage that is proportional to the angular rotation. The voltage is digitized by using 16 bit ADCs to sample each axes. The full scale dynamic range or angular rate range of ICM20649 is ±500, ±1000, ±2000, or ±4000 degrees per second (dps) [38]. Figure 23 shows the structure of MEMS Gyroscope and the work basic idea.

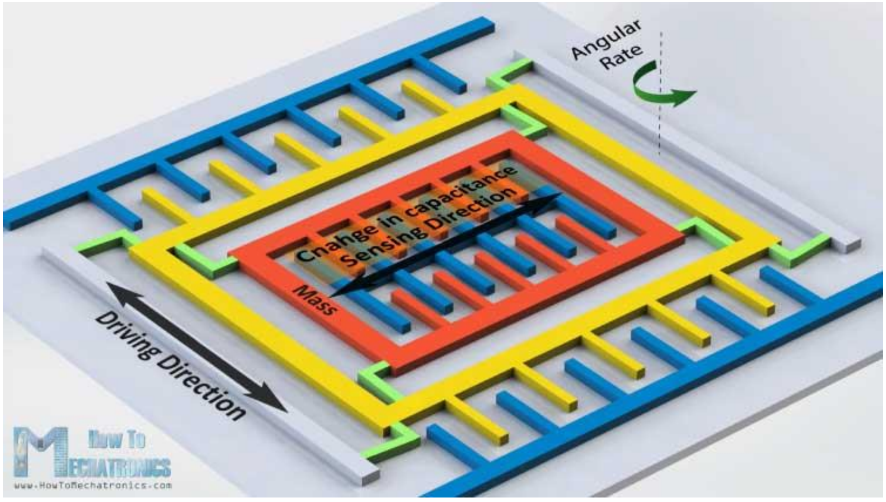

Figure 23. MEMS of Gyroscope [39].

Gyroscope ICM20649 sensor has the following features as mentioned in datasheet [38]:

- 3-Axis gyroscope with programmable FSR of ±500 dps, ±100 dps, ±2000 dps, and ±4000 dps.
- 3-Axis accelerometer with programmable FSR of ±4g, ±8g, ±16g, and ±30g.
- User-programmable interrupts.
- Wake-on-motion interrupts for low power operation of applications processor.
- 512-byte FIFO buffer enables the applications processor to read the data in bursts.
- On-Chip 16-bit ADCs and Programmable Filters.
- DMP Enabled:
  - SMD, Step Count, Step Detect, Activity Classifier, RV, GRV
  - Calibration of accel/gyro/compass
- Host interface: 7 MHz SPI or 400 kHz I^2C
- Digital-output temperature sensor
- VDD operating range of 1.71V to 3.6V
- MEMS structure hermetically sealed and bonded at wafer level
- RoHS and Green compliant

Unfortunately, the Gyroscope for some reason did not provide any result in the prototype, so its data was not transferred, and therefore no relevant result was shown on platforms.

6.4 Particle Photon

6.4.1 Overview and Features

The Particle Photon is a prototype hardware that works on Internet of Things over Wi-Fi. It mainly consists of ARM Cortex M3 microcontroller and a Broadcom Wi-Fi chip packed together in tiny thumbnail-sized module called PØ. Figure 24 shows the Particle Photon [40]:

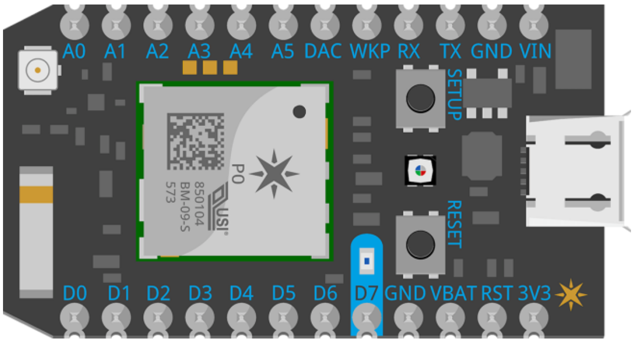

Figure 24. Particle Photon [40]:

The technical features of the Particle Photon are listed below [40]:

- Particle PØ Wi-Fi module [Appendix 1]:
    - Broadcom BCM43362 Wi-Fi chip.
    - 802.11b/g/n Wi-Fi.
    - STM32F205RGY6 120MHz ARM Cortex M3.
    - 1MB flash, 128KB RAM.
- On-board RGB status LED (ext. drive provided).
- 18 Mixed-signal GPIO and advanced peripherals.
- 6 analog input pins (A0 – A5) can read voltages.
- 8 digital pins (D0 – D7) can be configured as either inputs or outputs.
- 2 SPI, 2 UART and an I^2C.
- Open source design.
- Real-time operating system (FreeRTOS).
- Soft AP setup.
- FCC, CE and IC certified.

Due to IoT Wi-Fi board features, Particle Photon has been added to the Head Impact prototype as a convenient solution that makes the device more flexible, longer distance reachable and easier to access.

6.4.2 Power Consumption Modes

Photon can be powered by Micro-USB or directly over the VIN pin, but in this case it is needed to consider that the voltage should be regulated between 3.6-5.5VDC. When Photon is powered by USB, VIN will provide an output of 1A and 4.8VDC, due to existence of Schottky diode between V+ of USB and VIN. Pin 3V3 can also be used as an output with overhead limits of 100mA. However, the current in Deep sleep mode typically with the lowest limits of 80uA [40].

Power consumption is an essential advantage feature for a microcontroller. Photon contains a processor of STM32F20x family, which has three low power modes depending on three variables short time in startup, lower power consumption and wakeup [41]:

- Sleep mode: in this mode, only CPU is stopped while all other circuits are working properly. CPU can work again when an interrupt happens.

- Stop mode: it is considered as lower power consumption mode. As it stops the work of some chip components such as the PLL, crystal oscillator and all clocks in 1.2V domain, but keeps the contents of SRAM and registers. The voltage regulator can be adjusted on normal or low power consumption mode. The device is woken up from the stop mode as soon as receives any wakeup signal from the Ethernet, or the USB, or other wakeup components.

- Standby mode: it is considered the lowest consumption power, as it is switched off some chip component the PLL, crystal oscillator and all clocks in 1.2V domain. It also loses contents of SRAM and registers, except the registers in the backup domain and the backup SRAM. The device is gone out of Standby mode as soon as receives an external reset or other signals.

6.4.3 Particle Cloud

Particle company offers a public and private cloud that can be used to manage the IoT device. It makes Particle devices to communicate in secure and efficient way. Public cloud is available for subscribers free of charge, but the received data is deleted every 60 seconds [43].

For data security, it is necessary to create initial handshaking process using AES over TCP. Once the device connects to the cloud, all devices on Wi-Fi networks can be reached without needing to make any custom port forwarding or even changing in firewall [42].

Particle Publish sends data to external servers using 150-200 bytes of data. When a TLS / SSL connection is established directly to an external server, the device uses 5000 bytes of data for each piece of data sent including the TLS/SSL handshake data. Because TLS/SSL authentication is done off the device using a webhook or events stream that are sent by server [42].

6.4.4 Connect Adafruit to Photon

Different values of linear and rotational acceleration are collected by Adafruit through Accelerometer and Gyroscope sensors respectively. Then the collected data is transferred from Adafruit microcontroller to Photon microcontroller using UART communication technology, as the transferred data is small size, the communication UART is reliable, available in both microcontrollers, and easy to install, since it needs only two signal wires to be connected and GNDs. Figure 25 illustrates the UART connections were installed in practical prototype.

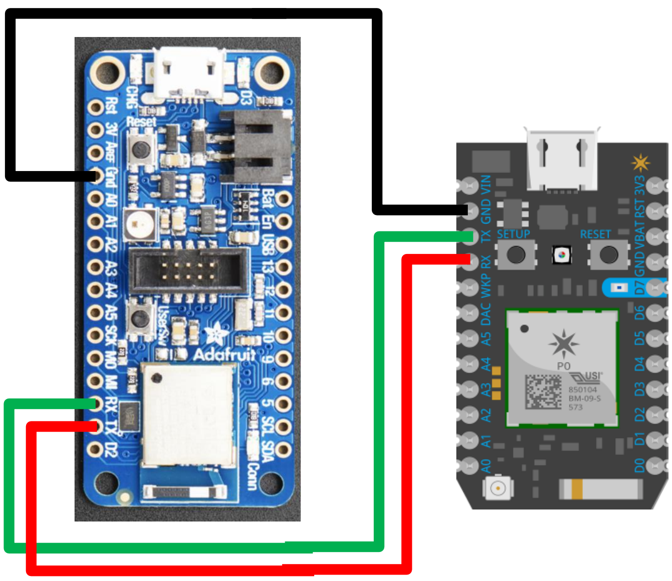

Figure 25. UART connection between Adafruit and Photon [35][40].

7 Software System

7.1 Adafruit Feather nRF52840 Express

Previously, the software of Adafruit microcontroller has been installed by another student Nargiza Deidieva as a thesis work [45]. The software was able to collect the data from Accelerometer, then sent it wirelessly over Bluetooth protocol in order to be received by any smartphone using "Bluefruit Connect" app, which is customized by Adafruit company. Unfortunately, Gyroscope functionally wasn't given any data.

A simple modification happened to the software which included re-editing and adding some commands to make the Adafruit Feather allow sending data to the Particle Photon. Additionally, a calibration code has been implemented for Accelerometer in order to fit the position where the device has been located. Figure 26 shows values of X, Y, and Z axes that had given by calibration software where the device assumed to put on a flat table.

```
please turn Y- up
start will be in 5 seconds
start will be in 4 seconds
start will be in 3 seconds
start will be in 2 seconds
start will be in 1 seconds
calculating ...
calculate success
please turn X+ up
start will be in 5 seconds
start will be in 4 seconds
start will be in 3 seconds
start will be in 2 seconds
start will be in 1 seconds
calculating ...
calculate success
please turn X- up
start will be in 5 seconds
start will be in 4 seconds
start will be in 3 seconds
start will be in 2 seconds
start will be in 1 seconds
calculating ...
calculate success
adjust value of X axis is -189
adjust value of Y axis is -161
adjust value of Z axis is 611
note: these data can be used in H3LISDL_Demo sketch
```

Figure 26. Accelerometer X, Y, Z values on a flat table.

7.2 Particle Photon

Particle Photon has been coded to act as a gateway IoT Wi-Fi device by receiving data from Adafruit microcontroller and sending it to Particle Cloud. The data is stored for a moment, then it is transferred again through HTTP or webhook to a platform or through designed HTML page in order to monitor the data graphically.

Simply, transmission process can be done by following three steps:

7.2.1 Transfer data from Adafruit to Photon

Adafruit has been connected to the Particle Photon via the UART port, where data can be transferred safely. The transferred data was the data that was collected by the 3-axis Accelerometer sensor, as the Gyroscope sensor did not give any result.

In fact, the process of transferring data was done by making some modifications to the software to make the data sent by Adafruit as a stream packet through serial port and received it by Photon.

However, to ensure that data was sent successfully, Putty software has been installed. The arduino software was used to show up the sent data by Adafruit, while Putty was used to show up the received data by Photon, as shown in Figure 27 where data has been sent and received successfully. The data was the Accelerometer data in the X, Y, and Z axis separated with comma.

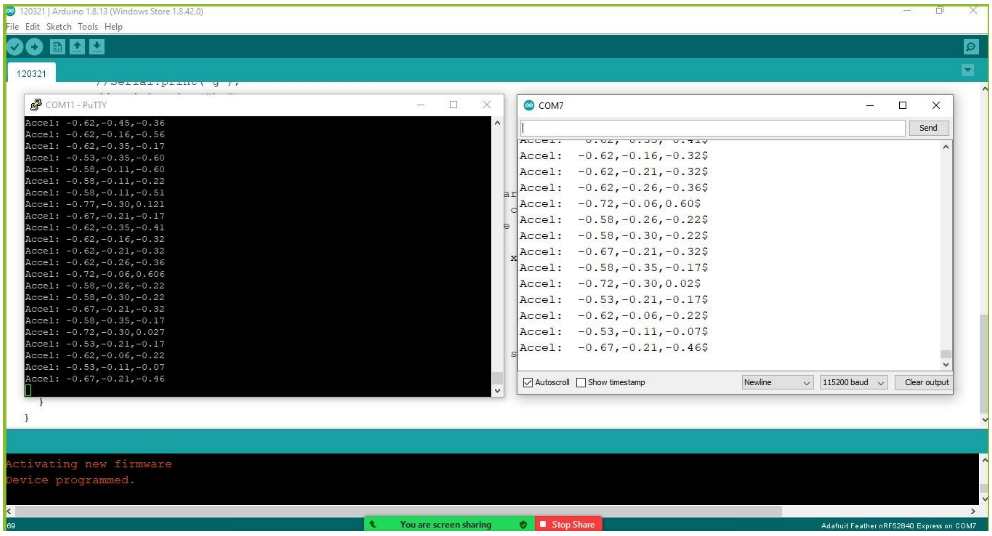

Figure 27. Transferred data from Adafruit to Photon.

7.2.2 Transfer data from Photon to Cloud

The received packet by Photon can be parsed into data, then the splitted data transferred again to the Particle Cloud where it can be viewed in Events part. Events in cloud can be stored for 60 seconds as a maximum duration for free membership, which is fairly enough to redirect the received data to a desired online platform. Figure 28 shows 3-axis Accelerometer (X, Y and Z) data while passing through Particle Cloud.

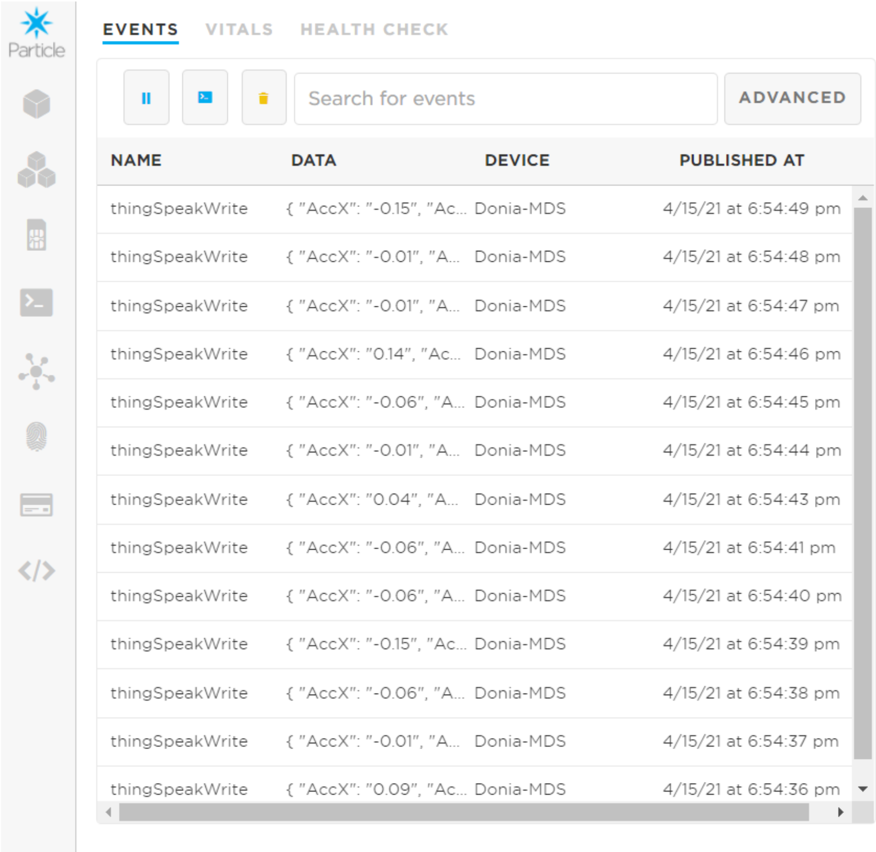

Figure 28. The data on Particle Cloud.

7.2.3 Transfer data from Cloud to Platform

The transferred data from Cloud to a platform server can be done using webhook, or HTTP protocol. A webhook is used commonly to deliver data from a system app such as Cloud to a web page address or user app, whereas HTTP is used to make a connection between the server and HTML page in order to be viewed by the user.

7.3 Platforms

Three platforms have been created during practical work of this thesis: Thingspeak, Blynk, and webserver.

7.3.1 Thingspeak

Thingspeak is one of the most commonly recommended by Particle team as an open source IoT analytics platform using MATLAB simulator. It can be used to visualize the posted data by devices instantaneously over webhook that carries data instantly as HTTP request (POST) to Thingspeak application. That means you view data as it happens immediately.

Simply, as soon as packet arrives to Particle Photon, it sends the splitted data directly to Particle Cloud, which acts as a routing device. A webhook was built to take the splitted data (X, Y and Z) from the Cloud over JSON transport protocol and sent it to Thingspeak website in order to be viewed graphically in channels.

The prototype was located on a flat table and was exposed to a slow movement in various directions. The graph in channels were responding to some movement resulting changes in axes values X, Y and Z positive or negative according to the direction of movement.

Figure 29 shows X, Y and Z axes values distributed in three channels separately for period of 8 minutes. These values have been taken by Accelerometer only, which were representing the values of linear acceleration for player's head.

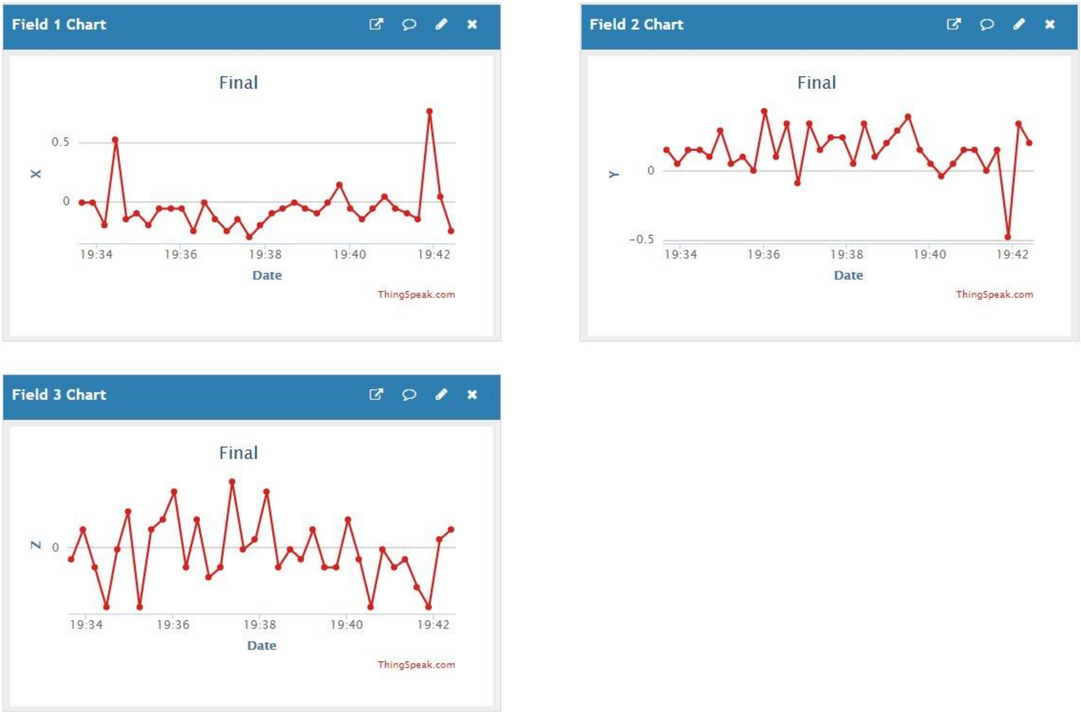

Figure 29. Accelerometer data on Thingspeak

According to Thingspeak website options, it was mentioned that Thingspeak can update the arrived data every few seconds for free subscribed members, but it can also offer updates every one second as a minimum time period for prepaid subscribed members, which might be not useful enough for a project like Head Impact as it needs at least few updates per each single second to assess the concussion accurately.

7.3.2 Blynk

Blynk is a platform that is designed to work with iOS and Android mobile applications over the internet to control microcontroller, such as Arduino, Particle Photon,.. etc. It is highly recommended by amateurs and professionals where it is possible to view, store and visualize the received data. Moreover, it can control the microcontroller remotely.

In practice, Particle fully supports Blynk platform through the existence of Blynk library that makes the connection between Particle Photon and Blynk server is easier. As soon as Blynk server is begun, the transferred data from Photon to Blynk app is handled, so that the received data is viewed on Blynk platform.

To begin with the Blynk platform, it is necessary to have Blynk application that is uploaded on mobile through which designs Blynk application for viewing data on chart. A

Blynk application TEST1 was designed to receive the splitted data (X, Y, and Z) using virtual pins, which were also added as a function instruction on Photon code. Figure 30 shows three different color lines representing the received data (ACCX, ACCY and ACCZ) by Blynk app. The prototype was located on a flat table and was exposed to a slight movement in various directions. The graph was responding to any change in movement instantaneously resulting change in lines ACCX, ACCY and ACCZ according to the direction of movement. Thus, it is considered an assessment of head movement when the prototype put in a helmet that moves according to the movement of the player's head.

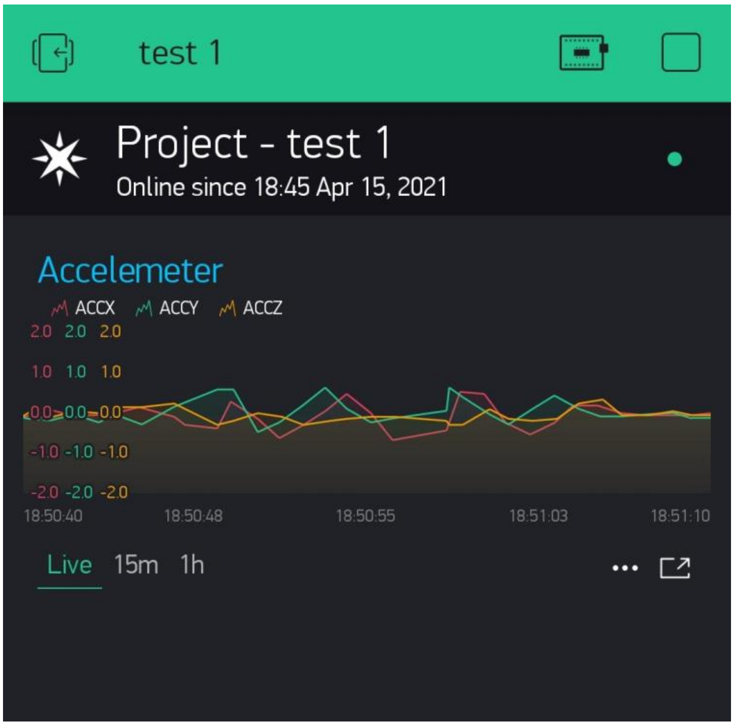

Figure 30. Accelerometer data in Blynk platform

Comparing to Thingspeak platform, Blynk is producing more effective timing response since it can update the received data every 100 milliseconds. It can also save the received data as csv file. Unfortunately, the chart can be displayed only on smartphone Android or iOS system. It can also be displayed on computer, but under emulator software such as using BlueStacks, YouWave … etc.

7.3.3 Webserver

A special platform has been designed to satisfy the requirements of the project. This platform was composed of webserver and static page using HTML, where both were uploaded to Photon. The webserver allowed receiving the sent data by Adafruit and saving it in a buffer temporarily till it was sent to HTML static page through HTTP transportation protocol. The IP address of HTML page was given to user by webserver through Cloud.

A static page has been designed to view the received data instantaneously in a graphical way. The chart has been taken from a webpage https://code.highcharts.com as a free data visualization graph, which can offer different types lined or scattered. In addition, the time axis has been adjusted accordingly to the data time, while the value of the acceleration was given according to the value of acceleration in X, Y and Z axes. Figure 31 shows the designed HTML static page before connecting to webserver.

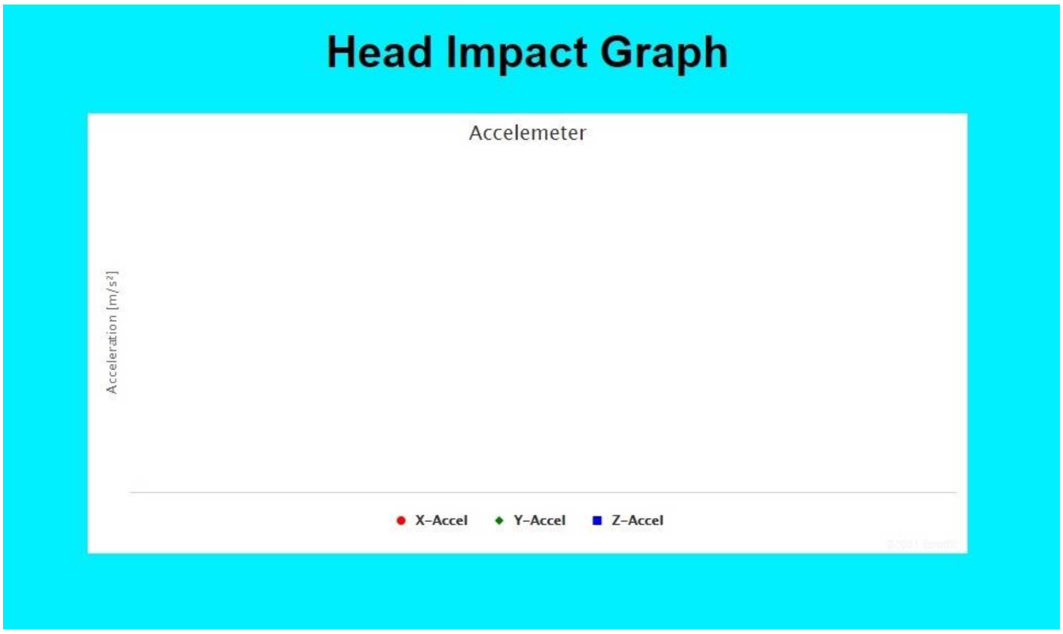

Figure 31. The designed HTML static page

Webserver was able to view data on HTML chart every 100 nanoseconds at its best case, but for testing purpose it has been built to receive and send data every 100 milliseconds. The received data (X-Accel, Y-Accel and Z-Accel) by HTML can be represented into three various color lines as shown in figure 32. The prototype was placed on a flat table and exposed to two fast hits resulting these two fast response values (one was negative colored blue, while other was positive colored red triangles).

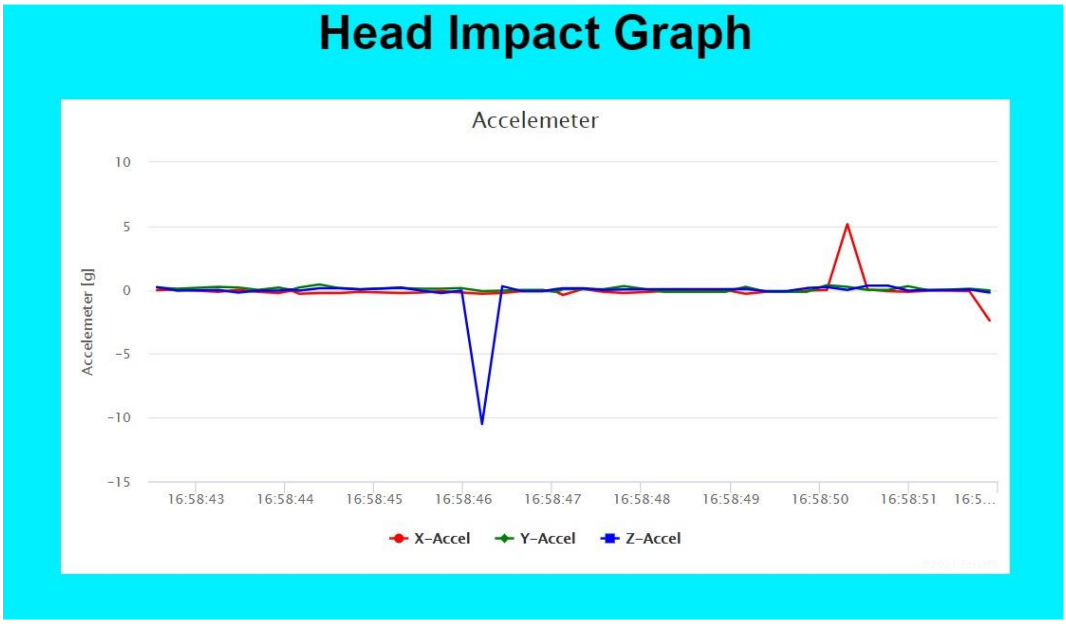

Figure 32. Accelerometer data in HTML via Webserver platform

Additionally, chart offers an option that makes it easier for the user to follow the graph. It can view the received data (X-Accel, Y-Accel and Z-Accel) separately through double click on the unwanted legend X-Accel or Y-Accel or Z-Accel to hide it. Figure 33 shows the received data are viewed separately X-Accel or Y-Accel or Z-Accel.

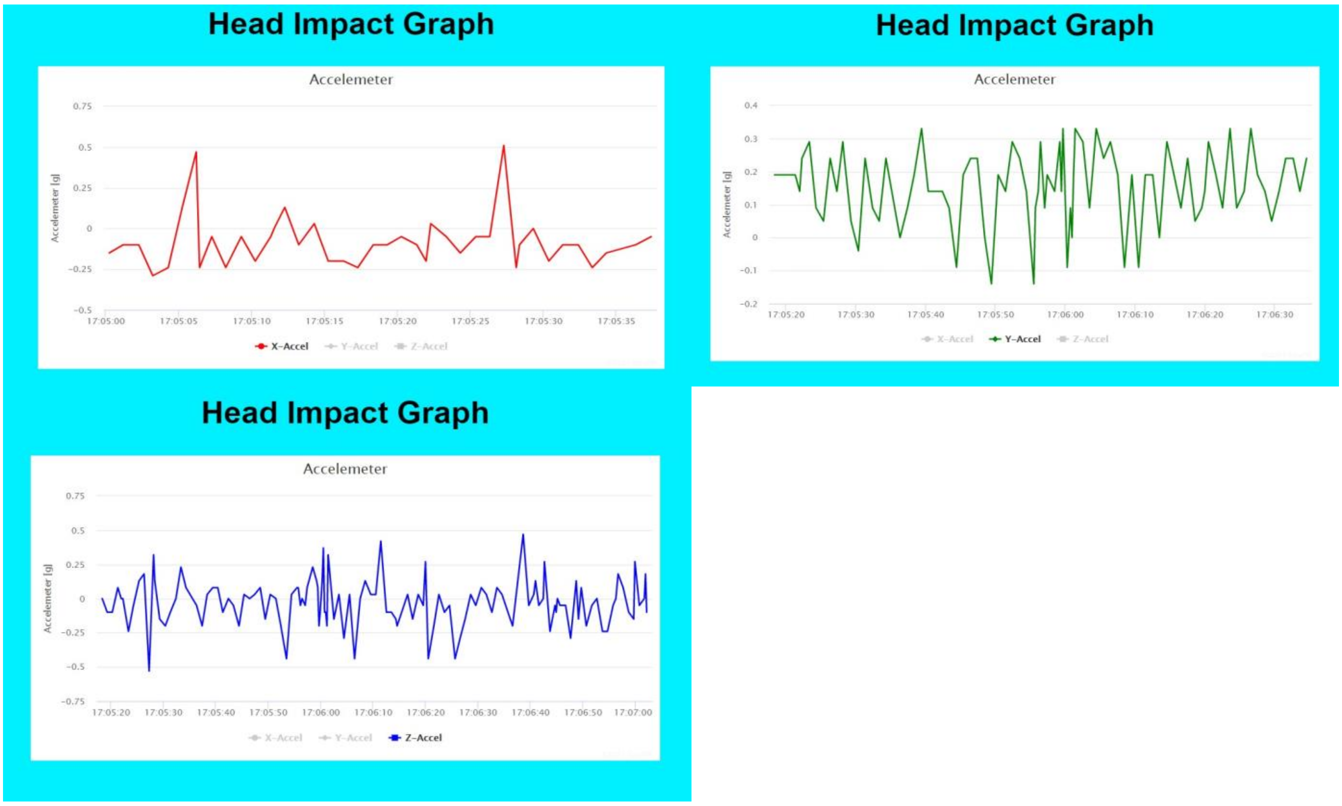

Figure 33. Viewing the received data separately

However, previous graphs show that the device was very sensitive as the data changed rapidly around the same value, so it needed to be filtered in order to get a more appropriate graph.

Making a comparison between webserver and Blynk platform, it has shown that webserver was more powerful in timing response than Blynk, since it can provide a faster response to the data approximately of 100 nanoseconds at its superior cases. However, webserver cannot process and store the received data.

8 Conclusion

To summarize, the goal of the thesis work was to find a transmission way to transfer the prototype data of Head Impact in order to receive it and view data in more practical and convenient way. An IoT system has been chosen to the prototype in order to handle and transfer data over Wi-Fi communication technology, which made the prototype able to broadcast the data to wider area, due to the wide spread of internet networks and moderate consumption to the power.

The data was successfully transferred from the prototype of Head Impact device to the Photon via the UART circuit, which is sent as serial packets, then packets are splitted into data and sent to the Photon to the cloud, where the cloud is delivered to a platform to display it graphically. There were several platforms for displaying data:

- Thingspeak platform: was not that functional platform, because it provides minimum time response to display the data in one second.

- Blynk platform: was kind of estimated platform, as it offers a minimum time response of 100 milliseconds to display data instantaneously, however, it cannot be viewed on a computer.

- Webserver platform: is considered the best platform that is used for the prototype, since it provides a minimum time response of 100 nanoseconds in its best case. In addition, it works on all smart devices such as computers, mobile devices and others within the network.

Future development can be done to make the project more distinguished and effective through adding a filter to the system in order to display data smoothly, making it easier to be followed and diagnosed. Moreover, it would be better to find a solution for data storage in order to save the head's evaluation data in case that needs to view it later.

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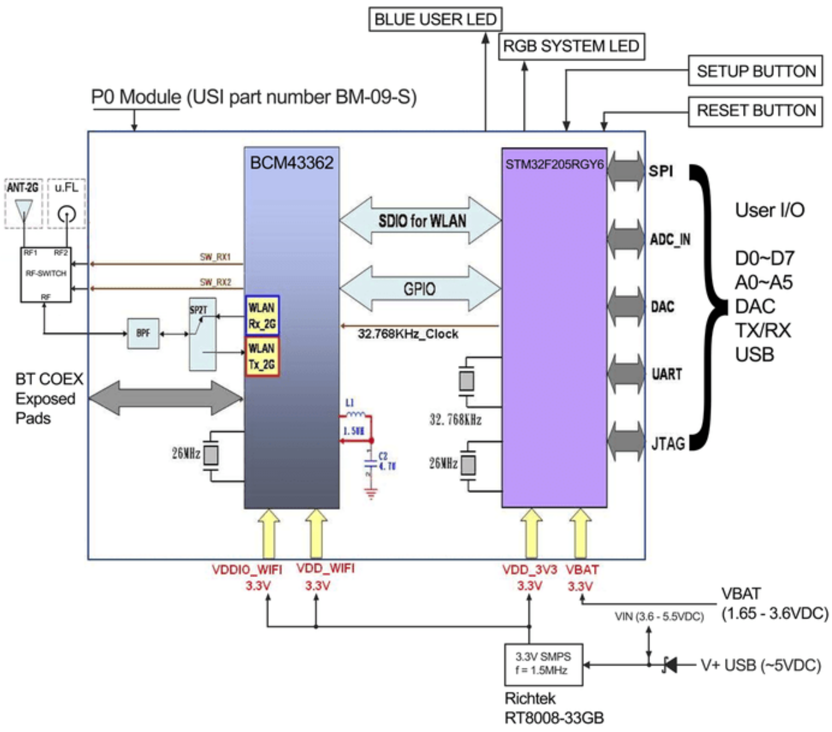
Particle PØ Wi-Fi module

This Figure shows a diagram of Particle Photon's main components: Processor, Wi-Fi, regulator, data buses, … etc.



The Prototype of Head Impact

After final work has been done, the prototype is appeared as shown in the following Figure.

The device can work in two modes: an IoT Bluetooth wireless system and IoT Wi-Fi wireless system.