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Head Impact Device in Contact Sports

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Concussions in contact sports are among the most prevalent injuries in sport such as American football, ice hockey, boxing, in addition to many others considered between high impact sports. The majority of concussions is unrecognized and undiagnosed. If the possibility of concussion to every athlete could be measured in real-time, coaches and medical professionals might possibly be alerted to any possible injuries as soon as they occur, and medical help can be provided right away.

This thesis work aimed to develop a new version of the head impact device prototype, and in addition, to study the wireless communication of the head impact sensor. Features needed to be considered in the development process of the device are the size, the cost, the data range, speed of data transmission, and the data storage to the cloud. The device needs to keep its old version features as to be a wearable device and capable to measure the linear and the angular acceleration.

The new version of the device prototype is to assess the magnitudes of the head impact which could cause concussion in real-time, and transfer the acquired data through Wi-Fi to the cloud and a mobile app. The acquired data will be utilized by medical staff to monitor and assess the head impact magnitudes.

The linear acceleration and the angular velocity were the measurements variables of the device. The development of the device took place in specifying the requirements, changing the hardware system to a modern version as well to implement the embedded software system. The tests were carried out using linear acceleration and angular velocity forces.

The results commensurate with the requirement target that was readied to develop the new version. The device prototype was successfully developed but more test on real player's data is needed for the accuracy and efficiency of the new version.

Keywords	Head impact measurements, Hardware system, Software Design, Wi-Fi, Internet of things, HITS device, Concussion.

Contents

List of Abbreviations

6DoF	Six Degrees of Freedom
BLE	Bluetooth Low Energy
BW	Bandwidth
CIoT	Cellular Internet of Things
CTE	Chronic Traumatic Encephalopathy
DEG/S	Degrees Per Second
GHz	Gigahertz
HIT	Head Impact Telemetry
HTTP	Hypertext Transfer Protocol
I2C	Inter-integrated circuit
IDE	Integrated Development Environment
IoT	Internet of Things
LPWAN	low-power wide-area networks
MBPS	Megabits Per Second
MCU	Microcontroller
MDS	Medical Devices and Services Finland
MEMS	Micro-Electromechanical Systems
MQTT	The Message Queuing Telemetry Transport

MS	Millisecond
mTBI	Mild Traumatic Brain Injury
PCB	Printed Circuit Board
RFID	Radio Frequency Identification
SPI	The Serial Peripheral Interface
TBI	Traumatic Brain Injury
UART	Universal Asynchronous Receiver/Transmitter
UARTS	Universal Asynchronous Receiver/Transmitter
USB	Universal Serial Bus
Wi-Fi	Wireless Fidelity

1 Introduction

The thrill of the sport is putting the most important part of the body at risk. Concussions in contact sports are among the most prevalent injuries in sport such as American football, ice hockey, boxing, in addition too many others considered between high-impact sports. The majority of concussions go undiagnosed and unnoticed. If the possibility of concussion to every athlete could be measured in real time, coaches and medical professional could be alerted to any possible injuries as soon as they occur, and medical help could be provided right away. Numerous new products nowadays concentrate only on the force applied to the head in these impacts, rather than how the impact affects other parts of the body. This method of data collection cannot reveal the results of head impacts on the inside of the body.

Ice hockey is one among the most common sports in Finland with the most concussion reports. Since most head impact measurements studies [2] were conducted in American football and less in ice hockey sports. Developing a comparable device that ice hockey players could wear within their helmets to monitor head impact accelerometers is necessary. As early diagnosis of concussion and determining the severity of the head injury, a device is indispensably required for the safety of the hockey players.

This thesis work describes the wireless communications as well as the development process of an old prototype that was developed by other two colleagues in the past two years to a whole new prototype. The purpose of developing the prototype is to monitor, measure and maintain the linear acceleration and rotational velocity of the cranium to warn the medical professional of any possible head injuries or concussions on athletes and players during contact sport or training.

The developed prototype of this thesis addressed the problem of ignorance in the effects of concussions during contact sports games by designing and developing a wearable system to be placed on the helmet of a sports player. That simultaneously tracks the acceleration and the magnitudes of head impacts that may result in concussion in the exact time and transfer the acquired data over Wi-Fi to the cloud and a mobile phone. The data sets are merged, and time stamped before being saved to cloud, where they can be retrieved later. The information of the data can later be accessed by a medical professional for measuring and evaluating the magnitudes of head impacts. The data will be saved in a datalog format, which makes it simple to parse for graphing or other purposes.

MDS Finland owner guided and supervised the progress of the device prototype. The MDS Finland company owns the device prototype. The device can assist in the early detection of concussions and the prevention of injury effects. The device would be important for measuring, assessing, and identifying the severity of a head injury.

2 Medical Devices and Services Finland

Medical Devices and Services Finland (or MDS Finland) is a specialist organization which was founded in 2015 and domiciled in Sipoo, Finland. MDS company was established to serve medical device manufacturers, distributors, and importers and the company main business area is Pharmaceutical Equipment and Supplies The company mainly produces quality and regulatory consultation services as well as product development for their clients. MDS Finland's main clients are medical devices start-up companies, hospitals, and individuals [1].

MDS company enable startup companies or projects in their early stages to enter the markets sooner, and in addition, to proceed their sales phase faster by reassessing the uses of their products and examining the product’s classification [1].

3 Theoretical Background on Brain Injuries

3.1 Traumatic Brain Injury (TBI)

TBI is known as a type of acquired brain injury to the head injury or to the penetrating head injury, caused by a blow or jolt, which results in interrupting the brain normal functioning [2]. This usually occur from striking the head through a car accident. It may also belong to an accidental fall or a stroke among athletes. Players during practicing sports or a match can also encounter head strokes. It is also associated with a military explosion or penetrating of the skull with sharp object. There are several different reasons behind traumatic brain injury. However, it is not always necessary to have a traumatic brain injury for a sufferer to hold skull fracture. Secondly, open head wound, or an un-consciousness are also not mandatory factors.

Traumatic brain injury consequences are very different from other injuries. Brain is considered as very complex and primary part of a human's body. It also represents who we are. A brain injury can impact our lives significantly and influences our personality. It can potentially cause physical, perceptual, social, psychological, and behavioural effects. Other results include ranges of full recovery to permanent impairment or even loss of life [3].

TBI indications could be minimum, medium, or high critical based on its area and size on the brain. TBI cases can be defined as follow [4]:

- Mild TBI case: An individual suffering from a mild TBI can be fully conscious or may encounter complete loss of consciousness ranging from couple of minutes or seconds. Headache, nausea, dizziness, blurred vision, or sleepy eyes, buzzing in ears, lack of concentration and focus are the other factors. Loss of thinking abilities is the other problem of mild TBI.

- Medium TBI case: Person with medium intensity TBI case seems to have changes in the brain functionalities that lasts longer than several minutes usually just after the trauma. These signs might be similar to a medium intensity TBI, but they do vanish completely, or it is possible to face even worse condition.

- High critical TBI case: Following a critical or serious TBI, a person can suffer a unexpected, prolonged duration of unconsciousness (coma) or amnesia that may also result in death or in irreversible trauma. Furthermore, it has the potential to cause a wide variety of long term or short-term changes in the functioning of brain activity.

High Contact sports are associated with elevated TBI injuries. The most common TBI injures associated with sports are the incidents of concussions which vary between mild to moderate cases. Therefore, this thesis work will focus on developing a prototype device that measures concussion mechanisms and the power of the head strike that occurs on the players during contact sport.

3.2 Brain Injuries in Contact Sports

Contact sports including rugby, American football, ice hockey, and boxing all have one thing in common i.e., causing severe impact on the bodies of sportsmen particularly brains. Athletes of different contact sports get concussions during practicing games which is basically a palpitation of the brain in the skull. When the impact occurs, the brain hits the bone wall sometimes. While doing it several times depending on the severity of the blow, ten percent of the cases concussion leads to a loss of the athlete’s consciousness at the moment of the impact.

A study [5] performed by researchers at Brigham Young University proposed that athletes of ice hockey have the highest rate of recurrent concussions at 21 with 20.1%. This is due to the high level of contact within ice hockey regulation. Recurrent concussions increase the likelihood that the concussive symptoms will persist at a long-term pace[]. Multiple concussions can add stresses and strains on the brain that are so extreme that the brain cannot return to its original form and functionality. This is analogous to increasing the strain on an object exceeding its elastic limit. This loss of form and functionality can result in longer-term consequences due to the structural and chemical balances of the brain being damaged after undergoing such extreme stresses. Strains with long-term symptoms include persistent and sudden mood changes with severe memory loss, chronic traumatic encephalopathy, chronic traumatic encephalopathy, or CTE [5].

Players of high contact sports are very often at high risk of being exposed to chronic traumatic encephalopathy (CTE) which is neurodegenerative disease. They are produced through repetitive head injuries mainly. It has been widely researched in the last decade for professional athletes. The effect on survivor's behaviour and health usually occurs later in the life. Many athletes with CTE faces developed symptoms in later stages of life after their athletic career. Experiencing behavioural and mood issues violence or dementia are other symptoms developed at later stages of life.

By minimizing the amount of head injuries sustained by players, protecting their brains from CTE can be a useful step. Allowing adequate time for complete recovery, having medical clearance before returning to everyday life and maintaining social lives while recovering can both help to prevent or reduce CTE's bad impacts [5].

Brain injuries do not recover the same way as other injuries do. Healing process is a type of physical healing that relies on mechanisms that are still unknown. Two brain injuries cannot be identical, because the consequences of two related injuries are very different. Indications can occur immediately or may take days or weeks to appear post injury. Another effects of brain damage are the individual's unawareness that he or she has suffered a brain injury.

3.3 Concussions

Concussion is recognised by a mild Traumatic Brain Injury (mTBI). It is a form of TBI that is induced by a knock, shock, or by body hitting. It suppresses the head and brain to significantly change rapidly. The brain can rebound around or twist in the skull, expanding and destroying normal brain cells while causing chemical changes in the brain and mental status [6].

Athletes in each of contact and non-contact sports are impacted with concussions repeatedly. Once an athlete is suspected of having a concussion either by the parent, coach, or athletic trainer they are removed from their sport or activity. Athletes are not permitted to return in this case. A physician trained in the evaluation and management of sports concussions should then evaluate the athlete. This evaluation process has been recognized as a very important step in the diagnosis and management of a concussion. Experts and players are subjected to increase their understanding of the hidden injury. The short-term effects of a concussion can produce additional problems or can be very unsafe when athletes return to game before they completely recover from a suspected concussion.

Athletes who experience physical symptoms of concussion may also face disorientation, dizziness, poor concentration, and mild to severe headache. Mostly people think that athlete can suffer from a concussion when they lose consciousness for prolonged time span. Well, this fact is not true because only ten percent of cases usually lose consciousness. While in most of the cases, suffering athlete do not lose consciousness [16].

High cases of concussions happen in contact sport while very few cases of athletes' concussions can be recognized at an early stage. Therefore, the aim of this work is to create a prototype device capable of measuring concussions, head strikes, and interpreting instant data on the magnitude of the strike to occur to avoid a concussion to facilitate the player for control and check-up.

Biomechanics of sport concussion is one way to prevent concussions which rely on understanding the medical issues related to sport concussion. Biomechanics is defined as how we apply physics to the human's functionalities and movement. Some important physics terms include understand our velocity and acceleration. Velocity is based on extent of objects movement in a certain amount of time. Acceleration is extent of velocity change in a certain amount of time. Figure 1 illustrates the diagram of the forces on the brain in a coup-countercoup concussion injury as well as the rotational and linear acceleration [14].

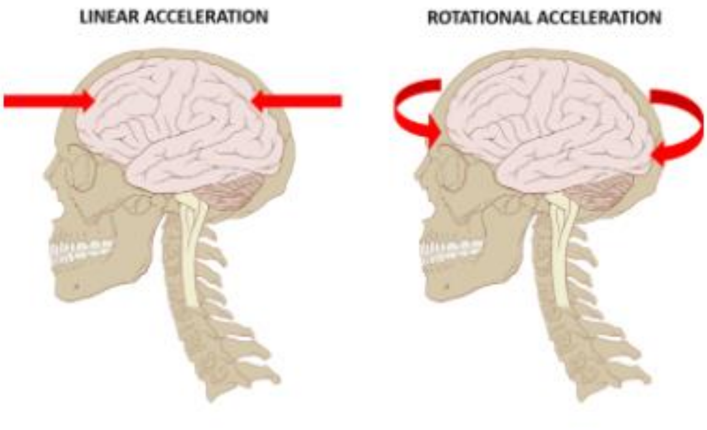

Figure 1.   Forces on the brain [8].

Concussions are caused by linear and rotational vector forces on the head and brain, that can be described using Newtonian laws.

As Newton’s first law describes: Until acted by an unbalanced force, an object at rest stays at rest; an object in motion stays in motion with the same velocity and direction. In concussions, brain will stay at rest suspended within the skull until acted on by an external force within the external force acts on the head, the cerebral fluid will be pushed aside, and the brain will accelerate and hit the head.

Newton's second law states,

$$F = ma \tag{1}$$

In the formula (1):

- F is the force which is equal to the mass multiple the acceleration.
- m is the mass of an object.
- a is the acceleration.

If external force is acting on an object are not balanced to acceleration of that object, then it is based on the net force performing on that object and the mass of object. The net force performing on the brain increases directly with the speed of the other player hitting another or the speed in which the affected player hits the wall.

Finally, Newton’s third law is described as for every action, there is an equal and opposite reaction. If collision occurs between two players on the ice, both will be impacted by a force equal to the magnitude. However, subsequent acceleration due to force is dependent on their mass. The reactive acceleration will differ, because If the player is against smaller in size player, then the smaller players are more likely to suffer from concussions. In player-to-player collisions if the hitter was on average taller and heavier than the other player, this can also cause a person greater impact because the hitter is bigger than the other player. In addition to linear motion, the brain is also impacted in rotational sense.

This leads to the basic rotational dynamics. Angular acceleration is the pace of change of an object rotating or spinning around the fixed point similar to its linear counterpart. Angular acceleration describes the pace of change of the angular acceleration if an object's speed is not constant. In hockey, if a player is struck by another player or a wall at an angle their body and particularly their brain will experience some degree of rotational motion. Thus, the subsequent force leads to a higher angular acceleration of the brain tissue while the tissue is mostly unaffected by small accelerations. This rapid increase in rotational speed causes an imbalance of matter in the brain which leads to a concussion.

In conclusion, the brain is a very important part of the body that has functionalities to take the right steps to protect it from harm or injury. It is important to wear a helmet when engaging in activities that could lead to head injuries and concussions while playing contact sports. In addition, making sure that the person is fully recovered before returning to the field or any activity is also important because that might cause damage to the brain.

3.4 Head Impact Telemetry System

The HIT system is considered as a hardware and software system which has been used to assess head impacts on the brain. Moreover, frequency and intensity of helmet impacts are determined by HIT. In addition, the system of the HIT is used to monitor and record linear head accelerations [7]. Helmet mounted accelerometers are used to calculate head acceleration in linear an angular form. Figures 1 and 2 presents how It is possible to use six single-axis accelerometers in-helmet systems.

Figure 2 shows the effect of location that arises on the head. The head impact is categorized into 5 bins and pre-define by azimuth (θ) and elevation (α). Azimuth (θ) is ranging from −180° to 180° with 0° at the X axis and positive (θ) to the right side of the head. Elevation (α) ranges from 0° (horizontal plane passing through the head centre of gravity, CG) to 90° (crown of the head at the Z axis). The XZ plane indicates the midsagittal plane encapsulating positive X related to the caudal direction. The XY plane indicates the coronal plane with positive Y to the right side of the head. Impacts with elevation > 65 are indicated as top. The remaining impacts are merged ranging from azimuth; −45° to 45° back, ±45° to ±135° side, and −135° to 135° front [6].

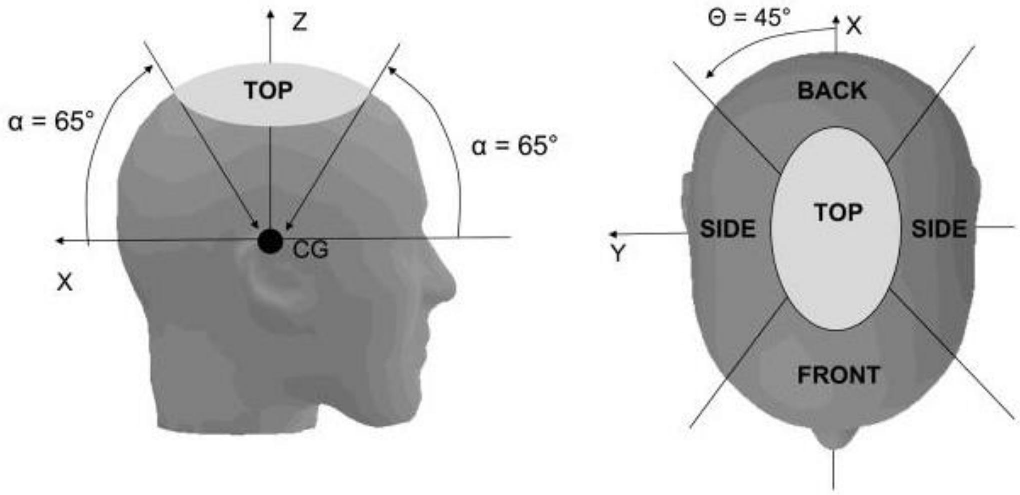

Figure 2. The head impact location [6].

Figure 3 shows that the related HIT System can be calculated with head impact location in azimuth degrees all over the head (A). In elevation degrees (B), the impact category is mentioned. Impacts > 65 elevation are usually classified as the top affected area without considering the azimuth degree calculation. Else, it may impact location category because it is determined by the azimuth degree falling into one of the four location bins (front, right side, left side, and back).

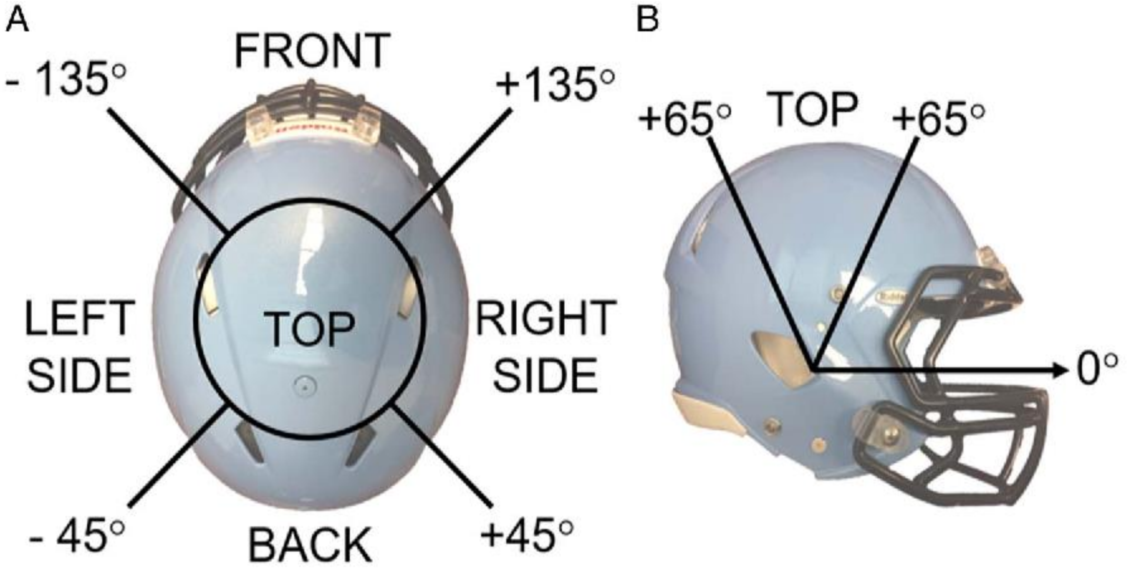

Figure 3. Head impact around the head [6].

Over last few years, researchers have estimated the concussion biomechanics with technology advancements. In order to calculate head impacts sustained throughout the play, two approaches are used i.e., laboratory reconstruction of open-field head contact and the helmeted device.

4 Modern Technologies

4.1 Wireless Communications

One of the keys enabling technologies for the mobile internet and the mobile web is wireless communication. Wireless communication is defined as the transmission of power or some information or among two or more points that are not linked through an electrical conductor. The electrical conductor means the wires so when it would be able to transmit a message or transfer a message or signal from one point to another point without any physical wires. Hence, it would be called wireless communication. So, the basics of how wireless communication works apply also to several different wireless technologies whether it is Wi-Fi, 3G or LTE, or Bluetooth all these technologies fundamentally operate in similar if not identical methods [9].

The key components are involved in sending a message from one point to the other point is that the message of data that will be transmitted will need to be generated first to a series of zeros and ones as binary data and the series of bites need to be converted into a waveform. To communicate information, two distinct aspects of this waveform can be monitored. The one is the amplitude of the signal, how strong is the signal at any specified point, and on the other hand, the second aspect is the frequency of the signal itself. So, when the message needs to transmit, it should be generated and already pre-processed. Modulation, encoding must be completed first.

A transmitter will be required for wireless communication. The transmitter will be sending a message from one point to another. Therefore, there must be a receiver to receive the message. When the message is transmitted from the transmitter to receiver a medium to communicate with the messages is needed. Since it is wireless, hardwire cannot be used. To connect the transmitter and a receiver a wireless channel as an app is going to act as a medium and the information or signals will be sent through the air, so that is why it is technically called a wireless channel. The medium is used to transmit messages from transmitter to receiver.

With these basic requirements these are all the very few components that is involved in wireless communication. Figure 4 depicts a standard wireless system, which is made up of three elements. Which are: One is transmitter, second is channel and the third is receiver wireless communication system structured diagram.

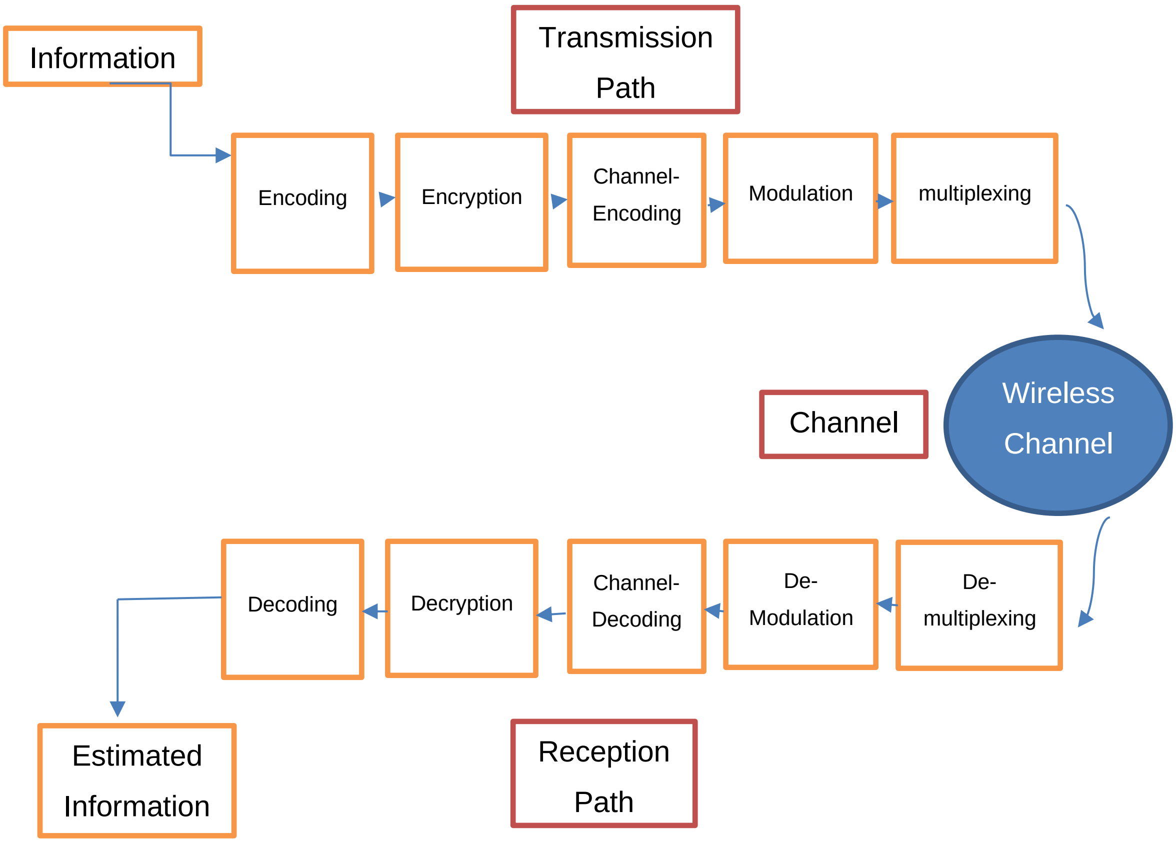

Figure 4. Block diagram of the wireless communication system.

In healthcare Wireless communication has progressed at a breakneck rate, dramatically altering the operating environment. Wireless communication systems are being adopted by healthcare institutions to recover, store, exchange, and send data. Healthcare practitioners now use wirelessly wired computers or tablets to enter data and use mobile phones or digital video cameras to track patients and patient data. Telemedicine is carried out using several wireless technologies that enable patients and healthcare providers to communicate with one another. Providers and Patients are being interlinked in new ways through smartphones, telephones, and the Internet of Things (IoT) [10].

Better medical treatment and more efficient services for patients are possible with real-time connectivity and access to data with documents. When time is of the essence, there is no more need for files or filing cabinets for patient history. No records are open left out or packed into slots in office cabinets, hoping for someone to pick them up Security thresholds may be allocated, restricting access to only those that have been granted permission. There is no need to wait for lab results to move into the facility's routing system. Real-time information is updated and accessible. Data is instantly open to any-body who needs it to help and treat patients. Cloud systems allow data to be stored and retrieved in a safe environment from various locations. This eliminates the need for faxes or messengers to share information between healthcare professionals.

Wireless infrastructure is increasingly being integrated into an ever-widening variety of medical instruments and applications, including both active and passive devices, in the time of digital health and the evolving Internet of Things (IoT). Wireless infrastructure provides networking between devices and applications, cloud providers, and the internet, as well as mobility, scalability, and widespread reach. Latest technological improvements minimize the costs of components permitting many more health services to use internet technology models to become achievable. This new usage model, on the other hand, ensuring that wirelessly supported functions are secure and safe, dependable, and functional.

A variation of wireless communication technologies is used to store and exchange healthcare information:

- Wi-Fi
- Bluetooth
- Z-Wave
- RFID (Radio Frequency Identification)
- WWAN (Wireless Wide Area Networks)
- Mobile Internet

Wireless medical devices utilizing Bluetooth, Wi-Fi, and cellular wireless technologies, and are spread over a wide range of medical usage and situations from observing ambulatory patients in hospital and even surgery or to track the location of devices, equipment, even personnel.

The wireless communication system has different forms and methods as shown :

- Satellite communication
- Mobile communication
- Microwave Communication
- Wireless network communication
- Infrared communication
- Bluetooth communication
- Radio frequency

Despite the fact that the underlying infrastructure of these networking technologies differs, all of them have a shortage of a physical or wired connection to their respective devices, to begin and conduct contact.

There are a variety of other systems each with its own set of benefits for multiple applications. Simplex, Half-Duplex, and Full Duplex are the three types of wireless communication schemes. Wireless communication has several advantages; the most important ones are cost-effectiveness, flexibility, speed, accessibility, etc.

4.2 Internet of Things (IoT)

The IoT is a huge network in which multiple devices are connected with each other capable of taking decisions without any involvement of human intervention. Not like some time ago when the internet was complete up to some limits while now with the help of IoT, all appliances and devices are connected to the internet largely observed remotely. IoT is developing the way people living their lives that helps them to get a deeper understanding and perception into the working environments or infrastructure.

IoT refers to a network of interconnected devices that use the internet to send and receive data. A smart home, as well as home appliances and electronic components such as sensors and microcontrollers, are best examples of IoT.

Apps are linked to exchange data with the user using a smartphone application, allowing the user to gain a detailed understanding of how the devices around him operate. Until recently, the internet allowed humans to communicate and engage with one another, but now inanimated objects or entities may feel their environment, interact, and collaborate with one another [11].

Figure 5 presents the architecture of the IoT system. The hardware of IoT systems, which can be divided into two categories i.e., general devices and sensing devices. General devices are the primary elements of the data hub and information reciprocity. They are connected through a wired or wireless interface, the best example of these types of devices are the home appliances. While on the other hand, sensing devices include sensor and actuator, which monitors high and low temperature, to calculate humidity light, intensity, and other different parameters. All IoT devices are associated with the network through gateways.

These gateways are also known as processing nodes, process data from sensors and send it to the cloud. The cloud is acting as a both storage plus processing unit. Wired and wireless protocols such as wi-fi, Bluetooth, ZigBee, and others are utilized to give access to assure its ubiquity, and activities are done on the collected data for a fuller insight and observations.

There is a need to support a complex set of devices and communication protocols from tiny sensors sensitive enough to detect and track the necessary element to powerful back-end servers used for data processing and information extraction by all applications to enable human understanding and operation.

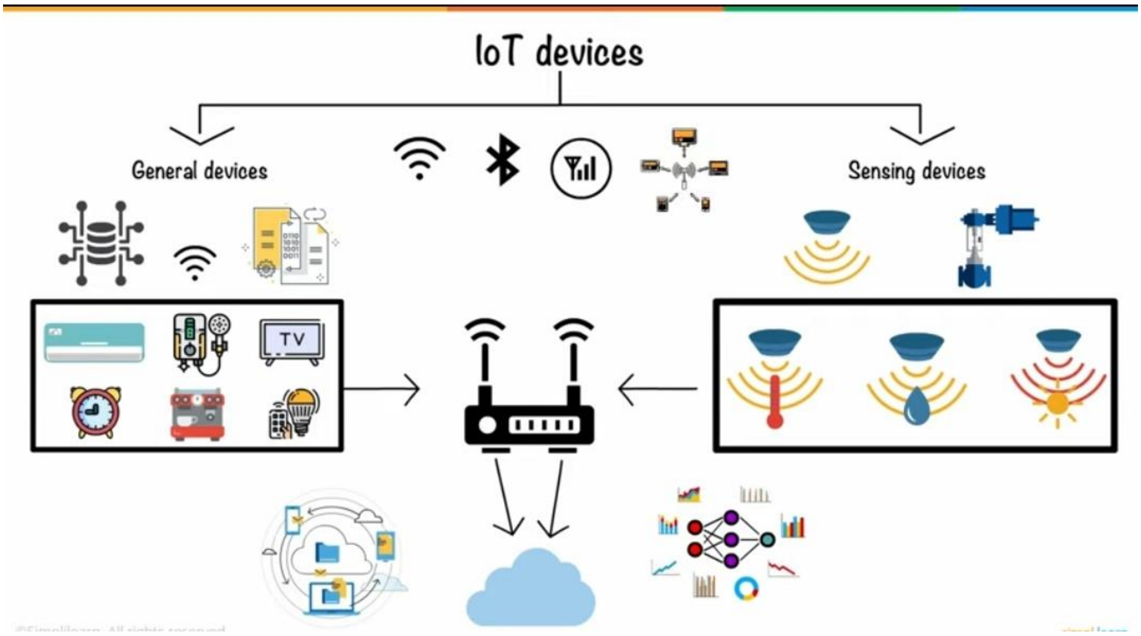

Figure 5. The architecture of the IoT system [11].

There are many types of wireless technologies compatible with IoT applications. To wirelessly interconnected computers and devices that include millions of machines in addition to smartphones and tablets are not connected in past with the internet. Multiple options are used for connectivity to receive and transmit the data or information through wireless systems and some specific methods are best suited to the specified application than others. When deciding on a specific option to use for a particular application, parameters such as battery life, coverage area size, the bitrate, and requirements need for its power must all be taken into account.

There are five significant wireless technologies for IoT devices are [21]:

- Wi-Fi: Stands for wireless fidelity, Standard Wi-Fi is a cost-effective technology that can be used for a number of IoT applications, such as in-building or campus areas. Familiar cases comprise home automation methods standard building with in-house energy management, where Wi-Fi is the main communication channel. All devices are linked to electrical outlets. It is built on the basis of IEEE 802.11

standards. To improve power consumption. It features native IP addressing ability with scalable data rates. These Wi-fi devices consume more electrical power in comparison to Bluetooth devices, which consume low power. On the other hand, Wi-Fi remains the one and only IoT networking technology with the maximum capacity and higher throughput, which is the basic necessity in all IoT infrastructure and deployments. Multiple Wi-Fi devices are available in the market and many more are in the development process. In the long run, it is the best fit for all interconnecting peripherals. Define by 802.11b standard, it can transfer data at the highest speed of 54 Mbps. Its range can be decided by multiple factors such as the location of its use with the type of antenna, and its power of transmission. The outside area where Wi-fi can easily work is 100 meters with a speed of 2.4 GHz [21].

- Bluetooth and BLE: This technology is having a good reputation in the consumer market but its communication range is considered short. Bluetooth Classic technology was originally proposed for point-to-point communication or point-to-multipoint communication (supports up to 7 slave nodes) data transfer between consumer devices. To optimize the power consumption, in later Bluetooth Low-Energy was familiarized to describe small-scale level Consumer IoT applications IEEE Standard 802.15.1 Bluetooth technology is used in multiple various medical and industrial peripherals. Same as Wi-Fi Bluetooth also works at the speed of 2.4 GHz. Systems comprising Bluetooth are designed to work only within a limited range (0-10 meters), so they use less power [21].

- Cellular (3G/4G/5G): Cellular systems are made for reliability, authenticity, security, and robustness. Cellular IoT (CIoT), grounded on 3GPP standards, uses existing infrastructure to offer excellent and efficient IoT coverage with a fast time compared to the market. Systems with CioT include everything starting from devices to a dedicated SIM card with a management platform. Its hardware is summarized with SIM cards which connect to networks via network 2G, 3G, or LTE connectivity, dependent on the cell tower available in multiple areas. Like 2G switch-off is already started globally. Data rate and latency are the leading differences among 4G and 5G technology for IoT. 4G technology delivers 100 Mbps and has a latency of 10 ms. 5G technology delivers 20 Gbps with 1 ms of latency. Because of these main variations, each option is best for different applications with many users [21].

- Zigbee and Other Mesh Protocols: Zigbee is considered as a low power with short-range wireless standard (IEEE 802.15.4), It is usually deployed in a mesh topology to enhance coverage area by relaying sensor data through multiple sensor nodes. Like Wi-Fi, it uses 2.4 GHz bandwidth, but it has low power requirements. It is designed for partial data exchanges, operating at 250 kbit/second. Since Zigbee and related mesh protocols (e.g., Z-Wave, Thread, etc.) have a range of up to 100 meters, they are ideally suited for medium-range IoT applications with an equal distribution of nodes in close areas [21].

- Radio Frequency Identification (RFID): A technology uses radio waves to transmit a small amount of data within a short distance range from an RFID tag to a reader. Businesses can monitor their inventory and properties in real-time by adding RFID tags to a variety of goods and equipment, allowing for easier stock and distribution preparation as well as improved supply chain management. RFID remains embedded in the retail market, allowing modern IoT technologies such as self-checkouts, smart mirrors, and smart shelves, in addition, to increase IoT adoption [21].

Table 1 represents the comparison of wireless technologies for IoT products based on the power usage, its data rate, its area, or range with its cost parameter. Every IoT application has its own distinguished set of network pre-requisites and requirements.

Table 1. Comparison of wireless technologies for IoT products.

Technology	Frequency	Data Rate	Range	Power Usage	Cost
2G/3G	Cellular Bands	10 Mbps	Several Miles	High	High
Bluetooth/BLE	2.4Ghz	1, 2, 3 Mbps	~300 feet	Low	Low
802.15.4	subGhz, 2.4GHz	40, 250 kbps	> 100 square miles	Low	Low
LoRa	subGhz	< 50 kbps	1-3 miles	Low	Medium
LTE Cat 0/1	Cellular Bands	1-10 Mbps	Several Miles	Medium	High
NB-IoT	Cellular Bands	0.1-1 Mbps	Several Miles	Medium	High
SigFox	subGhz	< 1 kbps	Several Miles	Low	Medium
Weightless	subGhz	0.1-24 Mbps	Several Miles	Low	Low
Wi-Fi	subGhz, 2.4Ghz, 5Ghz	0.1-54 Mbps	< 300 feet	Medium	Low
WirelessHART	2.4Ghz	250 kbps	~300 feet	Medium	Medium
ZigBee	2.4Ghz	250 kbps	~300 feet	Low	Medium
Z-Wave	subGhz	40 kbps	~100 feet	Low	Medium

4.3 Cloud

Cloud computing, also known as the cloud, is a service that helps users to access online services and web content from any computer using an Internet connection. This ensures that the customer would not need to be in a specific location to access such data. From computing analytics to reliable and protected data storage and networking infrastructure, the cloud will provide anything very swiftly. In order to provide more accessible resources and great access to data with speed with economized cost, Cloud computing aims to provide such services over the Internet. Every day, people use a new cloud-based service.

When a person shares an important file with another person through the internet while using a smartphone app, downloads a photo, or plays an online video game, they all are doing this very quickly and safely. The great thing is that the cloud saves a lot of money and there is no need to buy any hardware or software program, the cloud will take care of everything. Many technology companies which are supervising these applications, such as Amazon, Google, and Microsoft have already moved from conventional computing hardware to more modern cloud services architecture to power these applications. It is not surprising that these organizations are also among the most common cloud service providers in today's market.

The cloud has proven to be a very reliable medium for transmitting data over conventional Internet networks as well as a dedicated direct connection, and it has become a very essential part of today's internet world. When it comes to IoT, the cloud may be considered as an enabler and it is undeniably the best choice for meeting any of a company's data-driven needs. As cloud technology is emerging, it provides an agile and flexible forum for developers to build practical applications that will allow better data devices to be developed over the Internet.

The role of cloud computing in IoT is to store data as part of a common effort. Cloud computing refers to a main server which can be reached at any time. The Internet of Things (IoT) creates large data packages, and cloud computing is a simple way to transfer them. When IoT and Cloud Computing are used together, they enable applications to be automated in a cost-effective manner that allows for real-time management and data monitoring. Due to the fact both are associated with each and other, The Internet of Things acts as the source data and the Cloud serves as the ultimate storage location.

IoT devices are based on sensors that are able to gather data and further process it. Physical sensors are virtualized until data is transmitted to the cloud in the IoT domain. Though IoT devices can produce a lot of data, cloud computing makes it possible for the data to go where it needs to go. To connects a device or the sensors to the cloud, multiple methods can be used together with Wi-Fi, through cellular, via a satellite, using Bluetooth, direct connection to the internet through an ethernet cable, or using low-power wide-area networks (LPWAN). In each alternative there is some trade-off among these choices depends on the specific criteria like bandwidth, power usage, and its range.

Sensors are common in IoT devices, which gather data and transmit it to be analyzed. Physical sensors are digitized until data is transmitted to the cloud in the domain of IoT. Though IoT devices can produce a huge amount of data, cloud computing allows the data to progress. The sensors/devices can be connected to the cloud through a variety of methods including cellular, satellite, Wi-Fi, Bluetooth, low-power wide-area networks (LPWAN) or using an ethernet connection to link directly to the internet. Power consumption, range, and bandwidth are all trade-offs in each alternative.

When the data has appeared at the cloud server, after processing software analyses it and can decide to take action, such as sending a warning or alert or automatically modifying the sensors/devices without the need for the user's intervention. However, where user feedback or input is required, or if the user merely wishes to check in on the device, a user interface is available to do so. All changes or actions taken by the user are then directed in the reverse direction across the system: To make changes, the information goes from the user interface to the cloud, then back to the sensors/devices.

Figure 6 depicts the communication among the cloud and IoT devices. Gateway uses Multiple forms of connectivity with sensors or devices then advance execute and filter the data provided by the sensors or devices to reduce transmission. The processed data is finally interpreted into a protocol like HTTP/MQTT and transmitted to the cloud via internet connections.

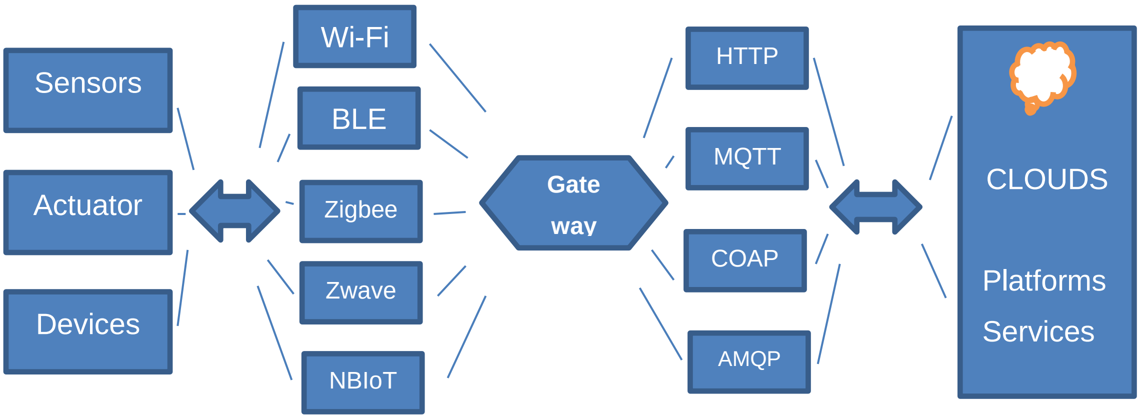

Figure 6. Communication between the IoT devices and the clouds.

5 Communication Protocols in Embedded Systems

Embedded Systems are electronic systems or devices that account for both hardware and software. In this situation, every component should communicate with one another to provides the predicted output. To exchange the information, every communicating part should agree to some specified protocol. For embedded systems, a variety of protocols are available, which are deployed based on the implementation environment.

The physical layer, which defines signal power, signal integration, and shaking technique, system addressing, bus arbitration, wireless and wired data lines, and so on, is connected to communication protocols. The application layer is responsible for the processes such as the selection of baud rate, the systems configuration, and the data communication. In Embedded systems, Inter System communication Protocols and Intra System communication Protocols are the two main categories of communication protocols.

The USB Communication Protocol, The UART Communication Protocol, and the USART Communication Protocol are the three classes of the inter-device protocol. The I2C Protocols, The SPI Protocols, and the CAN Protocol are examples of the inter-device protocols. Below is the explanation of UART, I2C, SPI protocols.

- I2C Protocol: I2C is a serial communication protocol, and it stands for Inter-Integrated Circuit. The key goal of this protocol is to make connecting peripheral chips to a microcontroller as simple as possible. To transfer data between devices, I2C uses two wires: SDA (Serial Data Line) and SCL (Serial Clock Line). It's said that these two active wires are bidirectional.

  I2C protocol is dominant over communication protocol. A Unique ID is assigned to each slave. The dominant device sends the target slave ID along the R/W (Read/Write) flag to start communication as shown in figure 7. Other devices will be turned off when the corresponding slave device switches to active mode. Communication between the master and slave devices begins until the slave device is ready. If the transmitter sends one byte (8 bits) of data, the receiver responds with a one-bit acknowledgment. When contact between devices comes to a halt, a stop condition is given.

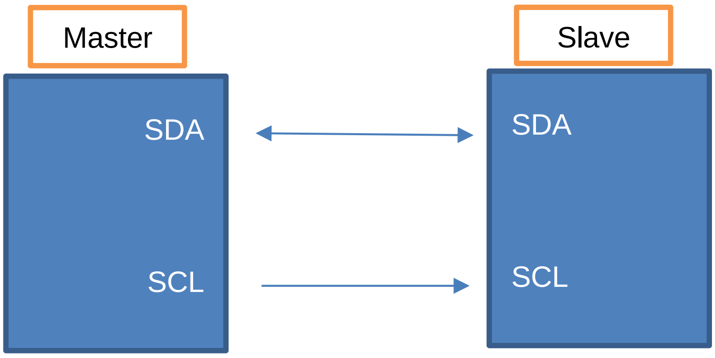

Figure 7. I2C Communication Protocol.

- SPI Protocol: One of the serial communications protocols is Serial Peripheral Interface. The MOSI protocol is a four-wire protocol (Master Out Slave In), MISO (Master In Slave Out), SS (Slave Select), and SCLK (Serial Clock). SPI, like the I2C protocol, is a master-slave communication protocol, as seen in figure 8. The master device configures the clock at a specific frequency in SPI. Furthermore, by pulling the SS line low from its usual high position, the right slave is selected. As soon as the required slave device is chosen, communication between the specified slave and the master device is provided. SPI is a protocol that operates in full-duplex mode. SPI does not limit the data transmission to 8-bit words.

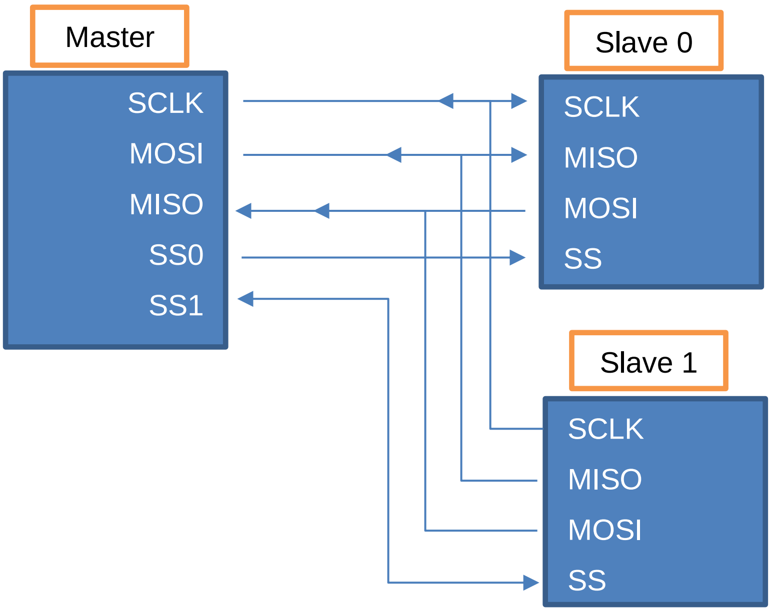

Figure 8. SPI Communication Protocol.

- UART Communication protocols: The Universal Asynchronous Receiver/Transmitter (UART) is a physical device that converts parallel data into serial data. It is not a communication protocol. Its primary function is to serially send and receive data. Due to UART is a two-wired, Tx (transmitter) and Rx (receiver) pins hold the serial data as shown on figure 9.

UART sends and receives data asynchronously, which means there is no clock signal involved in sending and receiving data. UART embeds start and stops bits with the real data bits instead of a clock signal, defining the start and end of a data packet. When the receiver senses the start bit, it begins reading the data bits at a certain baud rate, implying that both the transmitting and receiving devices should operate at the same rate. UART communicates in half-duplex mode, which means it either transmits or receives data at the same time.

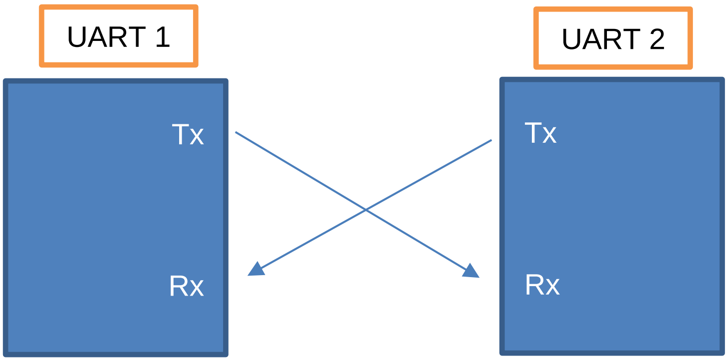

Figure 9. UART Communication.

6 The Scope of The Study

The goal of this thesis work was to improve as well as to study the wireless communication methods of the first version of a head impact device prototype. The hardware system and the software design of the first version of the device prototype were completed by another hardware developer colleague [13] and another software developer colleague [12].

To apply the ideal wireless communication method on the new enhanced prototype version was needed to have the accessibility and the possibility to transmit, store and save data to the cloud wirelessly.

The development of the new version of the prototype was processed based on the results and the measurements of the first version of the prototype. The type of the sensors, the wide range the sensors can measure, and all the required and accurate data and measurements were followed accordingly based on the first prototype version.

The new version of the device needs to measure the linear acceleration and rotational velocity forces. In addition, to help, monitor, and measure the head impact of the players during contact sport, and send the collected data to be saved in the cloud with an access to it later. The data will help the principal medical professional and the coach to observe and to keep up to date follow up with the player's during the contact sport or the player's training time in case of a serious and dangerous strike occur to the head of the player. That will enable the medical professional and the coach to provide urgent and immediate help to the player to avoid serious head damage and concussions.

The goal was to improve the first version of the helmeted prototype device and applying a wireless communication method to enable the prototype to connect to the cloud. Therefore, the new development plan is to offer:

- A development of a new version of the device prototype including both the hardware and the software system that would measure the head impact.

- Wearability: Since the device will be carried on the body, it must be compact and light enough to not block movement or throw the player's center of gravity off.

- Lifetime: The device should have enough battery capacity and storage space to last the length of a three-hour professional sports game, at the very least.

- A use of IoT microcontroller and sensor to obtain the data via wireless communication protocol to send it after to cloud and the collecting device (e.g., smartphone or computer).

- Wireless technology: the IoT components will enable the device prototype to send, store and save the data on the cloud which will provide access to the data for further analyzed and check-up.

- Low cost: providing a low-cost device prototype while having high proficiency and great performance.

6.1 Requirements

The requirements of the new version of the device prototype were followed by taking into consideration the requirements of making the first device prototype. Since the results and the measurements of the first device prototype were approved to present sufficient and accurate data, the design of the new device prototype must follow accordingly to deliver similar results.

Brief information regarding the requirements that was followed while designing the new version of the new device prototype based on the first prototype requirements are:

- To use a little power as possible while be used on a longer time, to be light and standalone since it will be a wearable device and will be inserted inside a helmet.

- To deliver a high-performance speed capability as well as real-time and event driven. And the wireless communication range must be as large as possible so that it covers the field of the game.

- The accelerometer sensor range was to be larger than ± 16 g with a sample rate of 1000 Hz. In addition, that the range was to be greater than 95 percent of head impact linear acceleration range in contact sports [12].

- The gyroscope sensor range of ± 2000 deg/s with a sample rate of 1000 Hz. In addition, that the range was to be greater than 95 percent of head impact linear acceleration range in contact sports [12].

When the selection of the new processor and sensor for the new design prototype was completed. The new components for the device prototype hardware were: ESP 32EU Microcontroller as the processor, and Adafruit ICM-20649 sensor as both the accelerometer and the gyroscope.

The plan on how to design the new device prototype was as such: To use the new IoT sensor and microcontroller and to find the best communication protocol to connect both IoT processors and sensors to receive and transmit data. Hence, when the data can successfully be collected from both the processor and the sensor a programming platform will be needed, and for that Arduino programming platform can be used. After that, using networking protocols such as MQTT or HTTP, with the advantage of Wi-Fi, the gateway effectively aggregates data and transfers it to the cloud. When the data reach the cloud then it will be possible to find a proper method to store and have access to it later.

After the development of the device prototype system is ready. It can be implemented inside the helmet of the player. During the game, once the device is suspected to have a high head impact the system is immediately triggered. However, since the data is stored in the cloud, a detailed review such as hit measurements, time of the day, the temperature of the player, all is possible to be sent over to a medical professional on a smartphone or a computer online or over an app.

7 The System of The Device Prototype

7.1 Hardware System of The Device Prototype

The hardware system of the device can be divided into five different subsystems as shown in figure 10: inputs/data collection, processing, storage, output, and power unit. The input/data collection comprised of two sensors: an accelerometer and gyroscope. The power unit (bottom of figure 10) consists of either a power bank or AA batteries and a boost converter circuit to regulate voltage powering the two main subsystems. The processing unit include the ESP 32EU microcontroller. The cloud is where all the information is processed as a storage unit, which is the third unit in the block diagram. The final part of the block diagram is the output unit, which is the user interface where the interaction between the human and the device prototype occurs.

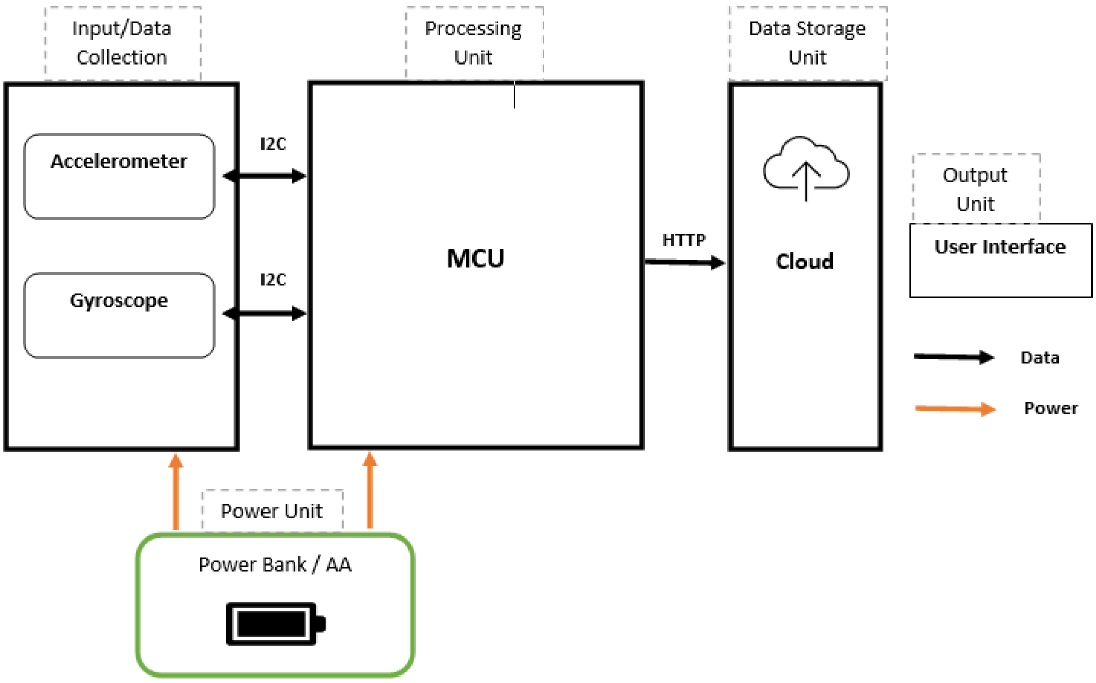

Figure 10. Hardware system architecture design.

7.1.1 Microcontroller Selection

The new microcontroller unit (MCU) serves as the processing unit. It was chosen due to its simplicity, its Wi-Fi support as well as its ability to achieve the desired goals. In addition, it meets all the requirements and features that are needed to develop the new version. The first version supported BLE wireless technology which has no direct connection to the cloud, hence, the new processor must have another technology to support the cloud accessibility.

An IoT processor with Wi-Fi technology can be the ideal solution for cloud connection, data storage, and easy access for data for further analysis.

The first part of this thesis work was to study the wireless communication of the first device prototype. To connect the first device prototype to the cloud it was needed to connect the device with another IoT microcontroller. The study of the wireless communication and the connection of the first device to cloud was completed by another colleague. The selection of the cloud connection of the device was achieved using the Particle Photon. The Particle Photon is a Wi-Fi IoT processor for creating connected projects. It is easy to use, powerful, and most importantly it is connected to the cloud. A more detailed thesis study on how to connect the first prototype to the cloud via wireless communication is under processing by another colleague.

Therefore, it will be complicated to connect the first device supporting BLE wireless technology to the cloud. The new idea was to find another microcontroller that supports Wi-Fi to have direct contact with the cloud via a Wi-Fi protocol. In addition, to have a low-power system, low-cost, and support all the required features and requirements that were needed on making the first device prototype. The ESP 32EU microcontroller was chosen as the main processor unit of the new device prototype.

7.1.2 ESP 32EU Microcontroller

ESP 32EU microcontroller was chosen and selected to be the new processor unit on the new version of the device prototype. What makes this microcontroller an ideal replacement instead of the one on the first device prototype is [18]:

- Hybrid Wi-Fi & Bluetooth Chip:

  1. ESP32 can operate as a stand-alone program or as a slave system to a host MCU, lowering communication stack overhead on the main application processor.

  2. Communication protocol with SPI / SDIO or I2C / UART interfaces.

  3. Support Wi-Fi protocol 802.11 b/g/n (802.11n up to 150 Mbps), 2.4 GHz.

  4. Support Bluetooth protocol V4.2 – Supports BLE and Classic Bluetooth.

- Ultra-Low Power Consumption:

  1. The ESP32 uses a mix of specialized software to achieve ultra-low power consumption.

  2. In addition, ESP32 provides cutting-edge features including fine-grained clock gating, several power modes, and the dynamic power scaling.

  3. 3.3V is the operating voltage. And a DC current of 50 mA on the 3.3V pin.

- Robust Design:

  1. Operating temperature ranging from –40°C to +125°C.

  2. External circuit imperfections can be automatically removed, and the ESP32 can respond to changing external conditions.

- High Level of Integration:

    1. Highly integrated with in-built antenna switches, RF balun, power amplifier, low noise, receive amplifier, filters, and power management modules.

- Processors:

    1. ESP32 uses a Tensilica Xtensa 32-bit LX6 microprocessor with 2 cores.

    2. The clock frequency accelerates up to 240MHz and it performs up to 600 DMIPS (Dhrystone Million Instructions Per Second).

    3. Its low energy consumption facilitates ADC conversions, computation, and level thresholds. All occurrences are in the deep sleep mode.

    4. FLASH supports up to four 16 MiB external QSPI and up to 8 MiB SRAMs. With 520KB RAM.

ESP32 state is retain within the RAM. It lowers the energy consumption and power usage through elevating one of the sleep mood. When the sleep mood starts working, on power-saving, ESP32 enters while not in the use to stop the power for any inessential digital peripherals. RAM usually gets sufficient energy to facilitate retaining the data. ESP32's significant power management facilitates five configurable power modes i.e., Active Mode, Modem Sleep Mode, Light Sleep Mode, Deep Sleep Mode and Hibernation Mode.

Each mode has its own set of features and power-saving abilities as shown in figure 11. The five configurable power modes are an effective place method to significantly increase the battery life of a project that does not need to be active all of the time.

Power mode	Description	Power consumption
Active (RF working)	Wi-Fi Tx packet 13 dBm ~ 21 dBm	160 ~ 260 mA
	Wi-Fi / BT Tx packet 0 dBm	120 mA
	Wi-Fi / BT Rx and listening	80 ~ 90 mA
	Association sleep pattern (by Light-sleep)	0.9 mA@DTIM3, 1.2 mA@DTIM1
Modem-sleep	The CPU is powered on.	Max speed: 20 mA
		Normal speed: 5 ~ 10 mA
		Slow speed: 3 mA
Light-sleep	-	0.8 mA
Deep-sleep	The ULP co-processor is powered on.	0.15 mA
	ULP sensor-monitored pattern	25 μA @1% duty
	RTC timer + RTC memory	10 μA
Hibernation	RTC timer only	2.5 μA

Figure 11. ESP32 power consumption by power modes.

7.1.3 Accelerometer and Gyroscope Selection

The first version of the device prototype used two separate sensors for the device prototype system as one is the accelerometer and the other is the gyroscope. The sensors were working and functioning well on the device prototype on providing the measurements data. But the two sensors were taking a larger space on the board, as the size of the two sensors together and the microcontroller along is quite big. The device prototype is made to be a helmeted device as to be placed inside the helmet of the player during the contact sport. Having a big size for a wearable device will not be very convenient or very suitable to fit well inside the helmet.

The prototype aimed to be as small as possible while functioning and providing accurate measurement data for the head impact. The idea was to use one sensor that combines both an accelerometer sensor and a gyroscope sensor while maintaining the same required technical specifications to function the same as the two separated sensors.

As it was mentioned earlier the technical specification required for the accelerometer sensor was to be three-axes accelerometer featured full-scale ranges of ± 2 g, ± 4 g, ± 8 g, or ± 16 g [12]. And for the gyroscope sensor is to be digitally programable ranges of ± 250, ± 500, ± 1000, or ± 2000 degrees per second (deg/s) [12]. Therefore, the selection of the new sensor was limited according to the mentioned requirements.

7.1.4 Adafruit ICM-20649 Sensor

The Adafruit ICM-20649 sensor InvenSense was selected to be the new sensor that will be the replacement of the two separated accelerometer sensor and gyroscope sensor from the first device prototype version to be used in the newly developed version of the device prototype. Choosing to the use Adafruit ICM-20649 sensor was for [19]:

- Adafruit ICM-20649 sensor is a Wide-Range 6-DoF accelerometer and gyroscope. Its accelerometer can measure up to ±30g and its gyroscope can measure up to ±4000 dps(degree per second).

- Adafruit ICM-20649 gyroscope will measure the angular velocity via rotation measurements around three axes: x, y, and z. The 3-Axis gyroscope is with programmable FSR of ±500 dps, ±1000 dps, ±2000 dps, and ±4000 dps.

- 3-axis accelerometer measures the acceleration forces acting on an object with programmable FSR of ±4g, ±8g, ±16g, and ±30g.

- The ICM-20649 6-axis inertial sensor offers the smallest size, the lowest power, and wearable sensor. Allows for precise assessment of high-impact sports and other uses. Furthermore, providing continuous motion sensor data prior to, during, and after impact provided more precise feedback.

- Communication can easily be connected to a microcontroller with I2C through two data wires connections or SPI through four wires connections.

- Adafruit ICM-20649 sensor comes in a very small 3.0x3.0x0.9mm QFN package. Its features include on-chip 16-bit ADCs, an embedded temperature sensor, programmable digital filters, and programmable interrupts.

The ICM-20649 is made up of three independent vibratory MEMS rate gyroscopes. It detects rotation about the X-, Y-, and corresponding Z- Axes. While the gyros are being rotated about respective sense axes, the Coriolis Effect effects the vibration that causes detection of a capacitive pickoff. The resulted signal is then amplified and demodulated afterwards. Filtered signals produce by a voltage is directly proportional to the angular rate. The corresponding voltage is mainly digitized using single on-chip 16-bit Analog-to-Digital Converters (ADCs) to sample every axis.

7.2 Software System of The Device Prototype

The software system of the device prototype covers the type of the communication protocol that was chosen to be used on the update of the new version of the device prototype as well as the programming platform that was used to program the software system of the device prototype.

Communication protocols serve as a link to enable two or more communications systems to transmit and send information and 'talk' to each other. The microcontroller processor was selected because it supports Wi-Fi wireless communication and has a direct and easy way to transmit data straight to the cloud and store it. In addition, to have the maximum range and little power consumption. Through gateways, data from the sensor is processed and translated into HTTP protocol, then it will be sent to the cloud through internet connections.

Arduino Software (IDE) was the programming environment that was used to program the ESP32 processor, and its language programming code can be written in C++ [20]. Arduino IDE has many processor modules and boards that support ESP32 which can make it easier when programming and speed up the development process.

8 Device Prototype Testing

8.1 Communication Protocol Connection

The communication protocol that was applied to connecting the ESP32 microcontroller and the Adafruit ICM-20649 sensor was the I2C wired connection. Where the MCU was the master, and the sensor was the slave and communicated by I2C bus interfaces. Both I2C and SPI communication protocol were possible but the I2C connection was applied because:

- I2C connection is better for long distance and it ensure when the data send from the slave device it will be received.
- Simple and easy at it need only two-wire connection. One for data and the other for the clock while SPI need four-wire.
- The clock stretching feature which enable the clock to stop communication if the slave is not able to send the data fast enough.
- I2C is cheap and its susceptibility to noise is less than SPI.

Figure 12 represents the I2C wire connection between the ESP32 microcontroller and the Adafruit ICM-20649 sensor. The connection was completed with two main wires for the data transfer.

The yellow wire which is the data pin (SDA PIN) on the sensor is connected to the microcontroller data pin (SDA PIN), PIN 21.

In Addition, the white wire on the sensor which is the clock signal (SCL pin) is connected to the clock signal (SCL PIN) of the microcontroller, PIN 22.

The black wire is the ground (GND), and the red wire is the VIN for the 3V both were connected from the sensor to the microcontroller.

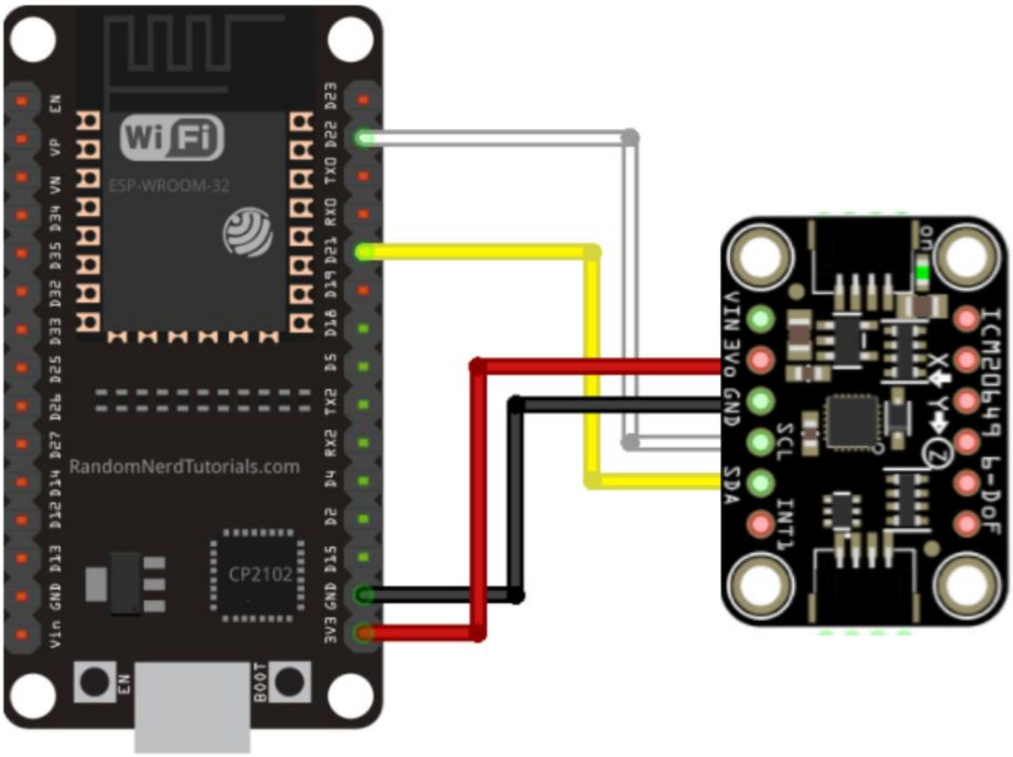

Figure 12. I2C wired connection between MCU and sensor.

The connection between both the sensor and the microcontroller was completed, therefore, Arduino IDE is needed to program the processor and receive the data from the sensor.

8.2 Software Test

8.2.1 Embedded System Development

The embedded system development starts with Arduino IDE software. Arduino hosts various processor modules in addition to different boards that support both the ESP32 MCU and the Adafruit ICM-20649. Having this functionality on Arduino is very helpful as it will be possible to break out ESP32 board datasheets so that it will be the guide to know which libraries to install and how to set up the ESP32 board. Once everything is completed Arduino will be ready for the development of ESP32 applications.

Adafruit ICM-20649 board datasheet was broken out to instruct the process of finding the required libraries that need to be installed. Thereafter, the main program needs to be written. The main program included breakout boards for both the MCU and the sensor libraries, Wi-Fi libraries, HTTP libraries, and the performance of the primary function. via writing a new code that will run the new version of the device prototype. The final main program will be able to transmit and receive the data from the MCU and sensor.

Figure 13 represents the main program architect and how it will function. The program starts from the set-up stage, then the second stage, and reading the data from the sensor thereafter the connection through Wi-Fi to the cloud. The final stage will enable the data transmission from the sensor to be stored in the cloud with access to it later online or via an app, smartphone.

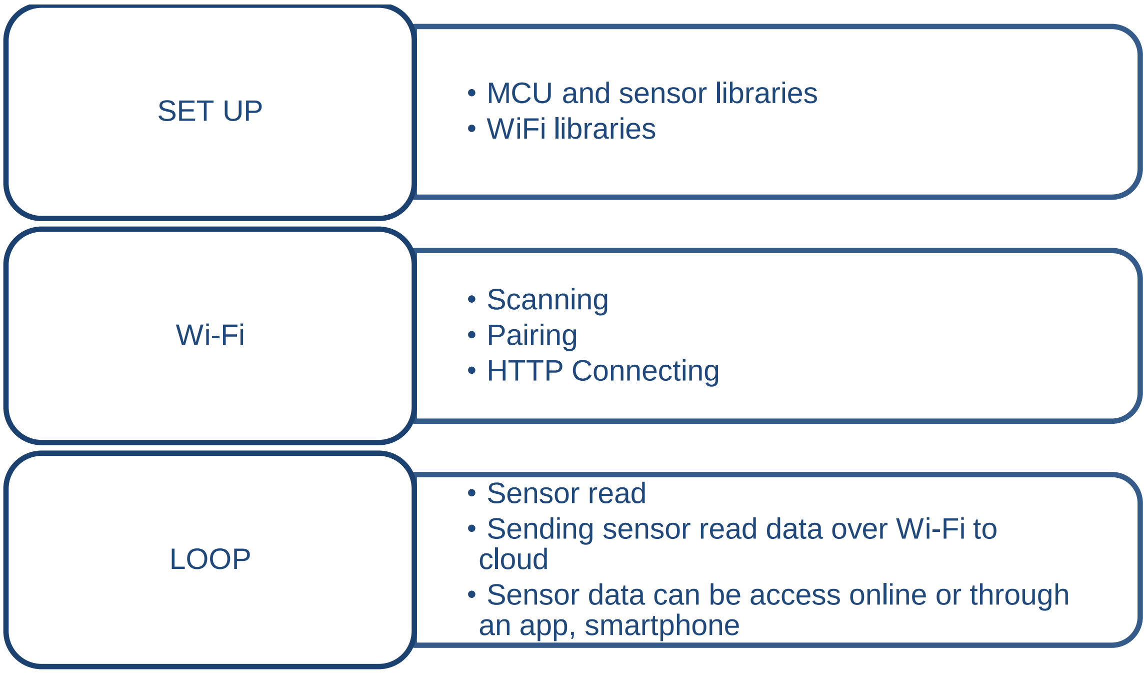

Figure 13. Embedded system main program architect.

8.3 Cloud Test

The new MCU is an efficient chip for building IoT devices and developing the new version of the device prototype because it supports a Wi-Fi connection. The connection of the MCU to the Wi-Fi network was by including the Wi-Fi headers. To be able to connect to Wi-Fi, two things are needed to be clarified, the name of the network that be needed to connect to, and the password of that network.

Timeout definition to control how long the ESP32 can attempt to connect to a Wi-Fi network, to not keep it trying forever. Instead, when it fails to connect to Wi-Fi, it might be better to restart the ESP or send it into deep sleep mode to save the battery. Hence, a new function called “connect to Wi-Fi” was created, and this function will take care of all the necessary steps. The results can be observed from the serial monitor of Arduino IDE, to print out the IP address of the project then the connection to Wi-Fi be completed.

For the new version of the device prototype three programs versions were implemented and designed that supported different features:

- First program was created supporting the MCU and sensor libraries using C++ programming language to program the MCU to enable the data transmission via the I2C connection from the sensor to MCU and then to connect to Wi-Fi with IP address.

- Second program is a completion of the first program but was modified to transmit the sensor data via the MCU by connecting it to Wi-Fi thereafter using HTTP protocol to send data to an IoT platform to allow the device prototype to connect, visualize and analyze the sensor data over the cloud.

- Third program was having the Blynk App feature. This program combines both abilities as to connect to the IoT platform and at the same time to connect to Blynk app so then data will be sent and be available to access online on the cloud or through the app that will be used over a phone, computer or any device that have internet connection.

First program was adjusted based on the first version of the device prototype and measurements been followed according to another colleague research [12]. The device features been adjusted as shown in table 2:

Table 2. System setup configuration and functionality.

Device features name	Sittings
Accelerometer's range	± 16 g
Accelerometer's sample rate	1000 Hz
Gyroscope's range	± 2000 deg/s
Gyroscope's sample rate	1000 Hz
Arduino baud rate	115200 bps
Data transmit every	100 ms

After compiling the program with the system setup configuration, the results on the serial monitor and the output of the sensor were as shown in figure 14. As accel X, Y, Z stand for X, Y, and Z axes of the accelerometer values in G-force, and the gyro X, Y, Z stand for X, Y, and Z axes of the gyroscope values in degrees per second.

The results represented in figure 14 are the linear acceleration and the angular velocity of the accelerometer and gyroscope sensors. Results were not fully accurate comparing to the first version of the device prototype. The new version still needs to go through some testing and adjustment on real players. Everything else was successful and operates well. The device was able to read and present the data of the sensors, to function in real-time providing the data as six axes.

```
**********************************************
        Temperature 27.18 deg C
        Accel X: 0.89   Y: 8.65         Z: 5.34 m/s^2
        Gyro X: -1.83   Y: 0.75         Z: -0.55 radians/s

*** requesting URL: http://api.asksensors.com/write/RKKVuqixkfvurZ


*** End
**********************************************
        Temperature 27.04 deg C
        Accel X: -5.40  Y: 2.39         Z: 7.23 m/s^2
        Gyro X: 0.37    Y: -1.59        Z: 0.54 radians/s

*** requesting URL: http://api.asksensors.com/write/RKKVuqixkfvurZ


*** End
**********************************************
        Temperature 27.37 deg C
        Accel X: 4.96   Y: 3.26         Z: 7.73 m/s^2
        Gyro X: -0.10   Y: 0.16         Z: 0.87 radians/s

*** requesting URL: http://api.asksensors.com/write/RKKVuqixkfvurZ


*** End
**********************************************
        Temperature 27.37 deg C
        Accel X: 2.55   Y: 0.34         Z: 10.03 m/s^2
        Gyro X: -0.45   Y: 0.32         Z: 0.22 radians/s

*** requesting URL: http://api.asksensors.com/write/RKKVuqixkfvurZ


*** End
**********************************************
        Temperature 27.42 deg C
        Accel X: 0.57   Y: -0.25        Z: 9.77 m/s^2
        Gyro X: 0.00    Y: 0.01         Z: -0.08 radians/s
```

Figure 14. Angular velocity and accelerometer output.

As shown in figure 14 the program has been compiled and tested on the system of the device prototype and it was successfully working, receiving, and transmitting the data to the MCU and connecting to Wi-Fi, and generating the IP address.

8.3.1 AskSensor IoT Platform

AskSensor is an IoT platform and one of the most convenient applications to use. It allows for a remote-control connection with the sensor and to easily manage the connected project device. In addition, to provide a real-time and analyze the acquired data over the cloud. This platform is one of the best, cheapest, to use while making the communication of the IoT devices and sensor simpler to focus more on big data analytic.

The reason of choosing this IoT platform is for its features of [17]:

- Platform for IoT devices: it was needed to find a platform that supports IoT devices to assist in connecting and controlling the networkable microcontrollers of the hardware system and the sensor of the device prototype with gateways to the Internet of Things cloud.

- Real-time Data: to receive real-time data when connecting the device system to the cloud as the device status, sensor data, and to have the ability to control it in real-time. Providing the option of REST and MQTT APIs to communicate with networked devices.

- Data Analytics: via IoT analytics, it will be better to understand the IoT data, boost business operations, reduce maintenance costs, and avoid technical glitches.

- Data retention: The ability to store data up to 18 months, with unlimited data storage, connecting to 10 devices, and custom dashboards. A speed data update and graph refresh when connecting to the device prototype as every one second.

Providing all those features met the requirement the device needed to connect to the cloud.

The HTTP protocol was used at this stage to enable the second program on Arduino to transmit the data from the hardware system through Wi-Fi wireless communication to the cloud.

Figure 15 to Figure 17 represents the sensor data analysis as six graphs that was transmitted to the AskSensor IoT platform and be updated every one second. The six graphs represent both the three axes of the accelerometer X, Y, and Z and the three axes of the gyroscope X, Y, and Z. Each graph represents real-time data which is updating every one second. The data of the graphs can be stored or sent via email as a CSV file for further monitoring and checking by the medical professionals or the couch to follow up on the player’s condition.

Figure 16 shows the data measurement of the device prototype on axis X and Z of the accelerometer.

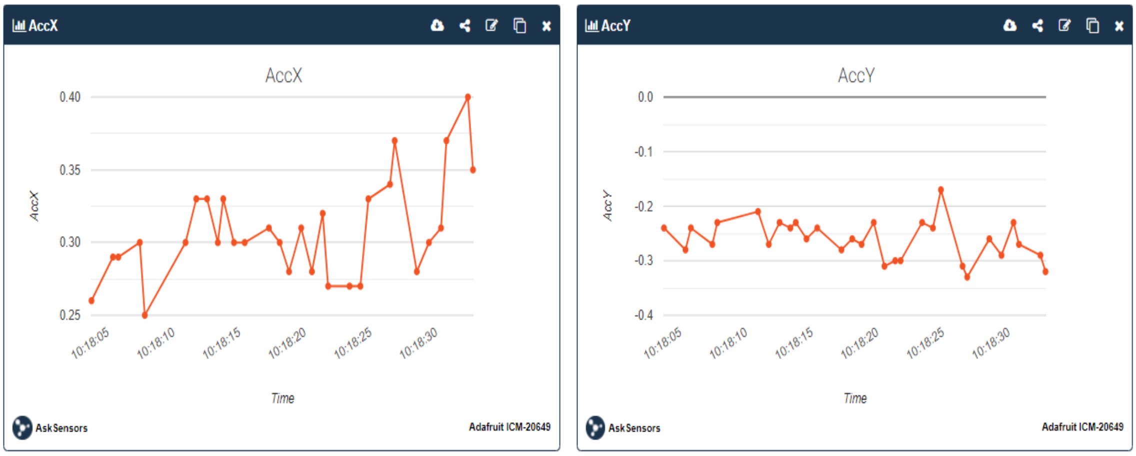

Figure 15. Data analyze on Accelerometer X and Y axes.

Figure 16 shows the data measurement of the device prototype on axis Z of the accelerometer and axis X on the gyroscope.

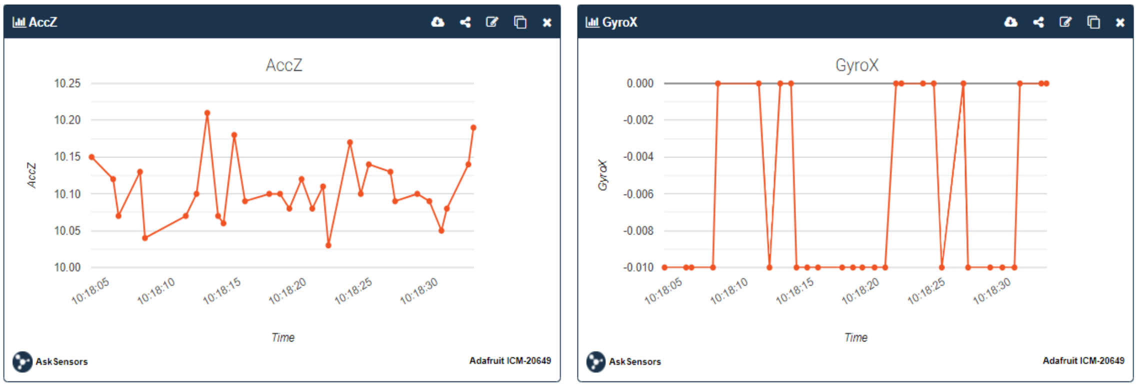

Figure 16. Data analyze on accelerometer Z and gyroscope X axes.

Figure 17 presents the sensor data measurements of the gyroscope Y and Z axes.

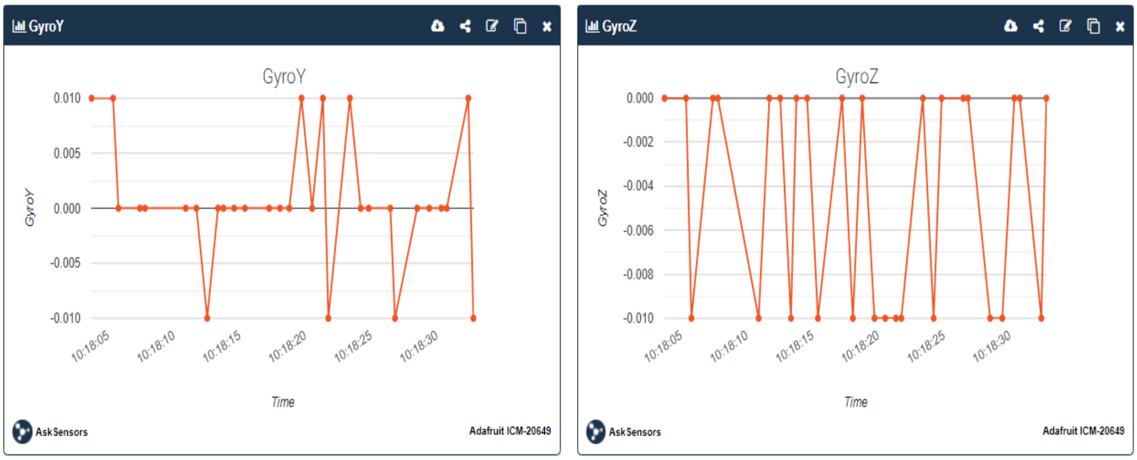

Figure 17. Data analyze on gyroscope Y and gyroscope Z axes.

Sensor data transmission to the cloud and, providing real-time measurements data for the six axes of the sensor to present them on graphs was successful. This part presents the wireless communication of the device and one of the main goals behind this thesis work and it was accomplished.

8.3.2 Blynk App

Blynk is an IoT platform that lets anyone command, track, and communicate with their IoT devices. It can be considered as the scattering of IoT. It comprises a list of orders on the libraries and a cloud server for Internet-connected devices such as an Uno Arduino, ESP32 baseboard, or a Raspberry Pi and there are many other boards supported [15]. A program with Arduino IDE and the blink libraries will create a connection between the device and the server, which can be accessed from a mobile app to design the user interface for the project.

Blynk app was chosen because it has a beneficial feature that can be used with the new version of the device prototype. Some of the features that helped with the process of relaying on Blynk instead of another app were :

- Cloud platform : it can connect any device and hardware module over the Wi-Fi, LTE, 2G-4G or Ethernet to open and secure cloud.

- Fast and reliable : Have the feature of providing real-time data and the Blynk server is ready to use in minutes. In addition, it is ready to manage a huge amount of request from the edge devices will be very helpful with the device prototype.

- Blynk Library: can connect the hardware devices that support the Wi-fi wireless communication technologies.

- Pre-designed widgets: that can help with designing the app interface of the prototype and use it to connect to monitor sensor data, store and share data and receive notifications.

This stage was completed to provide an access to the data measurements from an app either with a smartphone or a computer by using an emulator to enable running the Blynk app on the computer, laptop, or any device connected to the internet.

In this phase, the third program was used that combined both features of the Blynk App and the AskSensor platform. When compiling the project, the authentication code for the app project will be required for the data to be transmitted to the required project.

Figure 18 present the Blynk results after compiling the program. As it is shown there are two graphs used on the app one graph is used for the accelerometer with three axes X, Y, and Z, and the second graph is used for the gyroscope with three axes X, Y, and Z. Each axis is colored with a different color to make it easier to follow up on the data analysis. The data can be shown in real-time as will the option of specifying the time needs to follow the results.

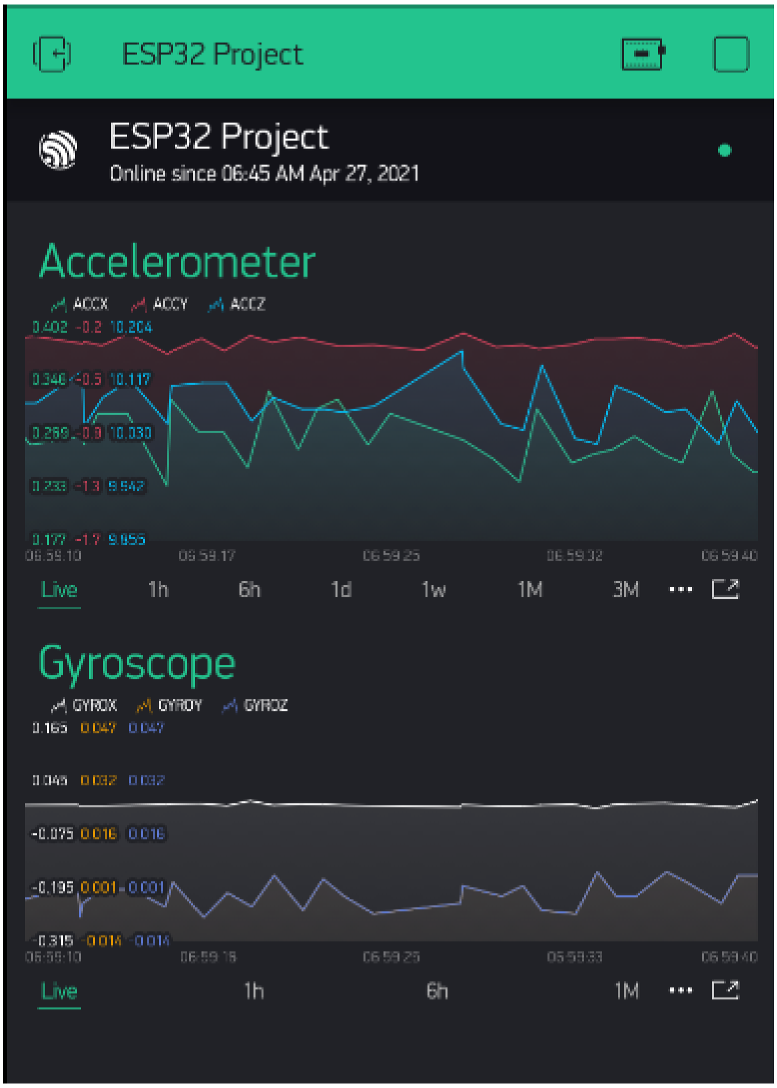

Figure 18. Blynk app results of sensor data.

Figure 19 shows the possibility of selecting a specific axis to follow up with via the medical professionals or the coach. When reviewing the data measurements and in case of suspecting unnormal situation rest of the axes can be made invisible to continue with the specified axis. The red line on the accelerometer graph represents the axis Y and the orange line on the gyroscope line represents the axis Y. The rest of the axes on both the accelerometer and gyroscope is placed on the invisible feature.

Figure 19. Axis selecting feature.

While the data is available on the Blynk app the same data is available as well on the AskSensor platform and the access will be possible through internet cloud or the app.

The three programs presented a successful outcome on connecting the device prototype to Wi-Fi, cloud, and Blynk App. As mentioned earlier more tests will be applied to the new version of this prototype to adjust the data measurements to receive accurate and guaranteed data of the gyroscope and the accelerometer. And, to provide higher efficiency, performance, and qualification design.

8.3.3 Results

When it was finally time to test out the device, its system was capable to collect the data simultaneously on a single MCU, which proved the design features were working. The acceleration data and gyroscope were read by the MCU properly and output onto a monitor where it could be read in real-time to prove that the design was reading data accurately and quickly. After the program startup, both accelerometer and gyroscope six axes were outputting the values of the measurements. However, data measurements were not 100% accurate comparing to the first version of the device, therefore, extra adjustments and tests will be applied.

The work on the new version is not finished and further work will apply as part of the internship. Hence, the development work including all aspects of the new version will remain in progress. From here the wireless communication is covered in addition to the cost and size. The data measurements will be adjusted again on the device to provide accurate measurements that balance the old version system. Also, test samples from a real player’s during contact sport will be added to achieve and accomplish the best outcomes, accuracy, high performance, and success. The goal of this thesis work was to develop and deliver the best possible results for a head impact device.

The development of the new version of the device was quite good compared to the short time that was available between hands, as well as the limited conditions due to the COVID-19 situation. The goal of the thesis work of developing a new version of the device prototype and its main requirements has been achieved.

Table 3 presents the development of the new device prototype and the changes that happened on the new version comparing to the first version of the device prototype:

Table 3. The results of the development of new device prototype.

Device Specifications	Old Version	New Version
The Size	1 main MCU + 2 sensors + 1 MCU for wireless communication. Relatively big and consume large space to be placed inside a player's helmet.	1 main MCU + 1 sensor. Small in size and space, can easily be placed inside a player's helmet.
Wireless Communication	BLE technology no direct connection to cloud unless with another mediator.	Wi-Fi support direct, easy and reliable connection to cloud.
Cost	Main MCU = 21,13 € Gyroscope sensor = 10,59 € Accelerometer Sensor=10,59 € Mediator MCU(Photon)= 20,92€ Total = 63.23 € per device	Main MCU = 8,47 € Sensor = 12,66 € Total = 21.13€ per device.
Transmission Range	BLE > 100 m.	Wi-Fi 100 m to several km (with boosters).
Data Rate	125 kbps to 2 Mbps	10 to 100+ Mbps
Power Consumption	Low	Medium

9 Conclusion

The development of the new version of the device prototype mainly aimed to smaller the size of the old version to make it fit and have little space as possible inside a player's helmet during the contact sport as well as to smaller the cost. In addition, the work aimed to cover the wireless communication methods of the head impact sensor to have access to the cloud. The first design data measurements system was approved for the MDS company. Therefore, the goal was to reach equal and similar data measurements results on the new version but with a new hardware system plus cloud access.

The wireless communication of the device prototype succeeded to send, store and connect to the cloud with the same measurements that was transmitted from the sensor to the IoT platform AskSensor. Also, the app version for the device was successfully obtaining the data wirelessly while displaying real-time data for the six axes of both accelerometer and gyroscope as the linear and angular acceleration.

The new version of the device prototype was designed with one MCU and one sensor only which make the new design smaller in size and take less space on the helmet of the players during contact sport and making it ideal as a wearable device and light in weight that does not cause extra weight on the players' head. Plus, the cost of the new design is very low and reasonable comparing with the old version.

The future work of the development of the new version of the device prototype shall be continued covering the aspects ahead:

- Data measurements adjustment and sample test on real players is required to achieve accuracy and proficiency for the head impact assessment.

- Power supply was decided to be as a power bank but have not been yet tested, therefore, further test on the power supply is also needed.

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