Cognitive Momentum

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ABSTRACT

Mobility is now more prevalent than ever. While there are many assistive technologies for people with disabilities around the world, they cannot offer independent mobility for those with severe neuromuscular diseases. This report details ideas in which an alternative method of control, which is the use of BCI to improve mobility. Investigating the product design specification and design criteria used as a basis for developing ideas, one concept is progressed and analysis and feasibility is of the idea is conducted.

CONTENTS

1. INTRODUCTION

Immobility is often a significant area of concern for those suffering from disabilities, illnesses or aging. According to the International Labour Organisation, there are approximately 600 million people who are classed as disabled worldwide as of July 2011, (Thibodeaux, 2016) of which 6 million people are living with paralysis in the US alone (Reeve Foundation, 2016).

While there already exists a number of assistive technology to improve the mobility of the disabled and the elderly to live more independent lives (Cowan, 2012), the technology for patients with severe neuromuscular disorders – such as ALS, brain stem, stroke and spinal cord injury – is still limited as they are not able to control electric wheelchairs using conventional methods (Lin & Yang, 2011).

However, with the recent advancements in neurotechnology - especially in the area of Brain-Computer Interfaces (BCI) – combined with existing assistive technology, there may finally be a solution that will allow improved mobility for patients suffering from some form of paralysis.

This report aims to present the chosen design specifications and the preliminary designs that were considered to achieve the purpose of the product, followed by an in-depth analysis of the chosen design and the simulations carried out for the prototype. The potential development of the idea of a BCI-controlled wheelchair is explored and the report concludes with a feasibility study.

2. BACKGROUND

Electric wheelchairs and mobility scooters have given those with a severe physical disability a tremendous amount of independence. However, in many cases, the disability that limits someone's mobility may also prevent them from reliably employing their hands with progression of the disease, e.g. intermediate spinal muscle atrophy (SMA, type II) (Tobias Kaufmann, 2014). As most electric wheelchairs currently on the market require the use of a joystick for control, engineers are exploring various hands-free, bio-signal alternatives for the control method such as brain-waves, muscular activity or eye posture (Torsten Felzer, 2007) (Asgar, 2013).

Considering the user's need to observe the environment during navigation, control with eye-tracking devices would not be feasible, as it would prevent accurate functionality of the device. Facial muscles may also lose their reliability as they are rapidly fatigued from frequent use (Brach, 1995). Thus, BCI seems to be the best alternative in terms of reliability, feasibility and speed as it has a faster response time to commands (Illumin - USC, 2016).

2.1 BCI

Research on BCIs started at the University of California in the 1970s (Brain Vision UK, 2014) and they allow for direct communication between a person's brain and the device (Cohen, 2007). While various BCI technologies have been developed over the years, electroencephalography (EEG) is the most used as it not only has good time resolution compared with neuronal activity but is also non-invasive, cheaper, and portable (IEEE Xplore, 2012). These factors are extremely important for usability and would make the product more appealing and affordable for the users.

EEG technology utilises the placement of multiple electrodes on the scalp to detect the brain's electrical activity (WebMD, n.d.). While the skull may obstruct and distort the electrical signals from the brain, this is the preferred method as it is non-invasive. Implanting the electrodes underneath the skull results in clearer signals; however, any invasive procedure comes with complications and is therefore undesirable for our product (Illumin - USC, 2016) .

However, as BCI is still in its research phase, it has limited accuracy and can only detect a few different commands. According to Jose del Millan, director of non-invasive BCI at the Federal Institute of Technology, the concentration required around a clustered environment creates noisier signals that can be more difficult to interpret. Since any error in operating the wheelchair may be dangerous to the user, 'shared control' systems, which is a combination of BCI and circuits for preventative measures, are used to ensure safety of the users (Graham-Rowe, 2010).

3. DESIGN

3.1 DESIGN CRITERIA

The design focuses mainly on performance and safety in order to maximise functionality. It consists of two main parts: an electric wheelchair and the BCI headset. They will be used in conjunction to improve the lives of disabled people who require the use of a wheelchair. The BCI headset will measure signals from the brain, which will be extracted and used to determine the direction the user wants to travel. These signals will then be redirected to the wheelchair which will follow the instructions. In order to implement this, we must understand the criteria that are most important to the design.

3.1.1 PERFORMANCE

The product should accurately follow the intended direction of the user. It must also be able to do so with minimal latency; ideally a response time of less than 100ms [16], (which is below average human reaction time) from thought to movement of the wheelchair. The algorithm used to detect the user's thoughts must be accurate to ensure their safety.

3.1.2 SAFETY

It is critical that the device always follows the user's intent as accurately as possible. It should also have additional sensors in order for the device to be aware of its surroundings. This could be implemented with sensors, and allows an additional layer of safety to be provided by the device.

3.1.3 HARDWARE RELIABILITY

The hardware components, such as the BCI headset, must be reliable as any malfunction could compromise the safety of the user. This is also true for the wheelchair itself. The product should perform consistently and should not have to be altered on a daily basis. This requires reliable hardware and testing to ensure consistency.

3.1.4 TESTING

It is essential that the device be tested before it is put on sale. Testing can be done at multiple stages of the design process. The main component that needs testing and refining will be the BCI headset. Testing can begin on the headset immediately through the computer program. Subsequently, the headset should be tested with the prototype and then finally with the full product before sale.

3.1.5 TARGET PRODUCT COST

The cost of electric wheelchairs vary greatly with the different available features (ranges from £1,000 to 10,000) [1]. However, the NHS has a voucher scheme to aid with the purchase of a wheelchair [2]; thus the price will be reduced, making the product more affordable. The cost of BCI headsets also vary, and are £300 on average. Therefore, it is apparent that this product will not be cheap; however, it is aimed to be reasonably priced.

3.1.6 CUSTOMER

The target market for the product is any individual with mobility impairment, especially those with severe neuromuscular disorders. The customer should already require the use of a wheelchair, and the product should increase mobility and allow them to live a more independent life.

3.1.7 ERGONOMICS

The ergonomics of the product are especially important. As the user could be in the chair for long hours, comfort and ease of use are crucial. In particular, the BCI headset should be easy to put on and the user should feel at ease when wearing it. The device should enhance the movements of the user in a positive way and should enable more efficient mobility.

3.1.8 INSTALLATION

As the product uses a BCI headset, some initial set-up will be necessary to calibrate the user to the headset. After this initial set-up, the product should not require any invasive day-to-day installation, and should be as simple as possible to 'wear and go.'

3.2 CONCEPT DESIGNS

Through consideration of the design criteria, three different concept designs were proposed as solutions to the problem at hand. Using the main concepts from the PDS, analysis was conducted into the specifics that all preliminary designs would require. An example would be having a safety feature to ensure that the user is not in danger, in case there is a fault with the BCI system or any other malfunction with the product.

As the basis of the designs, brain waves are used as the control mechanism which is done using a BCI headset. As the method of control is not being altered, the BCI headset needs to be able to read and interpret the signals obtained through the brain.

3.2.1 BCI HEADSETS CONSIDERED

Through research of different possible BCI headsets, we considered several options. These include:

- Emotiv EPOC
- OpenBCI
- MyndPlay - BrainBandXL

3.2.1.1 EMOTIV EPOC

This BCI headset is an electroencephalogram (EEG) system which is used for research, usability testing and neurotherapy. With 14 EEG channels and 2 reference channels, it offers us high resolution for the data collected. This headset provides us with access to high quality and raw EEG data through advance SDK and software. Furthermore, there are several application program interfaces (APIs) which the headset provided. These include facial expressions, mental commands and performance metrics. (Emotiv, 2016)

3.2.1.2 OPENBCI

Open-source brain-computer interface (OpenBCI) produces a headset and a board with a bio-sensing microcontroller, used to sample electrical brain activity (EEG), muscle activity (EMG) and more. There are several boards, with a different number of channels which can be used to interpret brain signal data. There is software present to visualise brain data and several other signals. A separate headset is needed to connect to the board, or electrodes can be attached to the boards for connectivity to the brain. (OpenBCI, 2015) (OpenBCI, 2016)

3.2.1.3 MYNDPLAY – BRAINBANDXL

This headset is a single sensor EEG headset which provides data that can be used to control several items. It is an all-in-one EEG neurofeedback recording and analysis tool which works with a media player. The headset has two dry sensors which measures raw brainwave activity, which is sent to a computer where this information can be used with different compatible applications. (MyndPlay, 2016)

3.2.2 COMPARISON OF THE THREE HEADSETS

	Emotiv EPOC+	**OpenBCI Headset with 32bit Board Kit (8-channel)**	**MyndPlay - BrainBandXL**
Number of Channels	14 channels with 2 references for optical positioning	16 channels of EEG	2 dry sensors
Sampling Rate	2048 Hz (internal)	-	512 Hz
Battery Life (wireless)	12 hours	Not wireless - board uses 4 AA batteries	10 hours
Signal Resolution	-	24 bits per channel	-
Compatibility with different platforms	Compatible with Windows, Linux, MacOS, Android and iOS	Compatible with Windows, Linux and MacOS	Compatible with Windows, Linux and MacOS
Software available for testing/data analysis	Many downloadable software available (some are paid - for extra functionality)	Uses OpenBCI GUI software	ResearchKit available at an extra cost of £449, also MyndPlay software
Need to assemble?	No need to assemble	Need to assemble the headset, not board	No need to assemble
Price (£)	282	353 x2 (for board and headset separately)	249

Table 1: Comparison of the different BCI headsets considered

Through the criteria set, the Emotiv EPOC headset provides the best usage and gives the greatest functionality for the price point it is at.

The BCI that is being used is the Emotiv EPOC. This system consists of a headset and drivers which perform interpretation on raw data from the headset to map neural oscillations (brain waves) to commonly used instructions (such as 'move left') or emotions (such as 'excitement'). (Emotiv, 2016) This is ideal for the project as the complicated task of mapping brain waves to spatial movement instructions that are needed to direct the device will not have to be performed. Although there is less flexibility in using a pre-constructed BCI in comparison to making one, the advantage of eliminating unnecessary complications in order to concentrate on implementation outweighs any disadvantage of being limited to Emotiv's proprietary software. The Emotiv BCI also includes test applications that can be used to easily calibrate and test the headset and software.

This headset has scope for a lot of flexibility and has the capability for further functions of the brain computer interface. Repeated use of the device enables efficient work with the program as well as writing the code that is used for controlling the mobility device. Increasing the reliability of the end product is one of the most important tasks as the aim is to increase the mobility of disabled individuals. Ensuring that the product has features for safety is essential and these will be incorporated in the concept design ideas.

3.2.3 Concept 1

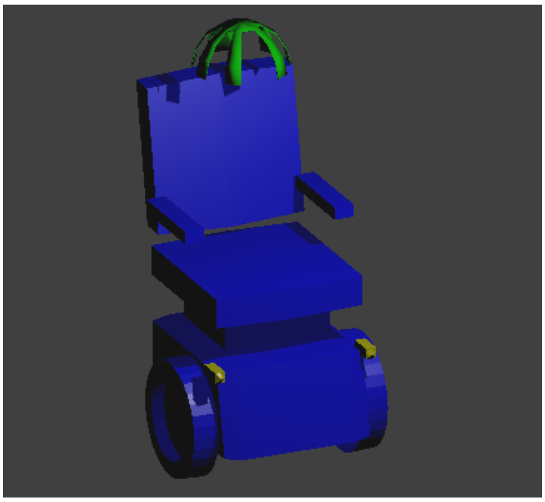

Figure 1: Wheelchair (blue) with BCI (green) and example sensor placement (yellow)

This design focuses particularly on performance and safety to maximize the functionality of the product and achieve the basic objective - to use brainwaves to control a wheelchair. It consists of two parts: an electric wheelchair and the Emotiv EPOC BCI headset. The electric wheelchair is connected wirelessly to the BCI headset, which allows for flexibility in the choice for method of control at the expense of requiring two power modules. This wireless connection means that battery life of the BCI headset is limited to 12 hours. The headset may be charged when not in use. There are also sets of sensors installed on the wheelchair for obstacle detection: at the front, at the back, and on each side. Upon detection of an obstacle within a close range (to be determined experimentally), a signal will be sent to the control centre to prevent movement in the direction of the obstacle. This safety feature is paramount as it will prevent collisions with objects. This device may be used outdoors on streets and in environments where there are flat pavements. The device will move at the speed of a normal electrical wheelchair so that the user is able to control it easily and the system has enough time to respond to the data it receives from surroundings.

A control panel on the armrest of the wheelchair includes two switches for selecting the control method – brainwaves or manual control – and a joystick controller to be used according to the user's choice or in the case of a headset malfunction. The implementation of two control methods increases the usability of the product; however, the integration of two systems may result in an increased cost of the product or may complicate the device for certain users.

For concept 2 and concept 3, please refer to the appendix 2.

3.3 CONCEPT SELECTION

The following table outlines the different criteria proposed earlier and compares to what extent each design meets these criteria.

Criterion	Design 1	Design 2	Design 3
Performance	Accuracy is dependent on algorithms yet to be developed and tested. The power consumption is high but not much extra is from the control system, so existing wheelchair power supplies will be sufficient.	Accuracy is dependent on human response and algorithms yet to be developed and tested. The power consumption is extremely small, with the only components requiring a low-voltage: BCI, indicators, and computer processor.	Accuracy is dependent on algorithms yet to be developed and tested. Power consumption is likely to be very high in comparison to traditional wheelchairs.
Customer	The customer here is a disabled individual, with impaired motor skills	The customer here is a disabled individual, with impaired motor skills - however, a human helper is required which may have a detrimental effect to user independence	The customer here is a disabled individual, with impaired motor skills - they may require movement outdoors
Ergonomics	Weight and comfort meet the specification.	The headset should meet specification. Otherwise, this criterion is not applicable to this design.	Does not meet specification as this design would probably restrict the movement of the user far more than a standard wheelchair
Quality and Reliability	Meets the specification	Meets the specification	Meets the specification
Safety	Meets the specification, primarily by means of the sensors.	Meets the specification, primarily by means of the discretion of the human helper. Likely the safest.	Meets the specification, primarily by means of the protective sphere.
Installation	Meets the specification.	Meets the specification, initial setup may be dependent on the device on which it is installed.	Meets the specification, though everyday setup may be complicated because of the sphere.

Table 2: The extent to which each design meets the important specification criteria

3.4 WEIGHTING AND RATING METHOD

This method was used to further compare the three concepts. Several more aspects of the PDS were used to further analyse the different ideas and provide an improved basis for the decision of which concept to take forward.

Design Criteria			**Concept 1**		**Concept 2**		**Concept 3**	
		Weight (0-10)	**Score (0-10)**	**Total**	**Score (0-10)**	**Total**	**Score (0-10)**	**Total**
Performance								
	Following instructions	10	9	90	9	90	9	90
	Latency	8	7	56	4	32	7	56
	Power usage	8	7	56	8	64	3	24
	Behaviour with different users	5	7	35	6	30	7	35
Specifications								
	Weight	2	5	10	9	18	1	2
	Size	3	5	15	8	24	1	3
	Cost	9	7	63	8	72	3	27
Product Quaility								
	Product Life Span	7	8	56	6	42	7	49
	Aesthetics	3	9	27	6	18	2	6
	Maintainence	7	6	42	6	42	5	35
Reliability								
	Reliability	10	8	80	9	90	7	70
	Response of sensors	10	9	90	9	90	8	80
	Safety	10	9	90	9	90	9	90
Customer								
	Ease of implementation	9	9	81	9	81	6	54
	Installation	9	9	81	9	81	6	54
			Weighted total	872	**Weighted total**	864	**Weighted total**	675

Table 3: The weighting and rating method used for comparison of the three concepts

After considering all three concepts, the group decided to use concept 1. The electric wheelchair that is controlled using the BCI headset with infrared sensors in place meets the design criteria to a great extent and has further advantages over the other designs. With the possibility of two different controls, one as a safety and one as the main, this design has the flexibility needed. From the weighting and rating method, we can see that concept 1 scored the highest point total, which further provides a basis for the decision.

Furthermore, comparing this design to the others proposed, there is greater potential for usage in the real world, and for further development with the possible addition of extra features. The usability and reliability of this design further instils confidence in working toward such a concept. Also, the customer specification is met as the use for less mobile individuals is accomplished. Overall, this design is chosen as it works best with the design criteria and as further research is conducted into the area, there is a possibility of adding to the current concept.

4. CONCEPT DEVELOPMENT

4.1 HIGH-LEVEL DESIGN

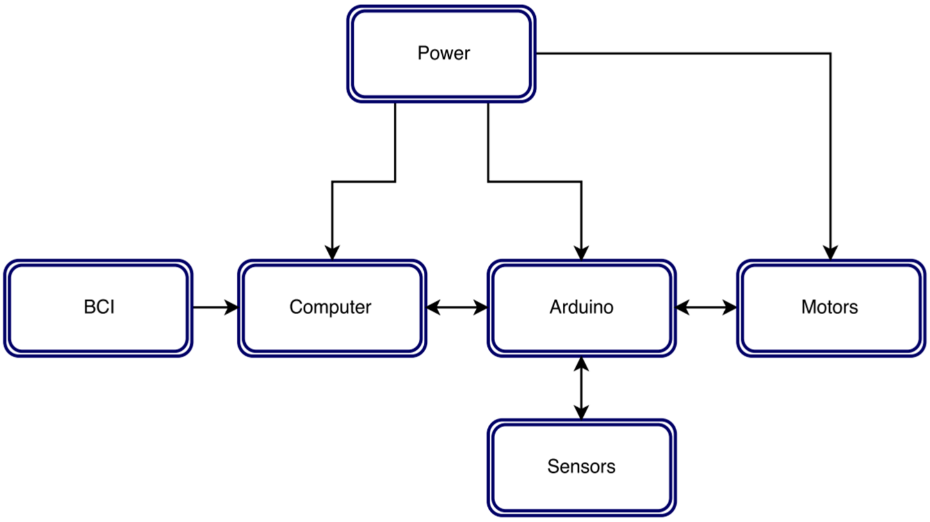

Figure 2: High Level Design of system

The design consists of five main modules: Power, Brain Computer Interface (BCI) Devices, Raspberry Pi, Sensors and Motors.

The BCI module includes the Emotiv Cognitive device which reads the signal from the user's brain and analyses the data with the Emotiv software. However, here we use the BCI simulation provided by Emotiv in place of the headset. Detailed information will be explained in the following section of the report. The raw data is processed by the Emotiv software into commands such as "Left" and "Right". This data is then translated into simple serial code for communication with the Arduino.

The Arduino module contains C++ code which receives the signals and controls the movement. At the same time it also receives the information from the sensors in order to determine the final action on the motor. The sensing module includes ultrasonic sensors which detect the environment around the wheelchair[1]. This will protect the user from hitting obstacles. Finally, motors receive the direction instructions from Arduino and power module responsible for providing power for Arduino and the motors.

For overall detailed design, see appendix 3

[1] We use EEBug as a prototype instead of the real wheelchair.

4.2 LOW LEVEL DESIGN

This following section outlines the low-level design of the whole concept. The software that is used is explained in detail and the different aspects of the development process is explored.

4.2.1 EMOTIV BCI SOFTWARE DESIGN

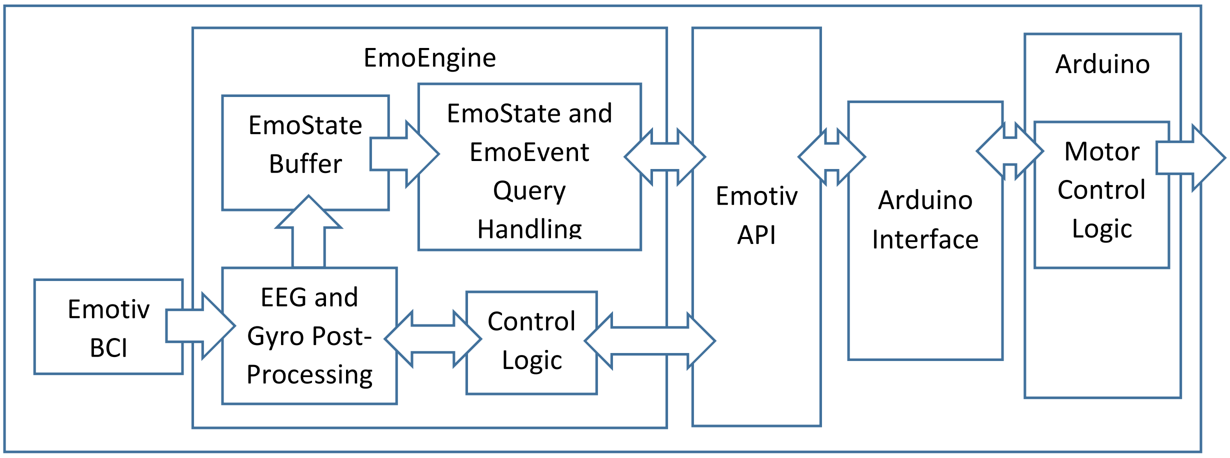

Figure 3: Visual representation of interactions between different modules

The Emotiv EPOC BCI headset has two sensory systems: EEG (electroencephalography) and a gyroscope. For the purpose of the project, only the EEG is being used. The BCI communicates wirelessly via Bluetooth to a USB receiver.

Development was carried out on Linux. This has several advantages: firstly, it is free to use and so does not add any licensing costs to the end product, as an OS like Windows would. Linux distributions generally always include a native C/C++ compiler, gcc/g++. Emotiv recommends Windows C++ code be compiled with Visual Studio, and their example code for this platform are written with this assumption. This software also has licensing costs though, unlike gcc/g++. Furthermore, developing for Linux means that the hardware isn't as limited: Windows is very restricted in the platforms it supports to powerful computers, whereas Linux can be run on smaller, less expensive, or more specialised hardware, including a Raspberry Pi. This means, depending on the computing power required by the final software, the final computer hardware implementation is more flexible: a heavy, power-hungry laptop would not be necessary to attach to the wheelchair.

Emotiv provides a device driver (in the form of rules for Linux's device manager, udev). This allows the BCI to be identified by the software. Software written in C/C++ can then communicate with the device using Emotiv's API (application programming interface), by including their library, "Iedk.h".

The EmoEngine given to the functionality provided by the API. It contains all processing of raw EEG data into simplified states (EmoStates). The inner workings of this processing are proprietary and access to these functions or the raw input data processed by them requires additional licenses. We have access to only the EmoStates, which is all that is needed for this project.

On the computer interfacing the BCI and Arduino is the following code. It sets up communications with EmoEngine, then goes through a training sequence for calibration, then starts sending then BCI data to the Arduino for control.

The first important actions in the main() function are:

```
    EmoEngineEventHandle eEvent  = IEE_EmoEngineEventCreate();
    EmoStateHandle eState        = IEE_EmoStateCreate();
```

This creates data structures and allocates them handles, eEvent for the functionality, eState to hold the current state of the BCI.

```
    try {
        if (IEE_EngineConnect() != EDK_OK) {
            throw std::runtime_error("Emotiv Driver start up failed.");
        }
```

IEE_EngineConnect() then initialises an instance of the EmoEngine which reads and processes the raw data from the BCI device. The code throws an exception if there is an error.

```
    int startSendPort = 20000;
    std::map<unsigned int, SocketClient> socketMap;
```

Then, communications over local UDP ports are setup. This was done to send data to a Python script intermediating the C program and serial port communications with the Arduino for easier debugging. In later versions of the software, this UDP connection and Python script would be replaced with direct communication with the serial port.

The main loop of the program is then started, which will continue until the program is closed.

```
while (true) {
    ...
    int state = IEE_EngineGetNextEvent(eEvent);
    if (state == EDK_OK) {
        IEE_Event_t eventType = IEE_EmoEngineEventGetType(eEvent);
        IEE_EmoEngineEventGetUserId(eEvent, &userID);

        switch (eventType) {
        ...
```

The loop continually checks the state of the EmoEngine, and stores the latest event type in the variable, eventType. The user also has a handle, and for the purposes of the project there is only ever one user, with an ID of 0. There is then a switch statement which will branch to different cases, depending on the event type.

```
case IEE_UserAdded:
{
    std::cout << std::endl << "New user " << userID
              << " added, sending MentalCommand animation to ";
    std::cout << receiverHost << ":" << startSendPort << "..."
              << std::endl;
    promptUser();

    socketMap.insert(std::pair<unsigned int, SocketClient>(
        userID, SocketClient(receiverHost, startSendPort, UDP)));

    startSendPort++;
    break;
}
```

The first case is when the BCI is first connected and a user is added. Communications over a UDP port (in this case, 20000) is set up. There is then an incrementing of the port in case a new user is added, though this should not happen in our case.

There is then an IEE_UserRemoved case for disconnection of the BCI and termination of the UDP connection.

```
case IEE_EmoStateUpdated:
{
    IEE_EmoEngineEventGetEmoState(eEvent, eState);
    std::map<unsigned int, SocketClient>::iterator iter;
    iter = socketMap.find(userID);
    if (iter != socketMap.end()) {
        sendMentalCommandAnimation(iter->second, eState);
    }
    break;
}
```

The IEE_EmoStateUpdated case calls IEE_EmoEngineEventGetEmoState(eEvent, eState); to update the eState and send information to the UDP port.

The sendMentalCommandAnimation looks as follows:

```
void sendMentalCommandAnimation(SocketClient& sock, EmoStateHandle eState) {

    std::ostringstream os;

    IEE_MentalCommandAction_t actionType      =
        IS_MentalCommandGetCurrentAction(eState);
    float    actionPower = IS_MentalCommandGetCurrentActionPower(eState);

    os << static_cast<int>(actionType) << ","
       << static_cast<int>(actionPower*100.0f);

    sock.SendBytes(os.str());
}
```

The functions IS_MentalCommandGetCurrentAction(eState) and IS_MentalCommandGetCurrentActionPower(eState) retrieve information from the opaque eState data structure, respectively the action type and the power of the action. The action type is an integer number where powers of 2 correspond to different actions (e.g. 1 = Neutral, 32 = Left, 64 = Right). Action power is a floating point number between 0 and 1 representing the confidence of the device that the current action is correct.

These two numbers are then sent, encoded as ASCII and separated by a comma, to UDP port.

```
import socket
import serial

UDP_ID = "127.0.0.1"
UDP_PORT = 20000

sock = socket.socket(socket.AF_INET, socket.SOCK_DGRAM)
sock.bind((UDP_ID, UDP_PORT))
ser = serial.Serial('COM6', 38400, timeout=1)

while True:
        data, addr = sock.recvfrom(1024)
        print "received messages:", data
        if((data[0])=='1'):
                ser.write('\x00')
          elif((data[0])=='3'):
                ser.write('\x01')
          elif((data[0])=='6'):
                ser.write('\x02')
```

Listening to the UDP port is the Python script. The IP 127.0.0.1 is localhost, i.e. the local machine, as we are not using a network to communicate remotely. The variable sock is then used to listen for the data from the C program, and the variable ser is used to open a USB connection to the Arduino, on which there is a matching baud rate of 38400 for serial communication.

4.2.2 Control Design

Figure 4: EPOC Control Panel

The EPOC Control Panel is the software provided by Emotiv Company which can be used to train actions and simulate movement. The box labelled ‘1’ shows how well the headset can detect the user’s brain. The box labelled ‘2’ is the simulation of the movement of the cube – determined by the signals from the user’s brain. The box labelled ‘3’ is used to set the training level. For instance, “left” is chosen to be the action, and the user needs to starting thinking “left” in order for the system to recognise the specific signal which represents “left”. (See Appendix 4 for testing data)

From testing data, the rate of success for each direction is as follows: left: 63% and right: 50%. From this we can see that the accuracy is high enough for safety reasons. Below is a summary of some issues which may cause difficulties for users:

1. The training simulation takes 8 seconds to read and gather the signals from user's brain.
2. Sometimes, it is easy to be distracted. Under this circumstance, the data is affected.
3. It requires a big effort for the user to "think" in order to move the cube.
4. Users with thicker hair may have losses in connectivity. Therefore we often need to adjust the headset in order to retrieve the signals again.

All the issues above need to be taken into consideration in order to design the safest device for the user. We decided to take lowest success rate to design the control system.

4.2.3 CONTROL ALGORITHM

4.2.3.1 OVERALL CONTROL CODE

```
const int leftmotor = 13;     //Pin 13 is left control of h-bridge pin 2 (control of left motor)
const int rightmotor = 9;     //Pin 9 is left control of h-bridge pin 15 (control of left motor)

void setup() {
  Serial.begin(38400);        //We use 38400 serial port to receive signal from the BCI simulation
  pinMode(leftmotor, OUTPUT);
  pinMode(rightmotor, OUTPUT);
}

void loop() {
  int rx;
  readcontrol(rx);
  if (rx == 0x02) {                   // left
    motordirve(leftmotor, leftmotor);
  }
  else if (rx == 0x01) {              //right
    motordirve(rightmotor, rightmotor);
  }
  else if (rx == 0x00) {              //stright(push)
    motordirve(leftmotor, rightmotor);
  }

  else {                              //brake
    analogWrite(leftmotor, 0);
    analogWrite(rightmotor, 0);
    for (int a = 255; a >= 0; a--) {
      delay(500);
    }


  }
}
```

Figure 5: main function for moor control

This is the main function of our algorithm for motor control. On an h-bridge, the voltage difference between the In1 (pin 2) and In2 (pin 7) will decide what direction and the velocity at which the motor is going to move at. Therefore, we have decided to set both In 2 and In 3 to be 0V as both of our motor will only be moving forward or staying still.

At setup, we used serial port 38400 to send in the signal from simulation so that the Arduino programme can read the command. Every time when a command is sent in, we will use the method mentioned in "deciding direction" part to read the data. Then we would use transient output to drive the motor. The function for driving the motor is as below.

```
void motordirve(const int& motor1, const int& motor2) {
  for (int a = 255; a >= 0; a--) {
    analogWrite(motor1, a);       //using PWM to output to the h-bridge
    analogWrite(motor2, a);       //decreasing one every time using the effct of the transient from 255 to 0
    delay(500);
  }
}
```

Figure 6: motordrive() function

For convenience, we input two pins at a time. When we are only driving one motor, then we will put in same parameter for both motor1 and motor2.

4.2.3.2 DECIDING DIRECTION

By using the success rate, Left: 63% and Right 50%, the function below is created to determine the correct motion that the user desires.

```
void readcontrol(int& motion) {
  int left;
  int right;
  int straight;
  for (int i = 0; i < 10; i++) {       //10 times iteration to determine the action
    while (Serial.available() =< 0) {

    }
    int tmpp = Serial.read();
    if (tmpp == 0x02) {                //counting the amoutn of each motion occured
      left++;
    }
    else if (tmpp == 0x01) {
      right++;
    }
    else if (tmpp == 0x00) {
      straight++;
    }
  }
  if (left > 6) {                     //if left > 6 (63%) then perform left
    motion = 0x02;
  }
  else if (right >= 5) {               //if right >=5 (50%) then perform left
    motion = 0x01;
  }
  else if (straight >= 5) {
    motion = 0x00;
  }
  else {                              // Do nothing (STOP) if non of the above is true
    motion = 0x03;
  }

}
```

Figure 7: readControl() function

The function readControl() contains a for loop which iterates 10 times and read the data from the simulation. We used a while loop to wait for the next command to send in. If 'right' is read in 6 out of 10 times then it returns the motion =0x01 (right), which follows the percentage of the research we did on correction rate.

4.2.3.3 SIMULATION OF CONTROL ALGORITHM USING MATLAB

We used PSpice simulation to test how pulse width modulation (PWM) drives the motor, and we determined to use transient output drive the motor.

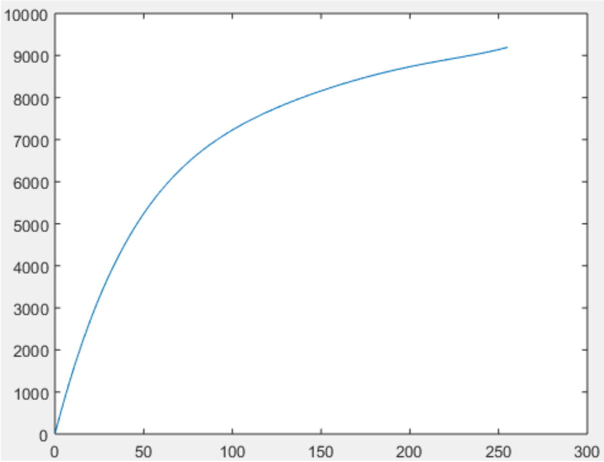

Figure 8: Plot of speed of motor against analogWrite

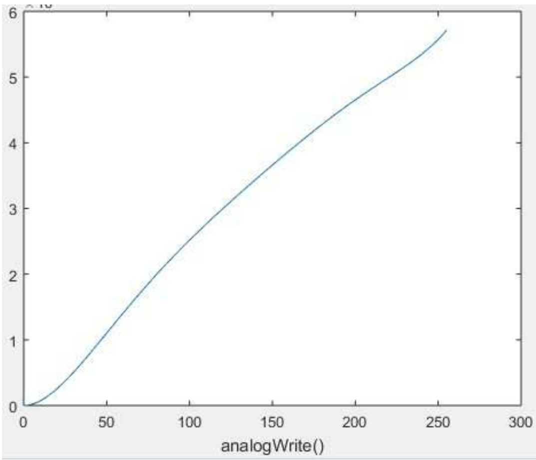

Figure 9: Plot of distance against anlogWrite

The graph on the left is the result of an analysis of the motor on PSpice. This diagram shows how the speed of the motor will differ with the change of analogWrite(x). We can clearly observe that the higher the voltage output is, the greater the speed is. However, the shape look sharper at lower voltage as the change of torque changes very rapidly at low voltage.

The graph on the right shows how the total distance on a turning with respect to its initial speed. It is an integration of the above diagram which can show what distance it can travel as different initial voltage is put in, because we use a for loop to decrease x in analogWrite(x) one by a time. However, in this simulation, we failed to take in account of inertia and resistance, which will compensate each other.

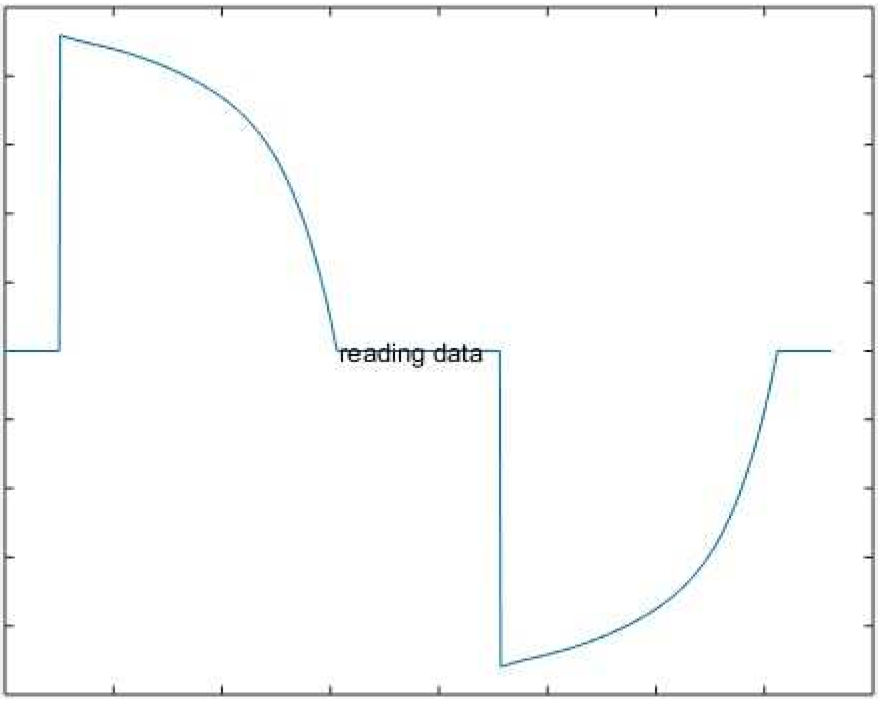

Figure 10: Graph to show how the speed of the motor changes in real time

This is a representation of how the speed of motor change at real time. Before the first pulse, we sensed the user intending to go left, then we input analogWrite(255), and decrease it one at a time.

When it eventually get to 0, we will start reading another data, which is going to right. Then we repeat the same procedure but on the right this time.

```
x=0:1:255;
y = 0.000000000026047*x.^6 + 0.000000006897490*x.^5 - 0.000017664991029*x.^4 +...
    0.007503989857923*x.^3 - 1.485058268299320*x.^2 + 162.469591375673000*x;
speedd=y;
turning_distance=zeros(1,256);
for i=1:255;
    y=y(1:257-i);
    x=x(1:257-i);
    turning_distance(i) = trapz(y,x);
end
turning_distance(i+1)=y(1);
turning_distance=fliplr(turning_distance);
speed=zeros(1,763);
speed(52:307)=fliplr(speedd);
speed(458:713)=-fliplr(speedd);
x=0:1:762;
t=0:1:255;
plot(t,turning_distance);
hold on;
xlabel('analogWrite()');
figure;
plot(x,speed);
hold on;
text(308,2,'reading data');
 ylabel('right                         left');
hold off;
```

Figure 11: MATLAB Simulation code

The code above shows when a "left" action is performed. After receiving the signal, full power is provided to the motors and gradually decreased to zero. The graph on the left shows the rate of duty cycle and with different analogWrite() input, and the right graph presents the voltage supplied change with left, right action is performed.

4.2.4 Distance Sensor Implementation

A safety sensor is implemented in order to prevent the wheelchair from crashing due to any faults or misreading from the BCI headset.

To implement the distance sensor a HC-SR04 ultrasonic sensor (ElecFreaks, n.d.) is used, and the data extracted will be used to stop the wheelchair from getting into a dangerous situation. An ultrasonic sensor was used because of its sensitivity to distance and high operational speed.

When detection of the distance of the wheelchair to a nearby object is needed, a trigger signal is sent to the sensor for 10ms. After the sensor receives this signal, the sensor will send out eight impulses of ultrasonic waves, which are focused in the direction of the object. Part of the sound wave will hit the object and get reflected back to the sensor. The sensor will output a high pulse after all eight pulses are sent until the echo reaches the sensor again. Then, half the duration of the pulse will represent the time taken for the ultrasonic wave to reach the object. Therefore the equation to calculate the distance is $0.034 * \frac{t}{2}$, where t is the duration of the pulse in microsecond and 0.034 represents the speed of sound per microsecond. All distances over 200cm are filtered out as they are not considered dangerous at present.

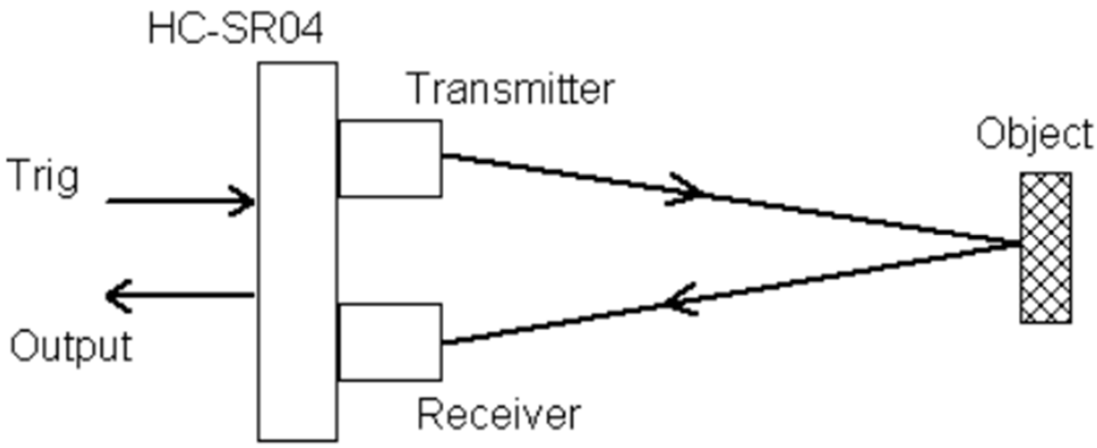

Figure 12: Diagram to show how the sensor works (Maa, 2012)

4.2.5 HARDWARE

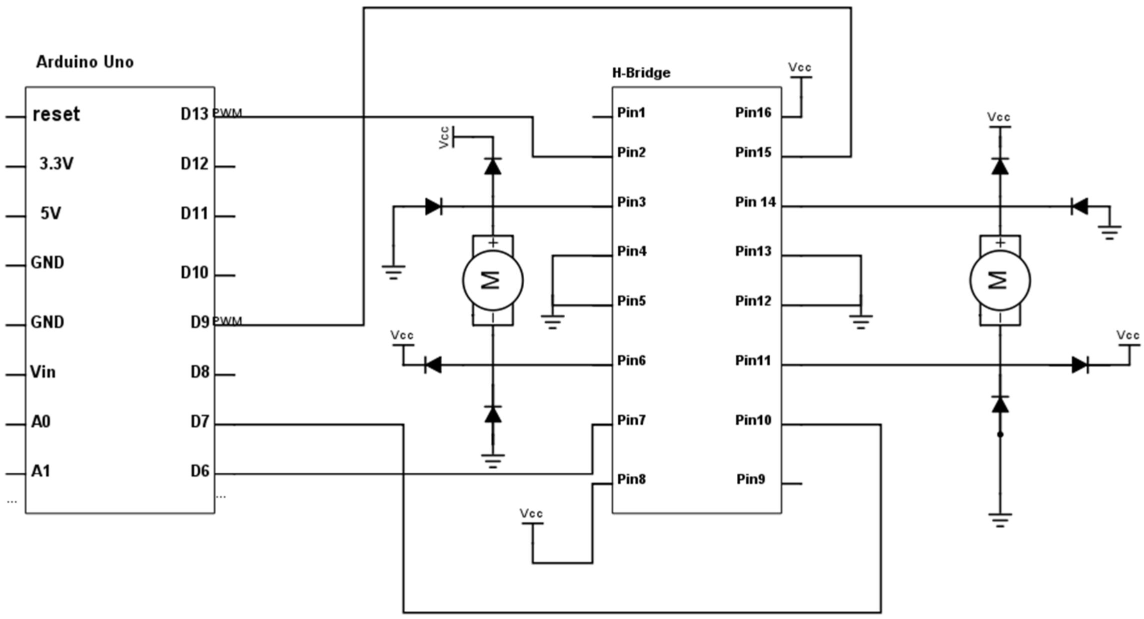

Figure 13: Schematic Diagram of the overall circuit diagram

The schematic diagram shows how the Arduino is connected with EEBug and the communication with it through the H-bridge chip. Pin D9 and D13 are used to send the PWM signals to the right and left motor. Pin D6 and D7 are used to control reverse and tighter turns.

5. PROJECT MANAGEMENT

The group had seven members who were each responsible for different parts of the project. The team combined the research and the report writing for the interim report and then split into two sub-teams of size three and four, who worked on the report and the creation of the prototype respectively.

Throughout the project the team used many forms of communication in order to ensure that the whole project was kept on schedule and all relevant information was conveyed.

Our main methods of communication were:

- Facebook page/messenger
- E-Mail
- Google Documents
- Dropbox

The team would also meet every week in order to present the work that they had done during the course of the week and others could then comment on how each other's work could be improved upon.

For the final report, the two sub-teams were as follows:

- Creation of prototype
  - Xiang Xiang Liu
  - Ziyang Zhou (also created the website)
  - Wenkun He
  - Mark Wright
- Compiling report
  - Aye Mon Myo
  - Prakhar Lunia
  - Vikrant Sethia

For a full breakdown of the project management, refer to Appendix 5 and 6.

6. FUTURE WORK

At the beginning of the term, a great amount of time and effort was devoted into implementing the Emotiv software onto the Raspberry Pi in order to transmit the signals from the cognitive device onto EEBug wirelessly. This meant that progress on other aspects of the product became delayed. In the future more effort will be dedicated to enhancing these parts of the product, in order to ensure it is ready for sale.

6.1 SOFTWARE

In the future code will be developed to directly interpret the signals measured by the BCI headset using a Raspberry Pi, instead of using the software development kit provided by Emotiv. This will allow the product to be closer to the original concept.

6.2 CONTROL AND SENSOR

Currently, simulation is used instead of direct control by the user, and there is a deviation from the signals sent by the computer and from the brain. In the future, direct implementation of the headset must be used in order for the product to be usable. In addition, the signals sent from the headset are currently not stable enough, and testing and further development will need to be done to improve the efficiency. The control system currently used for the EEBug would also need to be modified for the wheelchair. In addition to that, the sensors used at present only detect the obstacles, which is not safe enough. In the future more detecting schemes will be added, for instance edge detection to ensure the wheelchair will not fall if there are stairs. Boosting the reliability of the control system will also increase the safety of the product.

6.3 EMOTIV HEADSET

The headset is currently not stable enough, as mentioned previously. In order for reliable use, the headset requires concentration and effort from the user, which is not ideal. The aim is to provide a more accurate and easier to use device for the user, possibly through the use of a greater number of sensors, to obtain a more accurate reading whilst also reducing the amount of work the user has to do. Due to the time constraint and budget issue, there was no opportunity to find a better device, or ideally, a headset would be made from scratch. More market research and testing on the headset will be needed.

6.4 WHEELCHAIR IMPLEMENTATION

At the moment we are only using EEBug to test and demonstrate the design, however it will be brilliant if we can really implement it on the wheelchair.

7. CONCLUSION

From the design criteria, the most significant factors determining whether a product is feasible is if the design increases the mobility and independence of people who require the use of electric wheelchairs. Using the criteria, a weighting and rating method was implemented to compare three design concepts. From this comparison, the first concept involving a choice for method of control and sensors to detect nearby objects became the clear choice to develop further.

Due to the major amount of work and time required to make the final product, a prototype to demonstrate the concept was more feasible to create. This prototype involves using the EEBug instead of the wheelchair and a simulation in place of the BCI headset.

In conclusion, as the prototype works, the concept is feasible, however more work has to be done in order to achieve the original vision of implementing a wheelchair. The main challenges remaining are the implementation of the BCI headset and the final stage of testing in conjunction with the wheelchair before production.

8. REFERENCES

Asgar, M., 2013. *Automated Innovative Wheelchair.* [Online]
Available at: http://www.slideshare.net/ijitcs/automated-innovative-wheelchair
[Accessed 6 March 2016].

Brach, J., 1995. *Measuring fatigue related to facial muscle function.* [Online]
Available at: http://www.ncbi.nlm.nih.gov/pubmed/7487428
[Accessed 6 March 2016].

Brain Vision UK, 2014. *The Brief History of Brain Computer Interfaces.* [Online]
Available at: http://www.brainvision.co.uk/blog/2014/04/the-brief-history-of-brain-computer-interfaces/
[Accessed 2 March 2016].

Cohen, L. G., 2007. *Brain–computer interfaces: communication and restoration of movement in paralysis,* s.l.: The Journal of Physiology.

Cowan, R. E., 2012. *Recent trends in assistive technology for mobility.* [Online]
Available at: https://jneuroengrehab.biomedcentral.com/articles/10.1186/1743-0003-9-20
[Accessed 12 March 2016].

ElecFreaks, n.d. *Ultrasonic Ranging Module HC - SR04.* [Online]
Available at: http://www.micropik.com/PDF/HCSR04.pdf
[Accessed 9 March 2016].

Emotiv, 2016. *Emotiv EPOC.* [Online]
Available at: https://emotiv.com/epoc.php
[Accessed 1 March 2016].

Emotiv, 2016. *Emotive eStore.* [Online]
Available at: https://emotiv.com/store/compare/
[Accessed 10 March 2016].

Graham-Rowe, D., 2010. *Wheelchair Makes the Most of Brain Control.* [Online]
Available at: https://www.technologyreview.com/s/420756/wheelchair-makes-the-most-of-brain-control/
[Accessed 9 March 2016].

IEEE Xplore, 2012. *A self-paced BCI system to control an electric wheelchair: Evaluation of a commercial, low-cost EEG device.* [Online]
Available at: http://ieeexplore.ieee.org/xpls/icp.jsp?arnumber=6222185&tag=1
[Accessed 6 March 2016].

Illumin - USC, 2016. *Thought-Controlled Wheelchair.* [Online]
Available at: http://illumin.usc.edu/240/thought-controlled-wheelchair/
[Accessed 12 March 2016].

Lin, J.-S. & Yang, W.-C., 2011. *International Journal of Innovative Computing, Information and Control.* [Online]
Available at: http://www.ijicic.org/ijicic-11-05079.pdf
[Accessed 5 March 2016].

Maa, C., 2012. *HC-SR04 超音波感測器介紹.* [Online]
Available at: http://coopermaa2nd.blogspot.com/2012/09/hc-sr04.html
[Accessed 8 March 2016].

MyndPlay, 2016. *BrainBandXL & MyndPlay Pro Bundle.* [Online]
Available at: http://myndplay.com/products.php?prod=9
[Accessed 4 March 2016].

OpenBCI, 2015. *GETTING STARTED W/ OPENBCI.* [Online]
Available at: http://docs.openbci.com/tutorials/01-GettingStarted
[Accessed 4 March 2016].

OpenBCI, 2016. *OpenBCI.* [Online]
Available at: http://www.openbci.com/
[Accessed 9 March 2016].

Reeve Foundation, 2016. *Paralysis Facts & Figures.* [Online]
Available at:
http://www.christopherreeve.org/site/c.mtKZKgMWKwG/b.5184189/k.5587/Paralysis_Facts__Figures.htm
[Accessed 2 March 2016].

SpinLife, n.d. *LiteRider Envy.* [Online]
Available at: http://www.spinlife.com/Golden-Technologies-LiteRider-Envy-Travel/-Portable-Power-Wheelchair/spec.cfm?productID=95796&adv=googleads&tar=literider%20envy-p&utm_source=google&utm_medium=cpc&utm_content=96565774044&utm_campaign=Power_Wheelchairs
[Accessed 8 March 2016].

Thibodeaux, W., 2016. *The Disadvantages of Disabled Persons in the Workplace.* [Online]
Available at: http://smallbusiness.chron.com/disadvantages-disabled-persons-workplace-13485.html
[Accessed 2 March 2016].

Tobias Kaufmann, A. H. A. K., 2014. *BioMed Central.* [Online]
Available at: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3898245/#B13
[Accessed 5 March 2016].

TopTenReviews, n.d. *Electric Wheelchairs Reviews.* [Online]
Available at: http://electric-wheelchairs-review.toptenreviews.com/
[Accessed 12 March 2016].

Torsten Felzer, R. N., 2007. *Alternative Wheelchair Control.* [Online]
Available at: http://www.ims.tu-darmstadt.de/media/institut_ims/publikationen_5/felzer_rat07.pdf
[Accessed 6 March 2016].

WebMD, n.d. *Electroencephalogram (EEG).* [Online]
Available at: http://www.webmd.com/epilepsy/electroencephalogram-eeg-21508
[Accessed 9 March 2016].

WheelFreedom, n.d. *Choosing a Powerchair.* [Online]
Available at: https://www.wheelfreedom.com/regional/findoutmore/choosing_a_powerchair
[Accessed 6 March 2016].

9. APPENDICES

9.1 APPENDIX 1: PDS

1. Performance
   - It is of primary importance that the device accurately follow the intended direction of the user.
   - It should also do so with minimal latency, responding near-instantaneously to commands. Aim for less than < 100 ms response time, i.e. below average human reaction time.
   - The behaviour of the device should remain consistent between separate uses.
   - The power supply should be enough to fully power the wheelchair and integrated electronics for the duration of a day's use.
2. Environment
   - The device will operate in normal human living conditions, -5°C ~ 40°C, dry and wet weather – i.e. it must be waterproof or be shielded from water.
   - It may also be used both in quiet areas and in areas of high noise/distraction to the user.
   - The device may operate in areas of magnetic interference and its function should not be impaired by this.
3. Life in Service
   - Expected to be used 12 ~ 18 hours per day, every day for 5 years.
4. Maintenance
   - The amount of maintenance should be minimised, besides charging of the power supply and hydrosaline cleaning of BCI pads.
5. Target Product Cost
   - Considering the cost of other electric wheelchairs, the cost should be in the range of £1000 ~ £2000.
6. Competition
   - There are no products on the market specifically packaging mobility aid and BCI technology, though research projects do exist.
7. Shipping
   - Not applicable at this stage.
8. Packing
   - The product need not be packaged.
9. Quantity
   - No full prototype is to be produced, and the end product is low-volume, speciality market product.
10. Manufacturing Facility
    - The prototype should be buildable using facilities available at Imperial College London, and no specialised or expensive processes should be needed for manufacture of final product.
11. Customer
    - The customer is someone who has impaired motor skills in the legs and/or arms: someone who already requires the use of a wheelchair and would find this method of control more convenient than existing alternatives.
12. Size
    - The device should be the size of a regular electric wheelchair, i.e. additional systems involving the BCI should not add much bulk.
    - The BCI headset itself should fit the size of a standard adult head.

13. Weight
    - The wearable part (the BCI headset) should be as light as possible so that it is not uncomfortable to wear.
    - The rest of the wheelchair should otherwise not be heavier than a regular electric wheelchair.
14. Materials
    - The materials in the headset should not be hazardous or irritable to humans. They should also be lightweight if possible.
15. Product Life Span
    - The wheelchair should last a human lifetime, though the BCI parts need only last as long as technology is expected to outdate it (~5 years).
16. Aesthetics, Appearance and Finish
    - The BCI device should not be obnoxious and should be as discreet as possible.
17. Ergonomics
    - The headset should be comfortable to wear and easy to don. The wheelchair should be comfortable to sit in.
    - The device must also not impair the movement of the user any more than a standard wheelchair.
18. Standards and Specifications
    - At the prototyping stage, conforming to standards is not a priority.
19. Quality and Reliability
    - Reliability is of high importance and the device should never unexpectedly fail. In any case of failure, fail-safes should exist.
    - Quality of performance and build should also be as high as possible.
20. Shelf Life (storage)
    - The product will not deteriorate in storage.
21. Testing
    - Thorough testing of algorithms in simulation and practice will take place with the prototype. Testing involving human users of a full wheelchair may also be needed.
22. Processes
    - Mostly programming, though construction of an array of a sensors, including the BCI, and electronics integrating the control system and wheelchair/prototype actuation will need to designed and built too.
    - No processes not possible with standard electronics laboratory equipment should be needed.
23. Time Scale
    - One academic year for design and prototyping.
24. Safety
    - The device should always follow the user’s intent as accurately as possible, unless this places the user in danger.
    - The device should have sensors beside the BCI to be aware of its environment.
    - The electronics should also not present any risk to the user.
25. Company Constraints
    - Allotted budget of ~£200.
26. Market Constraints
    - Small market makes market research difficult.
27. Patents, Literature and Product Data
    - Several brain controlled wheelchairs exist in the market. However, no patents have been issued which clash. The use of an Arduino is
28. Legal

- May need to use proprietary hardware or software for BCI and should respect the rights of the owner.

29. Political and Social Implications
    - Not applicable.
30. Installation
    - The setup needs to be as simple as possible: wear and go. Some initial setup and calibration is acceptable.
31. Documentation
    - Full documentation for use and maintenance needs to be provided. This will be in the form of an instruction leaflet which will include detail instructions for setup, installation and use.
32. Disposal

- No hazardous or toxic parts.

9.2 APPENDIX 2: CONCEPT 2 AND 3

These two concepts were considered

9.2.1 CONCEPT 2

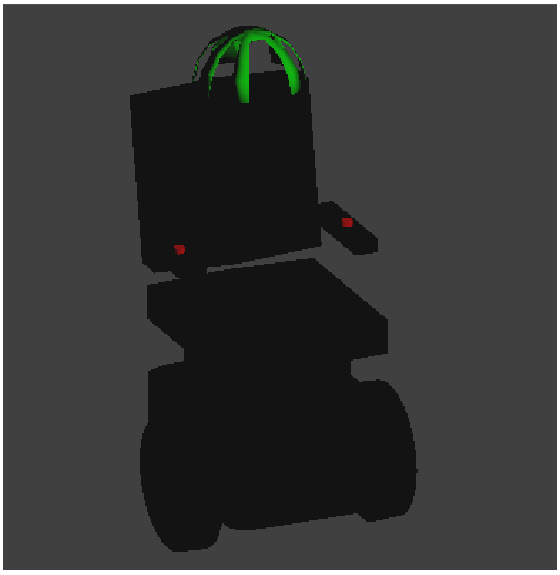

Figure 13: BCI (green) and example indicator placement (red), wheelchair not part of this design

The second design is a portable product that can be installed on any wheelchair or mobility device. It consists of two LED indicators which would be placed on the left and right arms of the chair, the Emotiv EPOC and a control circuit.

The BCI headset sends the information to the left or the right LED, in order to indicate the direction in which the person wants to move, through a control circuit which interprets the BCI data. However, in contrast to the first design, a human helper is needed for extra safety. For example, the person in the wheelchair delivers a message saying that he/she wants to turn right; the right indicator starts blinking, letting the helper know where to go. In this case, it drastically reduces safety concerns as the helper can control the movement.

This design's capability to be used outdoors depends on the type of wheelchair or mobility device it is attached to. There are certain wheelchairs with wheels that are durable to outdoor terrain, and some with only indoor use. This system may be installed on both types and has the same functionality in both cases.

In addition to the above advantages (safety concern and flexible installation), the second design also has a comparably lower cost as there is no need to embed the system into the wheelchair. However, the main disadvantage is that it does not match the original concept of independent mobility directly through thought commands.

9.2.2 Concept 3

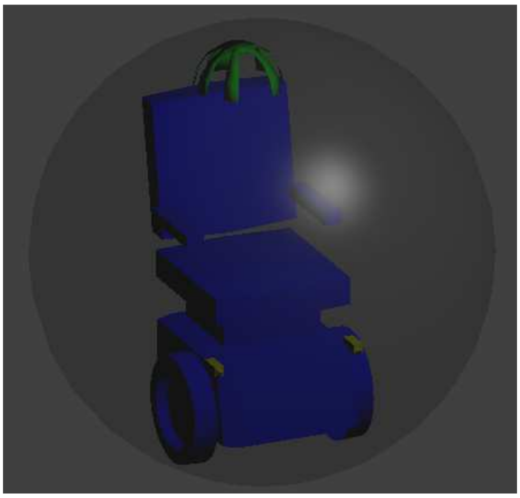

Figure 14: Wheelchair (blue) shown inside transparent protective sphere.

The third design focuses on constructing a system that can be used outdoors as a vehicle for relatively long distance movement. This alternative design would allow the user to go outdoors for longer periods, with minimum inconvenience.

The wheels on certain wheelchairs are not very suitable for moving on the street, which have stairs and rough surfaces. Moreover, travelling in a wheelchair is not very efficient, especially when travelling a long distance. Therefore, the objective of this design is a vehicle that would allow the user to use the BCI to travel in modern traffic safely. There is a possibility for higher speeds in this vehicle as it is specifically for outdoor usage.

In order to change the method of movement, the wheels on the wheelchair will be removed. The chair will now be placed inside a transparent sphere - for easy travel across different terrains whilst also allowing the user to be aware of traffic. Due to the nature of the spherical system, the wearing due to the device’s weight on the ground will be redistributed from a single point to the entire surface, allowing a greater lifespan.

The system is separated into three parts: BCI, control system and the drive of the sphere. The BCI part will use the Emotiv device to receive instructions from the brain. The control system will receive and analyse the data from the brain and then use them to instruct the motor of the sphere. Then the motor will drive the device via a gear system placed on the inner surface of the sphere. In order to turn, there will be two systems. When moving at a low speed on the walkway, the sphere will be able to turn very agilely, but when on high speed, it will not be safe to turn a very big angle. Therefore, the system will shift its weight to ensure the wheel turns a small angle.

The motor, control system and BCI are powered by a battery which can be charged similarly to Teale or other electric vehicles. BCI requires a special USB cable plug to be charged which can be exclusively designed in the control system or on the battery. To ensure the safety of user, there will be sensors placed on the sphere which detect the distance to surrounding objects.

9.3 APPENDIX 3: OVERALL DETAILED DESIGN

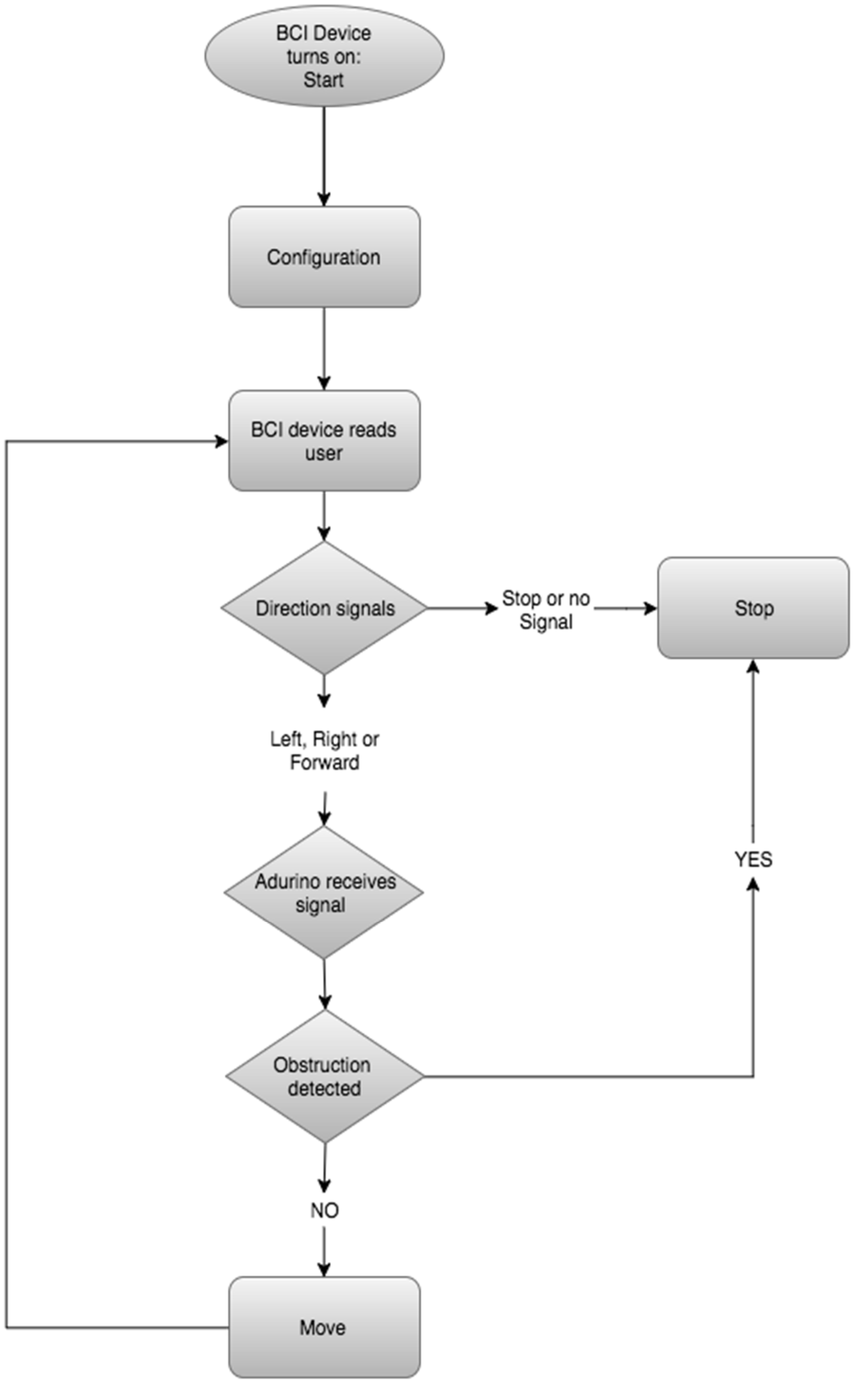

Figure 15: Flowchart of the overall detail design

9.4 APPENDIX 4: TESTING DATA OF THE EMOTIV CONTROL PANEL

User1		User2		User3	
Right	Left	Right	Left	Right	Left
F	S	F	F	S	F
F	S	S	F	F	F
S	F	S	S	F	S
F	S	F	S	S	S
S	S	S	S	S	S
S	S	S	S	F	F
F	F	S	S	F	S
S	S	S	S	S	S
50%	75%	75%	75%	50%	63%

Table 4: represents the rate of successful actions read by three different users.
NOTE: S=SUCCESSFUL; F=FAIL

9.5 APPENDIX 5: GANTT CHART

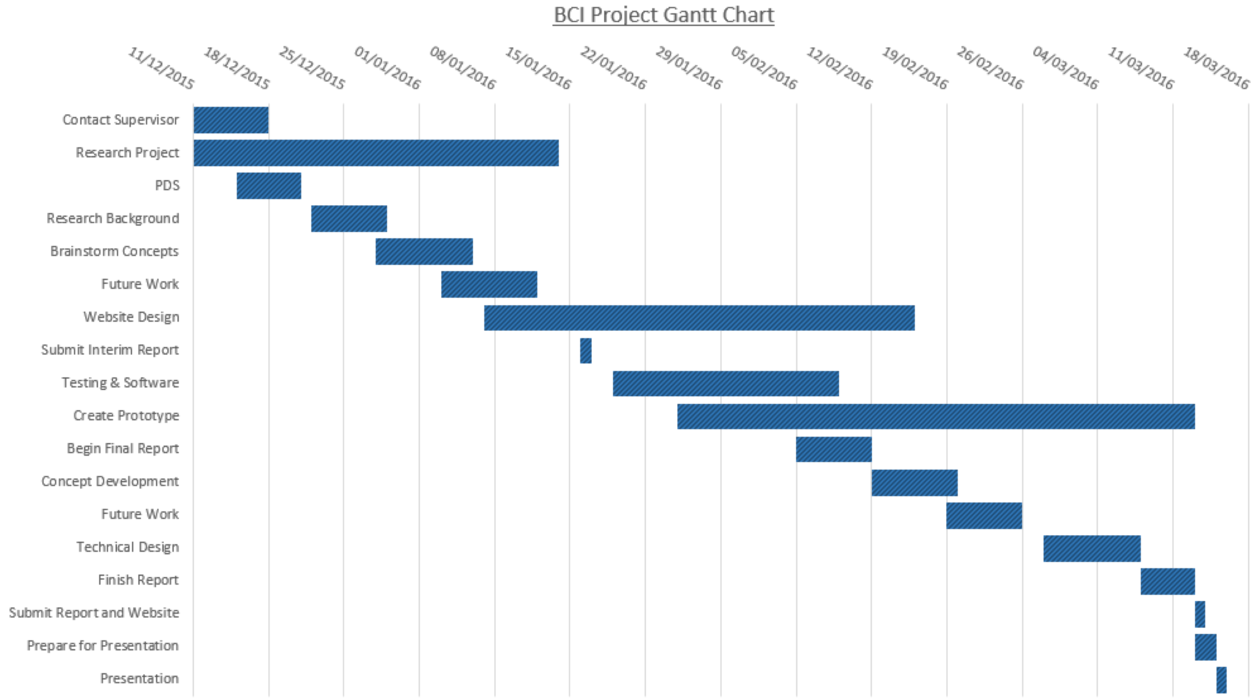

Figure 16: Gantt Chart

9.6 APPENDIX 6: MEETING MINUTES

Date	Location	Duration(hours)	Topic	Action Points
26/10/2015	EE Cafe	1	• Planning the project schedule	• Regular meeting on Monday between 13-15 • Meet Dr. Stott for discussing BCI device
02/11/2015	Dr. Stott's office	1	• Clarification of design	• Borrow device from personal robotics lab • share work for PDS
09/11/2015	Library	2	• Working, discuss and finish PDS	• Try out Emotive device
16/11/2015	Computer Lab	3	• Emotive device	• Building up • Device testing
23/11/2015	Computer Lab	2	• Emotive device	• Device testing
07/12/2015	Computer Lab	1	• Concept brain storming	
14/12/2015	Computer Lab	1	• Discuss report	• Finish individual part on 31/12/2015 • Skype Meeting on 06/01/2016
06/01/2016	via Skype	2	• Examine the report	/
13/01/2016	Computer Lab	2	• Report progress checking	• Future work • Conclusion
14/01/2016	Computer Lab	1	• Discuss report progress	• Missing parts adding • Finalise report
16/01/2016	Computer Lab	1	• Finalise interim report	• Proof read
22/01/2016	Computer Lab	1	• Begin work on final report	• Start researching
27/01/2016	Computer Lab	2	• Creation of prototype	• Testing of Emotive device
03/02/2016	Computer Lab	2	• Creation of prototype	• Testing with EEBug
05/02/2016	Library	1	• Final report	• Begin writing

19/02/2016	Computer Lab	1	• Discuss report	• Future work
24/02/2016	Library	1	• Report progress	• Future work • Technical design
02/03/2016	Computer Lab	2	• Prototype	• Testing with EEBug
09/03/2016	Computer Lab	2	• Discuss report • Work on prototype	• Compile master copy of report • Use simulation for testing
12/03/2016	Computer Lab	3	• Report	• Apply finishing touches
13/03/2016	Computer Lab	1	• Final	• Submit final report

Table 5: Meeting minutes

9.7 APPENDIX 7: TOTAL PRODUCT COST

Now that the design has been chosen, a good estimate of the total cost of the device can be made.

Having already compared BCI headsets, the one that will be used in the product is the Emotive EPOC device as it fits the requirements of the product and is a reasonable price.

For the wheelchair, after doing research (TopTenReviews, n.d.) (WheelFreedom, n.d.), the Golden LiteRider PTC is the electric wheelchair that will be used. It is which is reasonably priced, can be broken down into four parts, each of which weigh less than 35 pounds. It can be used indoors as well as outdoors and also contains a large storage basket which would contain equipment required for the BCI headset.

Item	Supplier	Manufacturer	Price
Golden LiteRider Envy (SpinLife, n.d.)	SpinLife	Golden Technologies	\$1399 ≈ £989
Emotiv EPOC headset (Emotiv, 2016)	Emotiv	Emotiv	\$399 ≈ £282
Raspberry Pi 3 - Model B	ThePiHut	Raspberry Pi	£30

Table 6: Item costs breakdown