

Think Control Group

Final Report

Universal Controller

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Revision	Date	Author	Description
A	12/03/2017	ThinkControl Group	First release

9 June 2017

Word Count: 11303

ABSTRACT

This report summarises the design and development of a headset aiming to provide users with novel, yet intuitive control inputs for interaction with digital and physical systems. Particular emphasis has been given to facilitating those with cognitive and/or motor impairments. These individuals often face numerous challenges, including limited educational and recreational activities, thereby creating a sense of exclusion from their community and peers. Our headset enables the user's attention level, voice commands and head movements to act as control inputs to a target system. These control inputs were chosen in order to accommodate for user's that may have difficulties in interacting with such systems normally.

In our testing we were able to wirelessly control a Scalextric racing car, computer mouse cursor and other digital devices; proving that these control inputs are versatile enough to interact with a variety of systems. Self-optimisation ensures that the headset is able to dynamically adjust according to a user's individual capability (e.g. their range of head movement), while vocal commands enable the user to switch between controlling a race car, mouse cursor or other system, highlighting the flexibility of the headset.

The least accurate control input is identified as the EEG hardware used to record user attention. Voice recognition has the most potential, for example further development could easily facilitate creating new vocal commands on the fly.

This headset can thereby allow users to interact with systems otherwise unavailable to them, facilitating a larger variety of available activities and promoting better mental health through training. Additionally, as this headset functions as a universal controller that can exercise cognition, controlled motor movement and speech. We envision applications in therapeutic environments where patients can make their daily tasks, education and leisure activities part of their rehabilitation, resulting in a more stimulating and engaging treatment programme. All of which can be done from the comfort of their home.

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1 Introduction

1.1 Background

Paralysis is the inability to move a part of the body and has various causes, the most common ones include strokes, spinal cord injuries and multiple sclerosis. The severity of paralysis can vary, ranging from inability to control one of the body's limbs (monoplegia) to paralysis below the neck (quadriplegia) ^[1]. Paralysis may also be accompanied by mental difficulties, such as decreased ability to focus, or physical difficulties including impaired eyesight ^[2]. One of the major problems faced by individuals with severe cases of paralysis or other physical and cognitive impairments is the limited recreational and educational activities available to them, due to poor accommodation of their difficulties. The lack of activities shared with their peers often causes a feeling of exclusion from the community, resulting in a negative impact on the mental health of these individuals. Moreover, absence of a platform enabling access to educational resources such as computers hinders the personal and intellectual development of these individuals. Devices that are currently used for leisure activities for these patients are expensive, excessively complicated and difficult to calibrate between different users. There is an increasing demand for more user-friendly and cost-effective devices that accommodate an individual's impairments, and provide access to traditional activities such as playing with racing cars or controlling a computer.

1.2 Aims

The initial aim of the project was to create an EEG-based headset that provides a user with remote control of a Scalextric race car. After investigation and feedback from target users, the project scope was expanded to better facilitate use by those with motor control and mental difficulties. The project fundamentally acts as a proof of concept for using a range of sensors to provide individuals with more intuitive control over the devices and systems they are forced to rely on, including mobility wheelchairs, learning apparatus and cognition training.

This project's primary focus is to allow children with mental and physical difficulties access to conventional activities that they would otherwise be unable to use. Furthermore, the product strives to provide a more intuitive interface to systems encountered in everyday life, digital or otherwise. We anticipate that the main beneficiaries will make frequent use of the product for everyday tasks, which they are currently unable to undertake, or have difficulty in doing so.

1.3 Objectives

With the aim of the project defined, the process of advancing the project was broadly broken down into several developmental stages. The progress of the project was facilitated by appropriate project management (Appendix A).

Definition of headset and target system functionality

Following the analysis of user and technical requirements, the first draft of desired functionalities was designed which elaborated on the features which could supplement the base EEG module, in order to fully satisfy user requirements. This included the addition of sensors as alternative user inputs, as well as modules to act as a user interface or improve ergonomics. A draft of the possible systems which could be controlled using the headset was also created. The physical layout of the circuitry, as well as the headset chassis to use, was also considered.

Functionality evolution and data interpretation

The possible functions of the headset were tested empirically for their viability as part of a hands-free wireless universal controller. This included testing for sensor's noise, power consumption and range of operation, both physically and in terms of output. The limited space in the headset was also taken into account at this stage. Another point to determine was how the output from the sensors could be interpreted. Rudimentary programs that gave clear, characteristic outputs in response to an input were created. In addition, methods to control the target system using these outputs were explored.

Processing unit, communication and programming language

Multiple brands and models of microprocessors at different price points are available across many markets. Research determined the most suitable microprocessor was a combination of a Raspberry Pi Zero W as the main processing unit, which interprets the data, and an Arduino Nano, as the unit that monitors the supplementary sensors and user feedback. The Raspberry Pi Zero W's built in Bluetooth 4.0 capability also allowed communication with the target system's "black box", which consists of an Arduino Nano with a Bluetooth module which received sensor data to pass into the target system. Determination of the microprocessors to be used directly chose the programming languages with which the project would be developed with; C, C++, Python, Bash.

Calibration and multiple users

As a platform for intuitive control, the calibration process is important to ensure that the output is meaningful and representative of the user's commands, without being too extensive or time consuming. As multiple users are expected to operate the headset, the calibration process needs to be robust enough to adapt to different user profiles. The possibility of saving these user profiles for future use was also explored.

Power source

Previous stages of the development process gave information on the power requirements of the microprocessors and sensors. Both calculations and empirical data were made to determine that the battery provided in the retail headphones is able to power the additional components whilst providing a desirable battery life.

Final design and manufacture

The list of components needed to create the design was finalised. Following this, circuit schematics and printed circuit board (PCB) designs were made using OrCAD and Allegro PCB editor. These circuits were verified using breadboards before they were created as PCBs.

Public demonstration and user feedback

Completion of the prototype allows the performance to be evaluated from observation of its usage during public tests. The feedback of the testers are also taken to help refine the calibration process, sensitivity and expand the list of potential target systems.

2 Requirement Definition

2.1 Background Research

Prior to design and development process, background research was conducted in multiple areas:

Market research: Market research was initially conducted through web-based searches and direct communication with staff from a special needs school (Appendix H). We were able to identify: the features that would be necessary for use by children in a special needs school, the appropriate complementary control inputs necessary to accommodate users with mental and physical difficulties and that there were no functionally similar products in our price range.

Research of the general market showed that there is potential to introduce the product in the domiciliary care sector, due to decreased number of carers, and child care services sector, due to increased spending ^{[7][8][9]}. Introducing the product to these sectors may obtain government support, enabling subsidies to reduce product cost for users in these markets.

Pre-existing solutions and similar projects: The existence of solutions using a commercially available headset to control a Scalextric racing car ^[20], which drove us to design a more comprehensive device for the target users - the 'Universal Controller'.

Hardware and structural platform: Upon expanding the scope of the project, there was a need to research housing for the electronic components that would fulfil our functional and aesthetic requirements.

Suitable Test Applications: It was necessary to choose applications that demonstrate our project's functionality. Each application required its own background research:

Remote control of Scalextric racing car using EEG: It was necessary to understand the relevant physiological aspect of human brain function, the creation of neural oscillations, and their interpretation in the context of user input ^[4]. After exploring existing solutions we decided to use extract the output of a commercially available EEG headset, benefitting from its proprietary software ^{[3][5]}. This is further elaborated in Section 3 of the report.

Remote control of cursor on the computer screen using voice commands and head movements: Relevant background research included search for pre-existing platforms for voice recognition, assessment and selection of gyroscopes required for measurement of head movement, and search for an ecosystem capable of integrating all components. We decided to use in-house built software, to achieve better control of system functionality.

Applications of the technology in alternative fields: We expect that universal controller could be used not only by users with physical or mental difficulties, but also by healthy users. It could serve as an interesting and novel leisure tool, especially if user inputs could be customized to perform desired function. This would significantly increase the number of potential customers. The product could be used in variety of the industries, such as toy industry, gaming industry, or communications.

Pre-existing applicable technology: We identified the NeuroSky Mindwave Mobile Headset as a suitable product to record EEG data of a user, as well as several voice recognition options, including: Google's API, PocketSphinx, SnowBoy by Kitt.AI and Amazon's Alexa API.

Regulations, requirements and standards that the product must comply with: [10][11][12][13][14][15][19]

1. IEC 62133 *Global Battery Safety Regulations*.
2. ETSI EN 301 489-1 IEC 62368-1:2014 and IEC 60950-1:2005 *Safety Requirements for Audio/Video, Information and Communication Technology Equipment*.
3. *CE Marking*
 - a. 91/263/EEC - R&TTE Directive *Standards for Wireless Communication*.
 - b. 73/23/EEC - Low Wattage Directive.
 - c. 89/336/EEC - Electromagnetic Compatibility Directive.
 - d. 88/378/EEC - Safety for Toys Directive.

We also looked to satisfy the: IEC 60601-1 *Standards for Medical Design*. This additional certification would help target a larger user base and create the possibility of developing the product for therapeutic use.

2.2 User Requirements

We contacted staff and met with students in John Chilton School, a special needs school. Here we were able to understand the difficulties that were faced by students that, in addition to their medical or physical needs, may have learning difficulties.

The students were representative of our target users, their feedback and anecdotes were insightful into developing the ideal product, serving as the primary source for formulation of user requirements for the headset (Appendix H):

1. The headset should be engaging and fun to use.
2. The headset should be lightweight and comfortable. It should allow the user to wear it for long periods of time without causing discomfort or negative effects on posture.
3. Secure fastening should ensure approximately fixed position of headset relative to the user's head for entire session duration.
4. Size adjustability of the headset should accommodate for the range of head sizes that may use it.
5. The surface in contact with the user's head should not reach uncomfortably high temperatures.
6. The headset should be easily sterilized by commercially available alcohol-based detergents, to comply with standard hygienic requirements.
7. The headset should be resistant to wear and frequent impact forces. The product is to be accessible to children, who might suffer from involuntary muscle movements. The device should be able to withstand being dropped or colliding with nearby objects/surfaces.
8. The circuitry is well contained in the headset, such that it is difficult to access internal circuitry and components without appropriate tools.
9. Headset will be suitable for outdoor conditions. It is expected to be used outside under various weather conditions, ranging from light sun, no wind and no rain, to mild rain, moderate winds and temperatures reaching a minimum of -20°C and a maximum of 50°C.
10. The headset should have low latency: the target system should respond seamlessly to the input stimulus.
11. The headset should be sensitive enough that input stimuli do not need to be exaggerated for detection by sensors.
12. The device works at most 8m within line of sight of the target system.
13. The headset should be quick to setup and easy to calibrate.
14. Training process required to use the device should be simple.

2.3 Technical Requirements

Note: Abbreviations used throughout this section are explained in Appendix G.

2.3.1 Functionality and Performance Requirements

1. Raw EEG data is periodically recorded and converted to a digital data stream. Anticipated output is 8-bit data at a baud rate of 9600.
2. Complementary sensors will monitor the user's head rotation and acceleration triaxially. The accuracy of the gyroscopes will be programmable to better capture the user's expected speed of head movements, deviating between a user playing sport or making subtle gestures.

Gyroscope programmability: ± 250 , ± 500 , ± 1000 , and $\pm 2000^\circ/\text{sec}$ (dps)

Accelerometer programmability: $\pm 2g$, $\pm 4g$, $\pm 8g$, and $\pm 16g$

The frequency of readings will be determined experimentally, but must capture enough data for seamless interaction and to not push the output bus over capacity.

3. EEG data will be either wirelessly sent to a PC based system or by direct connection to an Arduino depending on experimental data processing latency. Complementary sensory data will be sent to an Arduino by direct connection.
4. If EEG data is sent to a PC based system, it will be processed into commands using the commercially available Mindwave software. Any data sent to the Arduino will be appropriately processed into commands in-house written Arduino code.
5. Processed commands will be wirelessly sent to a receiving Arduino, the method(s) of wireless transfer is subject to experimental development.
6. The receiving Arduino will be connected to appropriate control systems and execute any appropriate commands. In the case of the Scalextric application it will operate a digital potentiometer from 0-100% of its resistance. The maximum resistance of the potentiometer will be optimized experimentally.
7. The ability to function normally despite mechanical disturbances, such as sudden movements of the user or knocks and drops.
8. The headset will incorporate mountings for electrical components to minimise their exposure to mechanical disturbances.
9. Immunity from possible interference from other electrical devices and signals.
10. Identify and remove any outlying data, voice recognition should distinguish commands from background noise.
11. The batteries used to power the device will be rechargeable.

2.3.2 Physical Requirements

1. As per the client's specification the headset must achieve a battery life of one hour. However, repeat charge cycles will lead to the battery becoming consumed, therefore the prototype must achieve a minimum battery life of 2.5 hours.
2. The device should not restrict the user's freedom of movement. The appropriate constraints for this are: a radial extension less than 70mm at the over-ear headphones and a radial extension less than 25mm across the headband; these are only constraints and throughout development they will be minimized.
3. The headset will not cover any of the rear of the head as some users may require this area to be supported.
4. Minimizing free space in the headset will consequently decrease thermal dissipation from electronic components; ventilation must be incorporated effectively whilst not providing a compromising ingress route for water.
5. Product must be able to comply with physical and technological requirements outlined in Table 3 below:

Parameter	Limit	Reasoning
Skin contact heat	25 °C	Prevent discomfort or burning the user
Size adjustability	50 mm	Accommodate variations in user's head size
Mass	600 g	Prevent straining the user's neck; typical headphone mass
Weight balance	50 g	Prevent straining the user's neck
Impact resistance	48 N	Assuming 2m drop height, impact lasts 0.25s
Ingress Protection	IP55	Dust ingress protection, unidirectional low pressure water
Latency	1.0 s	Provide a responsive solution

Table 1. Selected technical requirements for the Headset

2.3.3 Usability, Interface and Ergonomic Requirements

1. The headset size will be easily adjustable via snap in place extension. Volume level will be adjustable via built in potentiometer to adapt to both the user's preference and their environment.
2. Programmable thresholds will allow the device to calibrate itself between users based on their average cognitive function level, maximum head movements and vocal footprint.
3. Programmable accuracies for movement sensors will allow the system to optimise between a user at rest and one involved in physical activity, this may be achieved by via a button, voice command or directly changing the program.
4. User feedback will be given by built in facilities such as a battery indicator light, audible cues, miniature vibration engine(s).
5. Graphical representations of data are displayable via PC based Mindwave software. This will show current cognition levels, types of brain waves and their respective quantities, signal quality from the headset and other parameters such as attention and meditation levels.
6. The above facilities will require brief training as most are intuitive functions. Connecting the device, changing sensor accuracy and running the Mindwave software will require a short explanation from a manual provided with the product.

2.3.4 Environmental Requirements

1. The headset will be typically used at a temperature close to 25 °C, however, it should be capable of working in temperatures that range from -20 °C to 50 °C.
2. The headset may be exposed to sweat while used and particulates while in storage. Product will be designed to be suitable for an IP55 IP rating where it is resistant to dust and sustained low pressure water.
3. In a loud environment, the user should avoid using the voice recognition software. Its performance would be affected. During the product testing phase, the extent to which this true will be determined.
4. The device should not be used in a strong magnetic field as this could hinder the efficacy of certain sensors present in the headset.

2.3.5 *Safety and Security Requirements*

1. Restrict access to the circuitry inside the headset. The circuitry presents a risk of electrocution caused by skin contact between it and the user. This will be prevented by making the components difficult for the user to access.
2. Nullify the risk of electrical fires. This could be caused by poorly regulated voltage and current in the circuitry, general poor circuit design or exposure to dust and moisture. Regular simulation and testing of the circuit will be performed during the manufacture process to ensure that potential circuit malfunction is avoided.
3. Prevent choking hazards. There should be no detachable small objects, including those with sharp edges, which pose a hazard if attempted to be swallowed. This is especially important since the device will be used by young children.
4. Non-abrasive design for the electrodes in contact with skin. The material and structure will be such that damage to the scalp is avoided.
5. Will not contain toxic, carcinogenic or harmful substances. Use of mercury, lead and other harmful substances in the final product will be avoided.
6. Dismantling the device should not cause harm or the release of harmful substances.

2.3.6 *Life, Reliability and Maintenance Requirements*

1. Life expectancy of the product is at least two years,
2. The product will require minimal maintenance for the individual parts. There are no mechanically dependent systems, therefore any issues with the device would arise from the electrical connections or software. Electrodes may need to be replaced and cleaned depending on the product usage.
3. In case of a mechanical failure a series of tests would be performed to diagnose the problem. Firstly, all the connections will be checked and repaired where necessary. The software would also be examined and potential corruption investigated. This may be fixed by re-uploading the program or replacing the memory unit of the Arduino or Raspberry Pi.

2.3.7 *Legal and Regulatory Requirements*

As a software belonging to a third party is used for the voice recognition, design will comply with their legal requirements that they follow, including the Data Protection Act.

This is not a medical device and should not be substituted for use as one. The device will meet all required safety and health requirements set out for Children's Toys and Electronics as stated by the UK and EU government. This is inclusive of Restricting of Hazardous Substances (RoHS) and CE in electrical and electronic equipment requirements. Additionally, it will be required to following directives for its disposal:

- Waste Electrical & Electronic Equipment (WEEE) (Directive 2012/19/EU)
- Packaging and Packaging Waste Directive (Directive (EU) 2015/720 amending Directive 94/62/EC)

3 Final Design

The final design consists of headset containing sensors, power supply, processing units, user feedback, support circuitry, and communication unit. All circuitry is contained in the headset and there are no exposed wires, thus eliminating risk of electrical defects and subsequent user's injury.



Figure 3.1.1. The picture of the final headset

During development process, three sections were considered: **mechanical design** describing the design of the headset and housing of its components, **hardware section**, consisting of all the sensors and circuitry required to receive and process user inputs, and **software section**, describing code required for data processing and communication with target devices. Manufacturing process is discussed in the greater detail in Appendix D.

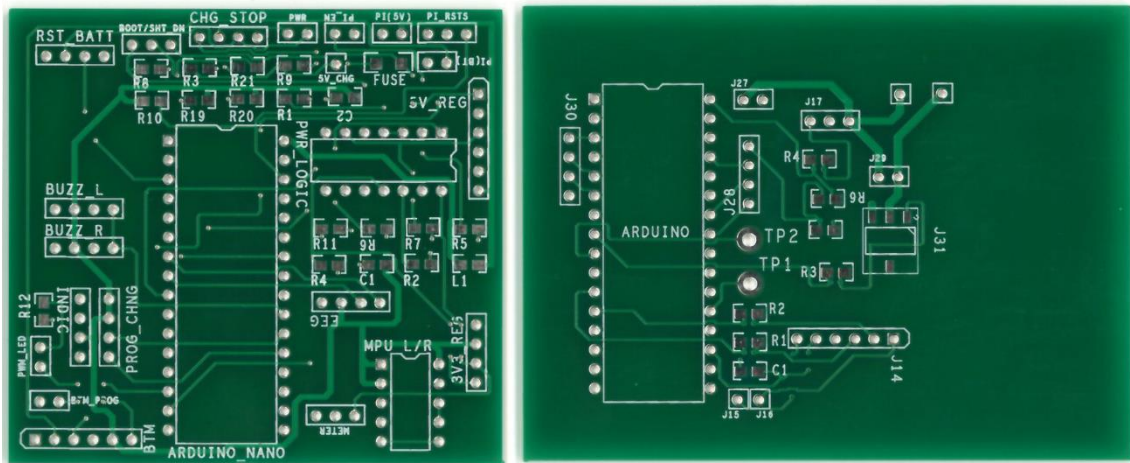


Figure 3.1.2. PCB Schematic for Headset and Black box

3.1 Mechanical design

Headset

For user comfort and electrical safety, a commercially available gaming headset was emptied and repurposed to become a chassis to accommodate the components for the product including: a power supply, a printed circuit board (PCB), a modified soundcard, a Raspberry Pi microprocessor, a buzzer, a battery indicator, two MPU6050 for head movement, a built-in microphone, non-invasive electrodes for the NeuroSky Headset and connection wires between components.

The left ear cup contains a battery indicator that is visible on the outer shell of the chassis. It also holds the reference electrode for NeuroSky, the PCB, Raspberry Pi, one of the two MPU6050 and power supply. The other ear cup accommodates the sound card and the buzzer. The measuring electrode from NeuroSky headset is mounted on the headband of the chassis gaming headset by an elastic hairband to avoid discomfort from long-time usage. The other MPU6050 is mounted onto the top and the centre of the headband of the chassis.

3.2 Hardware

Power

In order to make reuse of the headset simple, it was decided that the headset would be powered by a rechargeable battery. To minimise costs, the rechargeable 4.2V lithium ion battery present in the gaming headset was recovered and used to power the system. However, the sensors and processors in the system have different power requirements. This meant that a 3V3 Regulator and a 5V Boost Regulator had to be used to distribute the correct amount of voltage to the appropriate parts of the circuit.

System Control

In the original design of the system, a computer was intended to coordinate the system response to input data. However, it was later realised that a Raspberry Pi Zero (Model W) could perform the same tasks and would improve the portable aspect of the device. Hence, the system consists of three core processor units: an Arduino Nano, that collects and distils raw EEG and head movement data and can initiate haptic feedback; a Raspberry Pi Zero W that receives the input data to the Arduino Nano, via a USB connection, and uses it to form a command signal for the second Arduino Nano; a second Arduino Nano that is connected to the slot car tracks and uses the command signal to vary the resistance of the track and so the speed of the slot car.

System Logic

The circuit was programmed to turn off the components of the circuit in a specific order because suddenly removing the power from the Raspberry Pi Zero W would have led to data corruption. Hence, when the user puts the switch for the device in its off state, the Raspberry Pi shuts down and the Arduino turns off the 3V3 Regulator connected to the sensors - effectively shutting the sensors down. The Arduino then shuts itself down by turning off the 5V Boost Regulator.

Sensors

The data from various sensors is integrated to provide a detailed description of the user's state and so produce the appropriate response within the target system:

ThinkGear Module - The headset contains a NeuroSky ThinkGear Module that collects data on the user's attention at a given time. The module quantifies the distribution of Alpha, Beta, Gamma, Delta, and Theta brain waves within the user's brain and uses this to generate an attention value [3].

MPU6050 Gyro/Accelerometer Units - Modules provide the acceleration in the x, y, and z direction. The distribution of gravitational acceleration is suitable for keeping track of the user's head position. The gyrometer function provides the rotation in the 3 axis. However, reproducing readings within ranges small enough to allow implementing discrete levels was difficult for a normal range of head movements during testing. Thus, this feature was not included in the final product as seen in Figure 3.2.1.



Figure 3.2.1. Left ear cup of headset

Sound Card/Voice Recorder - The headset's pre-existing microphone is wired to a USB sound card that is connected to the Raspberry Pi. The sound card transforms the raw analogue microphone data into a digital signal. The Raspberry Pi has been set up such that when microphone data is requested (using [arecord](#)) the digital signal is pulled from the sound card and stored in data buffers.

In-built Stereo Audio - The sound card's output audio is wired directly to the original headset's PCB. This setup allows us to utilise the volume control knobs that were already built in the headset. Furthermore, the volume of L and R channels are independently adjustable as both the 'game chat' (L audio) and 'game volume' (R audio) potentiometers have been independently repurposed. This accommodates users of various sound perception strengths and abilities allowing for a more inclusive experience. The additional wiring made to achieve this can be seen in Figure 3.2.2.; a simple voltage divider was built around each potentiometer to ensure a smooth roll off of speaker performance. The optimal resistance network was found ultimately by trial and error as the inclusion of the soundcard made this circuit non-linear, Figure 3.2.3 shows the final model used.



Figure 3.2.2. Connection between PCB and built-in stereo

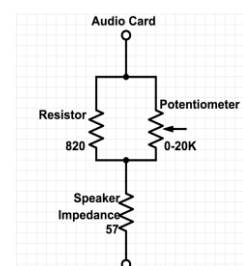


Figure 3.2.3. Schematic of Audio Card connection to PCB

3.3 Software

Sensors

Data is processed and transmitted through the system in such a way that it is easily interpreted at each stage of communication:

MPU6050 Gyro/Accelerometer Units - Data from this sensor is collected by the Arduino and sent, via serial port, to the Raspberry Pi. The Raspberry Pi performs a calibration routine, coded in Python, which first takes the average accelerometer readings over a 5 second period to determine the resting position of the user's head. The sensor's readings thereafter is divided into twenty quantised levels. The level gap is derived from the maximum recorded deviation to ensure the sensitivity corresponds to the individual user's mobility. The system response to increasing levels of deviation by x^2 to avoid a large head motion being required for any action. An effect of this method to determine level gap is that an initial turn of the user's head is needed after the resting position is determined to provide a baseline maximum recorded deviation.

Voice Recognition Programming - The main Python program, run in the Raspberry Pi, creates a process that runs the [Snowboy](#)-based voice recognition code in the background. The code constantly searches the microphone data buffers for pre-determined 'keywords'. Once a keyword has been detected, the voice recognition code changes global variables in the main program and causes a feedback sound to play through the headset's speakers. The modification of global variables allows the main Python program to change its flow.

Haptic buzzer - Haptic buzzer feedback is initiated by specific sections of code in the program, that runs continuously, in the Raspberry Pi. An auxiliary thread directly controls feedback. This thread keeps track of the number and duration of buzzes independently and it activates and deactivates the buzzers via the Arduino Nano. Triggers for feedback also exists in the Arduino code for operations, including battery life monitoring, that are not controlled by the Raspberry Pi.

Bluetooth - A custom header file was created that contained functions to enable use of the inbuilt Bluetooth chip of the Raspberry Pi Zero W. The functions allowed connection with a desired MAC address, sending data to the MAC address and closing the Bluetooth connection. A sample set of code is seen below. The changeMacAddr function allows the changing of the MAC address to a suitable format for the subsequent functions.

```

# -----
#           Bluetooth
# -----

def changeMacAddr(word):
    return ''.join(c if c != ':' else '_' for c in word)

def connBT(BTsubProcess, stringMacAddr):
    BTsubProcess.stdin.write(bytes("".join("connect "+stringMacAddr+"\n"), "utf-8"))
    BTsubProcess.stdin.flush()
    time.sleep(2)
    stringFormat = changeMacAddr(stringMacAddr)
    BTsubProcess.stdin.write(bytes("".join("select-attribute /org/bluez/hci0/dev_"
        + stringFormat +
        "/service0010/char0011" + "\n"), "utf-8"))
    BTsubProcess.stdin.flush()

def writeBT(BTsubProcess, listOfData):
    stringList = [str('{0: }').format(elem) for elem in listOfData]
    BTsubProcess.stdin.write(bytes("".join("write " + "".join(stringList) + "\n"), "utf-8"))
    BTsubProcess.stdin.flush()
    return

def clostBT(BTsubProcess):
    BTsubProcess.communicate(bytes("disconnect\n", "utf-8"))
    BTsubProcess.stdin.flush()
    return

```

Figure 3.3.1. Bluetooth header file

Parity Bits - To ensure accurate data transmission, each bit of data, numbered from 0 to 256, is padded by two parity bits. For example, the Arduino receiving Bluetooth commands has a function which receives Bluetooth data similar to the following:

```

SoftwareSerial BTS2(2, 3);

int getBT(int *value1, int *value2) {
    int temp = BTS2.read();
    int temp2 = 0;
    if ( temp != 205)
    {
        temp2 = BTS2.read();
        if ( temp != 202 && temp2 != 202)
        {
            *value1=temp;
            *value2=temp2;
        }
        else
        {
            *value1=-1;
            *value2=-1;
        }
    }
    else
    {
        *value1=-1;
        *value2=-1;
    }
    //return data;
}

```

Figure 3.3.1. Arduino parity decoding program.
For this example, parity bits are 205-[data bit]-202

4 Testing and Evaluation

4.1 Electronics Testing

System Shutdown - As previously mentioned, the elements of the system had to be shut down in a specific order. Experiments with the shutdown procedure of the circuit were gradually refined. They began with circuits where LEDs were used as indicators of the circuit performance and progressed to circuits that only contained the elements responsible for shutdown (resettable fuse). Originally, turning the device on or off was going to be controlled by a pushbutton, however, the device can be on, off or in a momentary state where the Arduino is reset. Hence, to make its operation simple for the user, a switch was used that could put the system in one of three states: on, off or reset. During testing, it was found that due to the circuit, it was impossible to recharge while the headset was on. This is a point that would be improved in subsequent iterations of the circuit.

Printed Circuit Board Tracks - Continuity testing was conducted on both circuit board designs to ensure build quality, schematic adherence and crucially short circuit avoidance. Breadboard models were assembled in parallel with PCBs to ensure circuits were soldered and assembled correctly. This can be seen in Figure 4.1.1. Several tests for thermal safety and performance from a battery supply were taken, as well as logic based circuits for power management and system resets. Test results showed these to work well within their defined limits and operating ranges. The breadboard connectivity and its design were found to function as intended, however several improvements to its layout can be implemented as wires currently have to be extended and crossover which increases both complexity and material build cost.

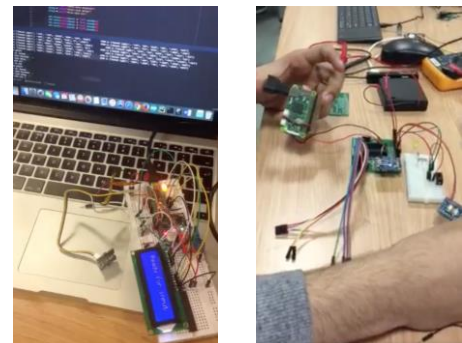


Figure 4.1.1. Verifying PCB circuitry using Breadboards

Microphone and Voice Recognition Sensitivity - The sensitivity and gain for the digital signal from the sound card was tuned by trial and error. Test recordings were made speaking at varying distances from the microphone, and the fine-tuned gain was then tested with the voice recognition system. Background noise was then synthetically added to recorded samples and run through the voice recognition program to test accuracy under varying relative noise. This gave us promising results, shown in Figure 4.1.2.

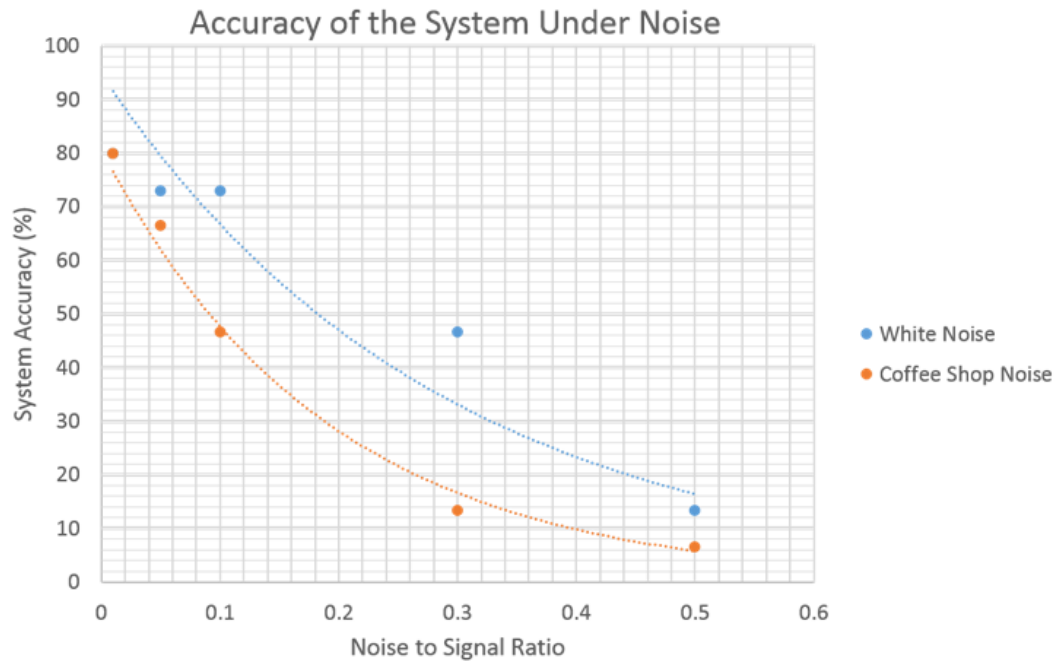


Figure 4.1.2. The graph demonstrates two types of synthetic noise effect on the accuracy of the system. System accuracy is the percentage of correct keyword detections in 12 test recordings

MPU6050 - It was found that MPU6050 noise was invariant to the state of the system. However, testing these sensors with different users showed that each had different ranges of motion. In order to provide a standard for each individual user, head movements were quantised to discrete levels. The level gap is determined from the maximum recorded deviation divided into a set number of levels. Testing was done on subjects in an upright sitting position to determine the number discrete levels required to remove the effect of noise while maintaining intuitive sensitivity over the small range of head deviation. The governing relationship between system response and levels of deviation needed to be nonlinear so as to avoid large movements being needed for any action. Exponential and x^2 equations were tested, with the x^2 found to give a more intuitive sensitivity.

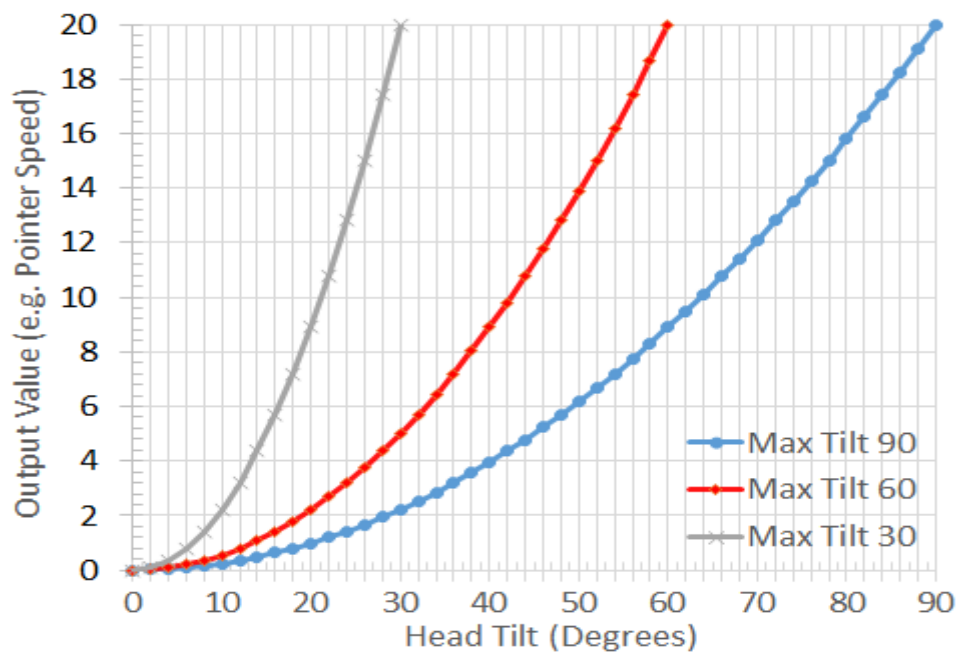


Figure 4.1.3. Each curve highlights how all quantisation levels are mapped given different extents of maximum head tilt

Battery - The battery used in the system is the 4.2V lithium ion battery provided with the headphones. The battery was charged for 8 hours to provide a full charge for testing. This was done by connecting the battery to a fixed load of 2A, the estimated current draw of the headset. Effective battery life was then considered time taken for the battery voltage output to drop from 4.15V to 3.7V. The tests did not incorporate the Mindwave EEG headset, which is powered by a separate source of 2 AAA batteries. Thus the battery lifetime of the EEG was taken to be 8 hours as given by the manufacturer for the purposes of our electronic design.

Wireless communication - Transmission of data both over Bluetooth 4.0 and Wi-Fi were found to work exceedingly well as low latency methods of wireless communication, typical speeds are documented in section 4.4. Figure 4.1.4 illustrates wireless streaming of data simultaneously from the EEG, MPU6050 and various status bits of the headset, transmission is from the headset to a receiving Arduino for Bluetooth 4.0 connection, and to a laptop for Wi-Fi. Testing showed using Bluetooth 4.0 and Wi-Fi built into the Raspberry Pi Zero W reduced the time taken for signal transmission and overall power consumption.

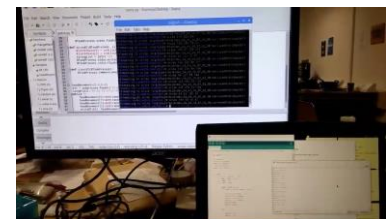


Figure 4.1.4. Demonstration of communication between Arduino Nano and Raspberry Pi via Bluetooth

Converting Raw Attention Value – Figure 4.1.5. shows the typical effect of processed attention values on the speed of the car. This plot is based on the headset predicting data trends and attempting to adjust to trends specific to a user's cognitive patterns.

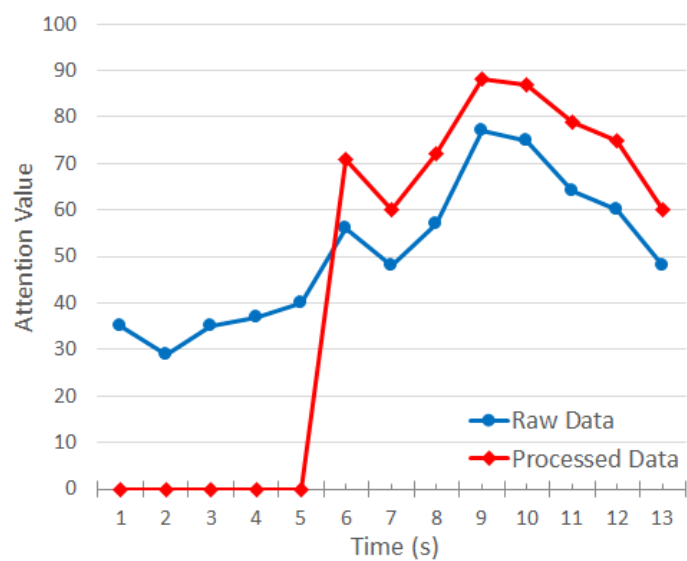


Figure 4.1.5. The graph highlights how output attention data is suitably scaled after Raw Data exceeds the set threshold

4.2 User Feedback

Feedback for the prototype of this product was given on the days that it was exhibited - Demo Day and Imperial Festival. The feedback suggested that the device satisfied many user requirements, but also highlighted those that should be addressed better in future iterations.

Users stated that the versatility of the device would make it more engaging and provide a more exciting experience. Given that the majority of the target audience are young children, it was important that the device satisfies the requirement of being entertaining. Moreover, the use of sensors was recognised as an effective way to make the device more accessible to those with physical or mental disabilities, as per the intended users. The requirements specified that the product must be comfortable so that it could be used over long periods of time. At both exhibitions, there were no negative responses given about comfort and users were able to use the prototype for prolonged lengths of time.

There were suggestions for improvements that could be made to the device. The users made comments about the disparity between how much attention they were devoting and how much the prototype recorded that they were devoting. To reduce this disparity, further testing should be done to ascertain what the users should focus on to cause a desired effect. Additionally, the mapping relationship for attention values to the resistance of the track should be revisited and refined. At both exhibitions, changing from user to user involved some calibration time that could last up to three minutes. This needs to be improved to ensure that the device is quick and easy to calibrate, which is a requirement. Finally, it was noted that the Raspberry Pi has a poor built-in power regulator, which means that the battery was not being used as efficiently as possible. Even though it met the minimum requirement of 2.5 hours, a suggestion for commercialising the product was to include a more efficient power regulator in the PCB.

4.3 Evaluation Matrix

Each system and sub-system were assessed by performance, user experience and fulfilling its intended design criteria. The assessment results are tabulated below:

	Electrically Safe	Thermally Safe	Typical Latency (s)	Operating Range (m)	Power Intensive	3rd Party Reprogrammable	User Adaptable	Child Friendly	Choking Hazard	Positive User Experience	Fit For Purpose
Headset Sensory											
EEG	Y	Y	0.45	n/a	N	Attention Values	Y	Y	N	Y	Y
MPU6050			0.32		Y	Y					
Voice			0.23		Y	Keywords					
Headset Feedback											
Buzzer	Y	Y	0.32	n/a	N	Y	n/a	Y	N	Y	Y
Stereo Audio			0.05		N						
Status LEDs			0.32		Y						
Headset Connectivity											
Bluetooth 4.0	Y	Y	0.24	34 (reliable)	Y	Y	n/a	n/a	N	Y	Y
Wi-Fi	Y		0.19	15 (reliable)	Y	Y					
Serial (TX-RX)	Y*		~0	~10 (unshielded)	N	Y*					
HDMI micro	Y		~0	~20 (unshielded)	Y	N					
Applications											
Scalextic	Y	Y	0.79	n/a	Mains Supply	Y	Y	Y	N	Y	Y
Mouse			0.61								

* Device should not be tampered with to reach the serial connections, any programming should be done wirelessly

Figure 4.3.1. Evaluation Matrix

Further to this, important design criteria which have also been satisfied are:

- Battery life exceeds the minimum 2.5 hours and runs up to 3.25 hours between charges
- The device is significantly more comfortable than the unmodified NeuroSky, and test volunteers confirmed lighter than expected, reflecting emphasis taken to reduce fatigue and discomfort over prolonged use
- The Scalextic application works and meets all of its design criteria, a dedicated housing for the system was also developed to allow plug and play capability with another analogue controller
- Gyroscopic control of a mouse cursor was achieved with satisfactory results
- The potential risks of use were reduced to greatest possible extent, as detailed in the risk analysis (Appendix B)

5 Discussion

The headset that we constructed successfully functions as a universal controller, providing users with wireless control over a Scalextric racing car using EEG sensors and control of a cursor on the computer screen through voice commands and head movements. Therefore, it meets the required “Suitable Test Applications” as formulated in Section 2.1. The manufacturing cost of the prototype is also relatively low, as demonstrated in the cost breakdown in the Appendix E. Also, during construction of the headset, several important ethical considerations were made and they are discussed in the Appendix C.

However, there is still room for improvement of the final headset design, key points that were identified during implementation and testing are discussed below:

Use of proprietary chassis

For the purposes of prototyping, the headset chassis used was a set of retail gaming headphones, modified to make room for microprocessors, sensors and other circuitry, with the EEG module grafted onto the side. During development, this presented an issue when the originally procured retail model was found to be discontinued when parts for a spare prototype was desired. Although a substitute model with the same dimensions was found, this highlights an inherent risk when the design of the physical layout of a prototype is based on platforms available on the market.

If the headset is to go into the market, it will be necessary to secure a reliable source of headset shells. Due to the relatively bespoke nature of the headset as a therapeutic device, in the short term it may be viable to rely on additive manufacturing, injection moulding or contacting existing headphones companies for a limited order of custom made shells.

Proprietary EEG data processing software

We utilised proprietary hardware and software developed by NeuroSky to obtain and process the EEG data of users. While a commercially available product is more likely to deliver more consistent performance, as it has been tested by the manufacturer and put into the market, it takes a fairly large part of our budget. It is a good option for prototyping, but an issue to keep in mind if the headset would ever go into mass production.

In such cases it may be preferable that we could come up with our own solution on detecting and processing raw EEG data from users. That would allow the filtering to be designed to focus on the desired input for the main Python program, in the long term this will cost less as we will not need to purchase the NeuroSky headset and will avoid any legal ramifications of using external software.

Increased number of target systems controlled by the headset

The headset compiles the accelerometer and EEG input commands into a Python list which is sent via Bluetooth to an Arduino Nano in a “black box” which is attached to the target system. The information sent was designed with modularity in mind and has been successfully used to control the Scalextric track and a computer cursor, although different “black boxes” were needed due to the different connection between the Arduino Nano and the target system.

The headset’s voice recognition system, while able to substitute for accelerometer or EEG input, is primarily intended to allow switching between target systems. This allows the user to switch between systems that are either connected to a black box or able to communicate with the headset via Bluetooth directly. The recent trend in implementing smart technology in home appliances gives a modular, hands-free control unit like the headset great potential. Currently, there are no other inputs within the headset which could serve this function of switching between target systems. It is foreseeable that voice input may often be inconvenient, so this needs to be rectified quickly. This could be done using a switch or sliding scale on the headset, or by a combination of head tilt and EEG inputs.

Precaution for potential component failure

The primary risk identified during electronic design was malfunction of the voltage regulators, resulting in damage to the microprocessors, either via a sudden power surge or unexpected shutdown. Fuses were thus added into the circuit to stop a potential power surge. However, due to the lack of an auxiliary power source, there are no means available to avoid corruption of the microprocessor's memory should an unexpected shutdown occur.

The headset's application means it would undergo frequent wear and weathering. As such it is important the user's manual recommend replacement or servicing of the headset after a certain lifetime, which has yet to be determined conclusively.

Improving gyroscope function

Head position and head motion functions currently use the data provided by the MPU6050 accelerometers. The system programming allows head tilting within a hemisphere, the centre of the hemisphere being the base of the user's neck. It also requires that the user be in an upright position. Difficulties in coding have presently prevented monitoring head tilt beyond this hemisphere, but this is not considered a problem as it is highly implausible for a user to tilt their head downwards by such a large amount. Further development to allow use of the program with a supine subject will be imperative in order to cater to patients in bedrest when used as a therapeutic device.

Although the gyrometer output would allow the speed of head rotations to be used as input commands, this was not implemented as the readings tended to show a very high variation even for the same subject performing to their best ability the same degree of rotation at the same speed. In addition, the output suffered from much greater noise. Even quantising the output could not remove the effect of the unreliable readings and noise unless the level gap was so great that an unreasonable speed of head rotation would be needed to register as any input.

Removing reliance of EEG sensors on non-rechargeable batteries

The EEG module currently uses a separate power source of 2 AAA batteries from the headset. This presents a problem in that the battery voltage is not monitored by the headset and the status is not displayed by the battery capacity indicator, which could cause confusion and it may not be obvious the EEG batteries have been fully discharged.

The EEG module could be modified to draw power from the headset Li battery through the 3.3V regulator. It will be important to check how the extra power consumption affects the battery life. Alternatively rechargeable batteries could be used in the EEG module, to be charged simultaneously with the headset. Although this does not solve the issue of the battery capacity indicator showing only the status of the headset battery.

6 Conclusions

We were able to successfully design and construct a universal controller enables users with a variety of impairments to wirelessly control various target systems through cognitive activity, head movements and voice commands. In addition to that, these sensors require little to no training, resulting in more intuitive operation and overall ease of use.

This controller actualises a new market for therapeutic devices - it encourages patients to use their avocations directly as rehabilitation, promoting a more positive and hopefully faster treatment. Moreover, the headset finds applications with the public, in the hands of developers and electronic enthusiasts, the open-source code can easily be modified to suit a variety of hands-free applications, in line with the recent trend towards interconnected smart technology, “Internet of Things” and use of wearable technology.

Some of the functionality w successfully tested in public demonstration. The next step involves release of the device to a group of target users and collection of their feedback. This feedback, in conjunction with further ideas for development collected during manufacturing process, can be used to further improve the design of the headset.

References

- [1] *Types of Paralysis*. [Online] spinalcord.com. Available at: <http://www.spinalcord.com/types-of-paralysis>
- [2] Minutes from Meeting in John Chilton School - See Appendix H
- [3] NeuroSky.com. (2016). *EEG - Electroencephalography - BCI | NeuroSky*. [Online] Available at: <http://NeuroSky.com/biosensors/eeg-sensor/> [Accessed 2016]
- [4] Rao, R. (2013). *Brain-computer interfacing*. Cambridge: Cambridge university press.
- [5] Transport Research Laboratory, (2014). *Investigating the NeuroSky Mindwave™ EEG Headset*. [Online] Transport Research Laboratory. Available at: <http://www.transportresearchfoundation.co.uk/PDF/PPR726-Investigating-the-NeuroSky-Mindwave-EEG-Headset.pdf> [Accessed 2016].
- [6] Mika, E. (2015). *Arduino library for reading NeuroSky EEG brainwave data...* [Online] GitHub. Available at: <https://github.com/kitschpatrol/Brain> [Accessed 2016].
- [7] Cone, Lewis (2016). *Children's Social Care - UK - February 2016* [online] Mintel. Available at: <http://academic.mintel.com/display/749800/> [Accessed 2016].
- [8] Cone, Lewis (2015). *Domiciliary Care - UK - September 2015* [online] Mintel. Available at: <http://academic.mintel.com/display/717203/> [Accessed 2016].
- [9] Official Statistics - Disability facts and figures [online]. First Published 16 January 2014. Available at: <https://www.gov.uk/government/statistics/disability-facts-and-figures> [Accessed 2016]
- [10] Leber, J. (2012). *Global battery safety regulations harmonised as IEC 62133*. [Online] Newelectronics.co.uk. Available at: <http://www.newelectronics.co.uk/electronics-technology/global-battery-safety-regulations-harmonised-as-iec-62133/45034/> [Accessed 2016].
- [11] Isvr.co.uk. (2014). *EN 50332 tests for personal music players with headphones*. [Online] Available at: <http://www.isvr.co.uk/labtests/en50332.htm> [Accessed 2016].
- [12] European Telecommunications Standards Institute, (2007). *Electromagnetic compatibility and Radio spectrum Matters (ERM); ElectroMagnetic Compatibility (EMC) standard for radio equipment and services*. [Online] European Telecommunications Standards Institute. Available at: http://www.etsi.org/deliver/etsi_en/301400_301499/30148901/01.07.01_30/en_30148901v010701v.pdf [Accessed 2016].
- [13] International Electrotechnical Commission, (2014). *Audio/video, information and communication technology equipment - Part 1: Safety requirements*. IEC 62368-1:2014. [Online] International Electrotechnical Commission. Available at: <https://webstore.iec.ch/publication/6932> [Accessed 2016].
- [14] International Electrotechnical Standard for Electromagnetic Compatibility and Radio Spectrum Matters Commission, (2005). *Information technology equipment - Safety*. IEC 60950-1. International Electrotechnical Commission.
- [15] International Electrotechnical Commission, (2012). *Medical Design Standards - 3rd Edition*. IEC 60601-1. [Online] International Electrotechnical Commission. Available at: <http://www.cui.com/catalog/resource/iec-60601-1-medical-design-standards.pdf> [Accessed 2016].
- [16] DSMT.com. (2016). *IP Rating Chart | DSMT.com*. [Online] Available at: <http://www.dsmt.com/resources/ip-rating-chart/> [Accessed 2016].
- [17] Metoffice.gov.uk. (2012). *UK climate information - Met Office*. [Online] Available at: <http://www.metoffice.gov.uk/public/weather/climate/> [Accessed 2016].
- [18] Conformance.co.uk (2016) *CE Marking and Product Safety* [online] Available at: <http://www.conformance.co.uk/> [Accessed 2016].
- [19] European Commission (2016) *EU Waste Guidelines* [online] Available at: <http://ec.europa.eu/environment/waste/index.htm> [Accessed 2016].
- [20] Jones, J. (2017). *Mind-controlled Scalextric slot car*. [Online] The UK's Leading Brain-Computer Interface, Neurofeedback & Brainwave Controlled Gadget Source. Available at: <https://thinktechuk.wordpress.com/2011/11/24/mind-controlled-scalextric-slot-car/> [Accessed 2016].
- [21] Developer.amazon.com. (2017). *Alexa Voice Service*. [Online] Available at: <https://developer.amazon.com/alexa-voice-service> [Last Accessed 2017].

Appendices

Appendix A – Project Management

Our team (that we decided to name as “ThinkControl Group”) consisted of 9 members: Callum Alder, Nathaniel Carpenter, Ifeanyi Chinweze, Miroslav Gasparek, Adel Haddad, Ling Li, Lucas Low, Artem Makarov and Kathy Tang.

The head supervisor of the project was Dr Ian Radcliffe, who provided support and guidance regarding the project on the high-scale level. Meetings with head supervisor were held approximately every three weeks to review progress and deliverables prior to deadline. He also assisted with sponsorship securement by provision of recommendation letter.

We sought technical help as required from Mr Paschal Egan and Niraj Kanabar, who assisted with design and manufacture aspects of the project. They provided assistance not only with circuit and PCB designs, but also with securement of the hardware resources and advices about the best practices.

Support on lower-scale level was provided by Graduate Teaching Assistant, Dr Christopher Phillips. He supported team with his advice and perspectives on overall development of the project during (on average) weekly team meetings.

Team selected Miroslav Gasparek to be a Project Manager. His responsibility was to organize regular meetings between team members and supervisors and micro-management of the individual tasks. He also secured philanthropic gesture from Newton Colmore Ltd. These resources allowed team to cover the expenses for the additional hardware and to extend the scope of the project.

Lucas Low was selected as Procurement Manager. His role was to purchase components and equipment required for the project development, to deal with budgeting and to track overall expenses.

Callum Alder, our Technical Manager, took large scale of responsibilities, ranging from significant portion of the background research to overseeing the construction of prototype and software design. He also liaised effectively with the Mr Egan and Mr Kanabar.

The specific tasks of the team members were allocated on meeting-to-meeting basis, as the project development required, although most team members had their area of focus broadly specified. This “modular” approach seemed to be very efficient, as team members could develop expertise in certain part of the project development, while keeping the whole project picture in their mind. Overall, the atmosphere in within the group was very good, as well as cooperation between the team members. We believe that this contributed to successful completion of the project significantly.

Gantt Chart of the Project Plan:

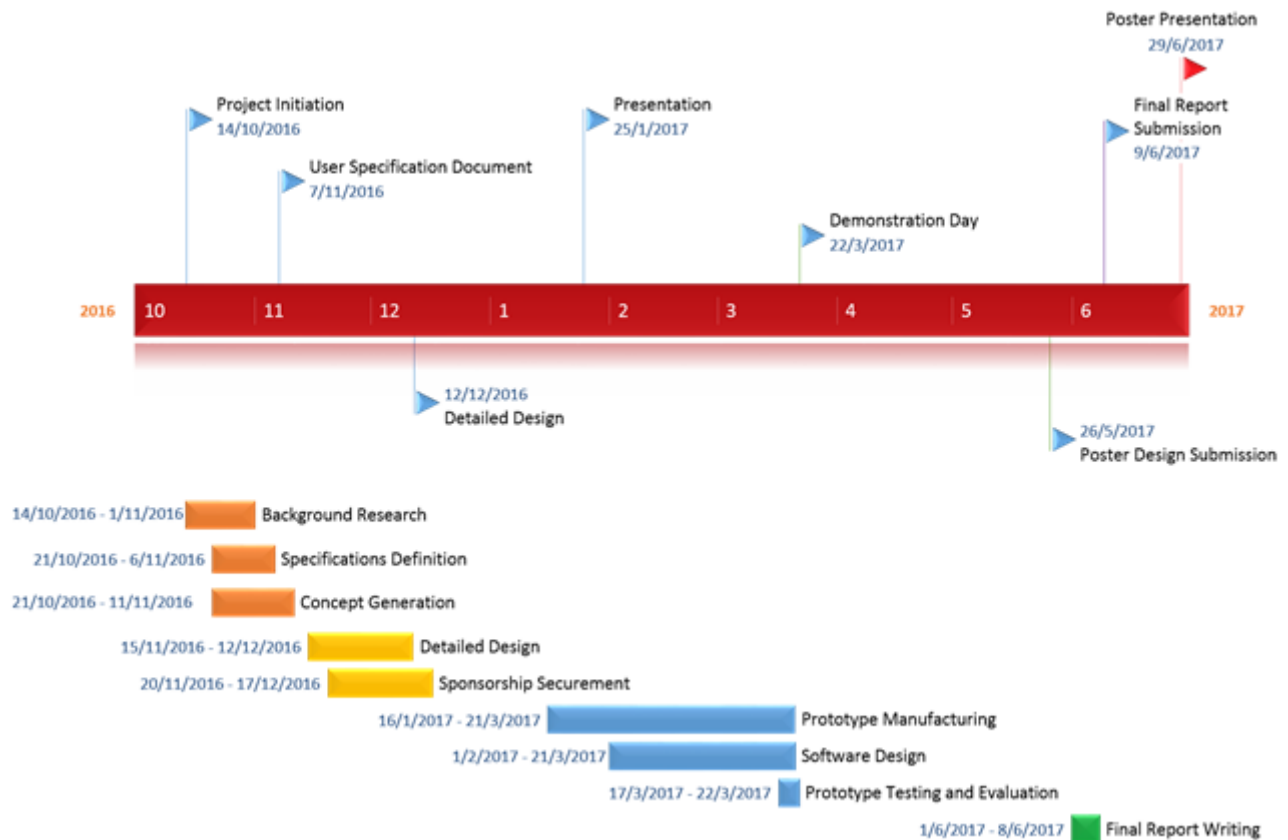


Figure A.1. Gantt Chart of the Project Plan

Appendix B – Risk Management

The failure and risk of each part of the assembly of our headset is analysed, and preventing measures explained in Table B1.

Critical Risk Priority Number

For our risk analysis, each risk or failure was assigned a coefficient of severity (S), occurrence (O), and detection (D). These range from 1, for low severity, low occurrence rate and high detection rate, to 10, for high severity, high occurrence rate and low detection. The product of these three coefficients is the Risk Priority Number (RPN).

We have chosen a critical RPN value of 75, meaning that for each risk or failure measures must be taken in order that the RPN for this risk or failure is less than or equal to the critical RPN value.

Factors of the Risk Priority Number (RPN)

Below are tables giving an indication of the values of the three coefficients of RPN (S, O and D) and their corresponding meanings. (Tables B1, B2 and B3).

RPN before is given by: **RPN before = (S1) x (O1) x (D1)**. This value is for the device prior to the addition of preventing measures.

RPN after is given by: **RPN after = (S2) x (O2) x (D2)**. This value is for the device after the addition of preventing measures.

Preventing measures are any action carried out in order to reduce either severity, occurrence or detection coefficients. These measures should have the overall effect of decreasing the RPN of that risk or failure.

S – Severity

Rating S	Criteria: Severity of effect	Consequence	Treatment
10	Death	-	-
9	Quadriplegia	Life-long medical care necessary / coma / permanent damage	Hospital stay
8	Amputations, paraplegia, blindness, deafness, traumatic brain injury (severe), fourth-degree burns	Life-long medical care necessary / coma / permanent damage	Hospital stay
7	Complex fractures, open fracture, inner injuries, traumatic brain injury (severe), third-degree burns	Permanent damage possible	Hospital stay
6	Gash, fractures, torn muscles, articular cartilage injury, traumatic brain injury (moderate), second-degree burns	Permanent damage possible	Hospital stay
5	Gash, fractures, torn muscles, articular cartilage injury, traumatic brain injury (mild), second-degree burns	Reversible injury	Hospital stay or ambulant treatment
4	Severe cuts, severe scratches, severe contusions, strains, first-degree burns	Reversible injury	Ambulant treatment or self-treatment
3	Minor cuts, minor scratches, minor contusions, stiff muscles, tension, blisters, excoriations, sickness, first-degree burns	Discomfort during application up to three days after application	Self-treatment
2	Slight sickness, pressure marks	Discomfort	-
1	No harm	-	-

Table B.1. Severity coefficient values

O – Occurrence

Rating O	Criteria: Probability of occurrence
10	Occurs or may occur very likely during every use of the session
9	Occurs or may occur likely during every use of the session
8	Occurs in 1 of 5 sessions (less than once a day)
7	Occurs in 1 of 10 sessions (less than once a day)
6	Occurs in 1 of 50 sessions (less than once half a month)
5	Occurs in 1 of 100 sessions (less than once a month)
4	Occurs in 1 of 500 sessions (less than once half a year)
3	Occurs in 1 of 1000 sessions (less than once per year)
2	Occurrence very unlikely
1	Occurrence nearly impossible

Table B.2. Occurrence coefficient values

D – Detection

Rating D	Criteria: Likelihood of detection by design control
10	No chance of detection
9	Very remote chance of detection
8	Remote chance of detection
7	Very low chance of detection by indirect methods (hardware or software)
6	Low chance of detection by indirect methods (hardware or software)
5	Moderate chance of detection by indirect methods (hardware or software)
4	High chance of detection by indirect methods (hardware or software)
3	High chance of detection by direct or indirect methods (hardware/software)
2	Direct and indirect detection: Hardware or software
1	Direct detection: Hardware or safe software (category 4, performance level e)

Table B.3. Detection coefficient values

Risk Analysis

Assembly	Failure & Effect	S1	O1	D1	RPN before	Preventing measures	S2	O2	D2	RPN after
General Headset Assembly	Direct exposure to electrical components - potential user discomfort and reduced durability of device.	3	4	5	60	Careful sheltering of all electrical components into headphones, physical check of the headset before use. [Decreases D]	3	4	2	24
General Circuitry	Components overheat -: potential user injuries and damage of device.	4	3	9	108	Ventilation space between electrical components and the surface in contact with the skin, to allow dissipation of heat. And testing of components prior to assembly. [Decreases S&O]	2	2	9	36
Sensor	Failure to measure input stimuli.	1	2	5	10	Device programmed to report absence of input from sensor [Decreases D]	1	2	1	2
Data Transmission	Failure to communicate with target system - malfunction of device.	1	6	5	30	Device programmed to report absence of communication [Decreases D]	1	6	1	6
Power Supply	Battery failure - malfunction of device.	1	3	7	21	Battery indicator provided [Decreases D]	1	3	4	12
General Circuitry	Failure of individual components - malfunction of device.	2-3	3	4	24-36	Periodic maintenance of the device and setting of a recommended lifetime, after which device replacement is recommended. [Decreases D&O]	2-3	2	2	8-12
Target System(s)	Inappropriate use of target system - potential user injury.	1-3	N/A	N/A		Guidance in the proper use of the target system, and suggested supervision for individuals at higher risk of injury. [Decrease O]	1-3	N/A	N/A	
Headset Chassis	Hygienic issue - potential cross-contamination among users.	2	9	N/A	18	Suggested superficial cleaning between users who may be carrying contagions or are at high risk of infection. [Decrease O]	2	2	N/A	4
User Incidents	Possible epilepsy of user, etc. - user injury.	3	N/A	5		Warnings/guidance with headset to ensure informed use of the headset [Decrease O]	3	N/A	5	

Table B.4. Risk analysis and measures taken to decrease the risks

Appendix C – Ethics

The nature of the project brought in important and specific ethical aspects. The main purpose of the project was to increase the accessibility to leisure activities and modern technology to people with physical and mental impairments. It was therefore necessary to have special consideration of users, not only in terms of translation into design and development, but also in direct contact with them during background research (such as during the visit in John Chilton School, when we ensured that we approach them in friendly and constructive manner).

Although we performed some user trials and demonstrate function of the prototype, we have not had an opportunity to examine effects of the long-term use of the device on users. We believe that potential risks for users are described thoroughly in Appendix B (Risk analysis). The product is also intended for use by human users, therefore animal testing was not considered and no issues were raised.

Another concern worth examining comes from the possibility that device could cause exertion of very motivated user trying to achieve top performance while playing with racing car, or disappointment of the user that is having difficulties in achieving optimal output while controlling the mouse on screen. These drawbacks could be eliminated by proper instruction given to user prior to use and by provision of appropriate user manual.

It is also important to avoid the use of device to represent opinions and views of the user through third party manipulation. This can be easily realized through resetting device prior to use of different users and by abiding by the basic rules of data protection.

Honesty and openness were important aspects of our project – through detailed referencing, we tried to make our background research transparent. In our user trials performed during demonstration day (22 March 2017) and during Imperial festival (6-7 May 2017), we explained the principles of function of our headset to the users if they wanted to know about it, while we warned them about the potential dangers during the use (such as Scalextric car leaving the track in some instances).

As we obtained financial support from external sources, it was important to have clear and transparent rules governing respecting of the intellectual property. The funds donated to our project were donated as philanthropic gestures and the legal aspects were covered by donation contract. We agreed to mention the support of external parties in several instances (such as presentation, poster presentation), while their logos and names were displayed only if agreed by project supervisor.

Overall, we believe that we covered all the important ethical aspects of design and development of the final product.

Appendix D – Manufacture

The manufacturing of the final product can be broken down into four stages. The preliminary tasks, program building, assembly and manufacture testing (see Figure D1).

The preliminary tasks involved finalising the mechanical, electrical and software aspects of the design, the sourcing of the required components and ordering PCBs. This closely precedes and overlaps with program building, with its debugging stages feeding back into the design aspects and components required.

The main features requiring programing for their function were voice recognition, the EEG interface, tilt sensors and the target system, these were done in Arduino and python.

Once the program building was complete production moved on to the assembly of PCBs, the chassis, the interface with the target system, and the programs into one functioning system. Soldering was used for assembly of the PCBs; for the chassis a commercially available headset was adapted; and the interface with the target system, in the case of the Scalextric, was in the form of a PCB board held in a 3D-printed box that plugs into the track.

This last stage involves an aspect of trial and improvement, and manufacture testing, as improvements for the design may be thought of during the period between finalising the aspects of the design and finishing manufacture.

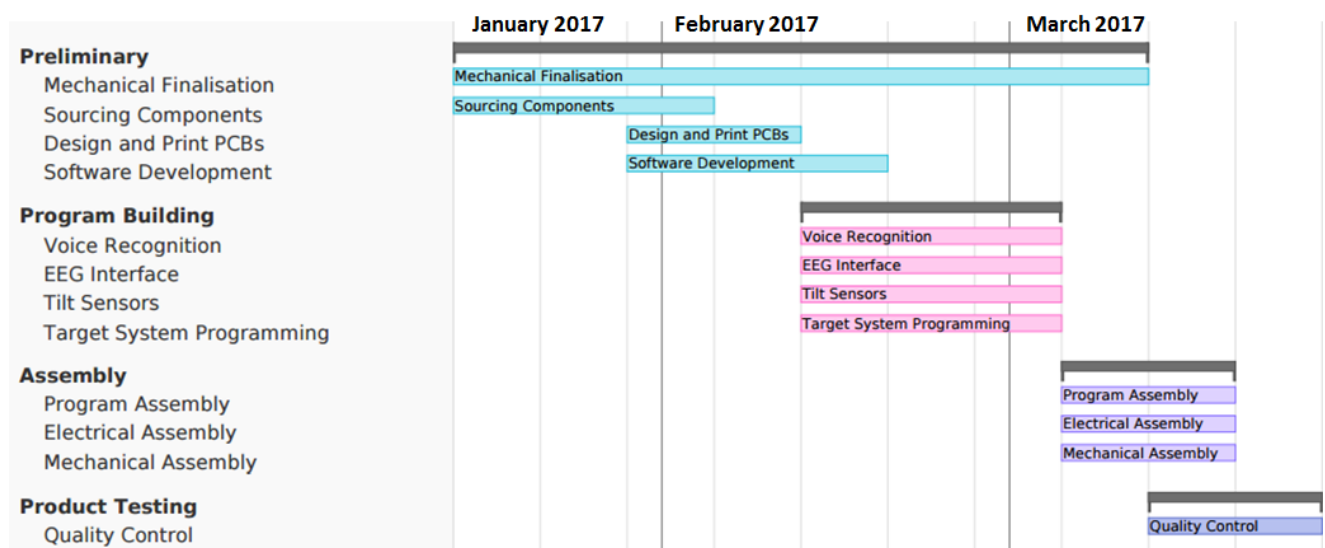


Figure D.1. Timeline of the manufacturing plan

Appendix E – Bill of Materials

Headset Bill of Materials

Item	Item details (Item code)	Seller's code	Quantity	Usage	Cost per unit (GBP)
Audio headphones	Kitsound (KSSTORMBK)	B00XCEUI6M	1	Headset chassis	30
Headband	Red Dust Active - yoga headband (LYSB017IEWCV0-SPRTSEQIP)	B017IEWCV0	1	Headset chassis	12.89
Microprocessor	Arduino Nano	696-1667	1	Headset processing unit	17.28
	Raspberry Pi Zero W	The Pi Hut	1	Headset processing unit	9.6
EEG sensor	Mindwave Brainwave Starter Kit (Ver 3)	B00B1B1H68	1	Headset sensor	122
Gyroscope/ accelerometer	MPU-6050 ARD001	RB-Suf-16	2	Headset sensor	7.06
Bluetooth modules	HM-10 Bluetooth 4.0	-	1 (pair)	Headset/target system wireless capability	23.95 (pair)
Battery capacity indicator	(FIT0466)	FIT0466	1	Headset UI	3.68
Haptic buzzer	Seedstudio Grove (105020003)	RB-See-210	2	Headset UI	2.62
DC Volt/Amp sensor (DC multimeter)	Arduino DC sensor	122009685432	1	Headset circuitry	2.99
Voltage regulators	3V3 regulator (LM3671/-Q1)	ADA2745	1	Headset circuitry	4.58
	Adafruit PowerBoost 1000 Basic 5V regulator	ADA2030	1	Headset circuitry	12.92
Cables/ adaptors	Approx USB 2.0 4 port hub (APPHM4B)	B00EUZN6MA	1	Development tool/ headset circuitry	6.99
	UGREEN USB sound adapter (30143)	B016CU2PEU	1	Development tool/ headset circuitry	6.99
Fuse	Littelfuse (1206L110THYR)	2383294	1 (10 pack)	Headset circuitry	2.11 (10 pack)
Switch	Adafruit toggle switch (1684)	1684	2	Headset circuitry	8
PCB	Elecrow	Elecrow	1 (10 sets)	Headset circuitry	15.2 (10 sets)
Total					306.54

Table E.1. Bill of materials and cost breakdown for the headset
NOTE: Materials acquired from College resources rather than purchased are not included

Target System Bill of Materials

Item	Item details (Item code)	Seller's code	Quantity	Usage	Cost per unit (GBP)
Racing track	Scalextric set	-	1	Target system	30
	Scalextric controller	-	1 (pair)	Target system	6.29 (pair)
Microprocessor	Arduino Nano	696-1667	1	Target system processing unit	17.28
Bluetooth modules	HM-10 Bluetooth 4.0	-	1 (pair)	Headset/target system wireless capability	23.95 (pair)
LCD display	Wingoneer LCD display	B01DC07WTQ	1	Target system UI	5.49
LED	Multicomp (MCL-S270SBLC)	1581243	1 (10 pack)	Target system UI	2.9 (10 pack)
	Kingbright (KPT-1608LVVBC-D)	2610410	1 (10 pack)	Target system UI	3.11 (10 pack)
	Kingbright (KPT-1608LVSECK-J3-PRV)	2610406	1 (10 pack)	Target system UI	2.59 (10 pack)
Voltage regulators	Tracopower 8V to 5V regulator (TSR 1-2450)	6664379	1	Target system circuitry	3.94
Cables/ adaptors	FTDI USB to TTL Serial Converter (FT232RL)	192025312906	1	Development tool/ target system circuitry	6.84
USB Dongle	Accenter USB 2.0 wireless Bluetooth adaptor (NLBT-CLASS2)	B0013BFQUE	1	Development tool/ target system circuitry	1.99
	Plugable USB Bluetooth 4.0 Low Energy (USB-BT4LE)	B009ZIILLI	1	Development tool/ target system circuitry	12.95
Fuse	Littelfuse (1206L110THYR)	2383294	1 (10 pack)	Target system circuitry	2.11 (10 pack)
PCB	Elecrow	Elecrow	1 (10 sets)	Target system circuitry	15.2 (10 sets)
Total					134.64

*Table E.2. Bill of materials and cost breakdown for the target system.
NOTE: Materials acquired from College resources rather than purchased are not included*

Appendix F – Acknowledgements

We would like to thank Dr. Ian Radcliffe and Dr Christopher Phillips for their supervision throughout the year and for their guidance in the process of project development. We would also like to thank to Paschal Egan and Niraj Kanabar for their advice relevant to electronics design. Thanks also goes to staff of John Chilton School in Ealing, for sharing their views based on their work with pupils with mental and physical impairments.

Also, we would like to thank to Newton Colmore, Ltd. and CamNTech, Ltd. for their philanthropic gesture and financial support for development of our project.

Appendix G – Nomenclature

ISO	International Standards Organisation
COGS	Cost of Goods Sold
NHS	National Health Service
IP	Ingress Protection
EEG	Electroencephalography
IDs	Individuals with disabilities of either a physical or mental nature that limits control of the body.
SATP	Standard ambient temperature and pressure: 298.15 K (25 °C, 77 °F), 1 atm (101,325 Pa).

Table G.1. Explanation of some abbreviations used throughout the document

Appendix H – Minutes from meeting with John Chilton School

Main interviewee: Yasin, Danielle and their carer

The interviewees showed up today are among the most complicated students in the school. The communication was very smooth and rather relaxed. Both interviewees spend most of the day on their wheelchairs, so no large range of movement will be involved.

It looks like that Yasin has limited control over his head movement. He is also limited at hand movement and oral communication, but finger pointing works fine for him. Thus he uses an application on iPad to “talk”---pressing a button with some phrase and the iPad will play the audio file that phrase. Yet voice recognition control will probably not be applicable him. Also, due to epilepsy, he is currently not using any medical device. He is able to concentrate but not for a long time, and sort of easily distracted by the surrounding.

Yasin needs someone else to control his wheelchair.

Danielle looks older and more mature than Yasin. There’s no big problem communicating with her. She has greater control over her hands (typing on a PC single-handedly) and head (able to nod and turn around). Also according to the teacher, she focuses better than Yasin. She asked if the headset would let her type with her mind, but that’s probably very hard due to limitations on our device.

The teacher and Dr. Radcliffe also mentioned that some users had limited eyesight, so it can be difficult for them to see the racing car on the Scalextric and know when to speed up/slow down the car. Some mechanism should be developed to resolve this problem.

So the situation varies among different individuals. While most of them should have little problem with the EEG part, not everyone is capable of voice control or head movement control. Even so, extensive training and good calibration may be required for some individuals to use the headset.

Miscellaneous:

There is an assistive tech company called SmartBox that was about to visit the school to assess the children and provide some equipment for them. Some of their equipment is similar to what we are doing. Their website is <https://thinksmartbox.com>

All the computers in the school use Windows operating system.