

**YAŞAR UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
MASTER THESIS**

**Analysing Brainwaves with a Portable EEG Device via
Mobile Platforms**

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2016**

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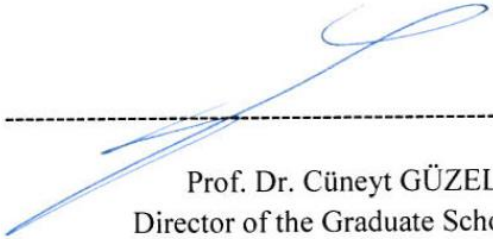

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ABSTRACT

ANALYSING BRAINWAVES VIA PORTABLE EEG DEVICE ON MOBILE PLATFORMS

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MSc in Computer Engineering

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Electroencephalography (EEG) devices measure electrical activity of brainwaves and they are widely used in cognitive science, neuroscience and psychophysiological research. In clinical usage, many of electrodes are placed on the scalp over the multiple areas of the brain in order to make a research with recordings. In the last few years there has been a growing interest in development of portable EEG devices that provide the possibility of measuring brainwaves in easiest and cheapest way. Current research shows portable EEG devices used in many areas and applications such as improving memory, imaging tools, neurofeedback etc. The main advantage of portable EEG devices is that provides a communication and control devices with brainwaves in an easy and cheapest way. This thesis basically covers the usage of portable EEG device in order to control devices hardware based and software components as well as related works about EEG devices.

Keywords: Data Mining, Electroencephalography, Brainwave Analysis, Control with Brainwaves, Classification, Portable EEG Device, EEG Signals, Wheelchair Control with Brainwaves

ÖZET

PORTATIF EEG CİHAZIYLA BEYİN DALGALARININ MOBİL PLATFORMLARDA ANALİZ EDİLMESİ

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Yüksek Lisans Tezi, Bilgisayar Mühendisliği Bölümü

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Elektroensefalografi kısaca EEG, beynin elektriksel hareketlerini ölçen bilişsel bilim, sinirbilim ve psikofizyolojik araştırma alanlarında sıkça kullanılan bir alettir. Klinik uygulamalarda kafa derisine deęen birden fazla elektrot ile beynin farklı bölgelerinden sinyaller toplanır. Teknolojinin gelişmesi ile birlikte son yıllarda kolay ve uygulanabilir olması açısından portatif EEG cihazları geliştirmek için yatırımlar yapılmaktadır. Yapılan çalışmalarda portatif EEG cihazları hafızayı geliştirmek, beyni görüntüleme ve nöroterapi gibi birçok alanda kullanılmakta. Portatif EEG cihazları cihazları yönetebilmek adına ucuz ve kolay bir çözüm sağlamaktadır. Bu tez, portatif EEG cihazı kullanarak hem donanıma dayalı hem de yazılım bileşenlerini kullanabilmek adına çözüm sunmakta olup, bu alanda yapılmış çalışmaları ve sonuçlarını alt bölümlerde incelemektedir.

Anahtar sözcükler: Veri Madencilięi, Elektroensefalografi, Beyin Dalgaları Analizi, Beyin Dalgasıyla Kontrol, Sınıflandırma, Taşınabilir EEG cihazları, EEG sinyalleri, Tekerlekli Sandalye Kontrolü

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Finally, I would like to thank to my parents and my friends for their constant support.

Tuğçe KALKAVAN
İzmir, 2016

TEXT OF OATH

I declare and honestly confirm that my study, titled “Analysing Brainwaves with a Portable EEG Device via Mobile Platforms” and presented as a Master’s Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions, that all sources from which I have benefited are listed in the bibliography, and that I have benefited from these sources by means of making references.



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INDEX OF SYMBOLS AND ABBREVIATIONS

Abbreviations

EER Equal Error Rate

DTW Dynamic Time Warping

ZCR Zero Crossing Rate

MSP Mean Sample Power

VAZ Values Above Zero

PF Peak Frequency

FMR False Match Rate

FNMR False Non-Match Rate

1.Introduction

A brain–computer interface (BCI), sometimes called a mind-machine interface (MMI), direct neural interface (DNI), or brain–machine interface (BMI), is a direct communication pathway between an enhanced or wired brain and an external device. BCIs are often directed at researching, mapping, assisting, augmenting, or repairing human cognitive or sensory-motor functions ("BCI," 2016) . BCI is considered as the next level of communication as means of controlling devices without any physical interaction.

BCIs are considered as most significant discoveries in last decades that gives hope to disabled people for living comfortably and aims to eliminate the barrier due to the disability such as providing vision to blind person, hearing ability to deaf and help physically paralyzed etc. One top of technique to capture users thought that is capturing user's brainwaves is electroencephalography (EEG) which is most of the time non-invasive method except some medical applications uses invasive way to get brainwaves from user. EEG records and patterns give more information if scalp has more electrodes; that provides information coming through your brain with different places. People who have ALS or motor neuron disease are potential user of EEG devices to control their wheelchair with brain.

The aim of this thesis is to provide solution for controlling a car with NeuroSky Mobile device together with additional gyroscope sensor in a cheaper way and also provide solution for keyboard usage with brainwaves. Several works show that one sensor is not enough for controlling devices with multiple commands rather it is easy for switching in on/off manner Work by (Chen *et al.*, 2014) and also by (Fladby, 2008) examined detailed research that aims to provide authentication mechanism for users and made a conclusion one sensor is not enough to distinguish clients with tasks. (Bose *et al.*, 2016) used attention values for controlling web browsers and getting feedback from user to improve advertisement quality. In this work, they are aware that is better to use EEG device with more electrode, but instead they used MindWave Mobile

attention values and they concluded that to control something it is hard to keep concentrated in specific task interval therefore using attention value could be not enough along to control something because attention values easily effected by unexpected movements. Usage of both double blink and attention values for switching options gave good results according to (Dobosz and Wittchen, 2015) after examining different options with clients. According to studies, usage of both attention and blink values provide appropriate solution for giving multiple commands as means of controlling devices with brainwaves. Combination of blink, attention and head movement values proposes real time solution as means of controlling prototype car with brainwaves thus gives a perspective for real life usage. Likewise, usage of blink values provides efficient solution for typing letter which aims ability to write words without any physical interaction. Both solutions offer cheap and reliable solution on behalf of controlling both software and hardware components with MindWave Mobile device.

During this thesis, research's related with portable EEG devices examined in 2 Literature Review section to show related works and advantages/disadvantages of NeuroSky Mobile device. Leading with idea cheaper solution for driving wheelchair and applications based on MindWave Mobile device has been developed together with Arduino. Chapter 3 Brainwaves section starts with historical review of brainwaves and continues to give motivation for understanding basic concepts of brainwaves such as how can be measurement done, frequency bands etc. Chapter 4 MindWave Mobile gives detailed information about features of MindWave Mobile device. Apart from other EEG devices, MindWave Mobile device provides extra fields (eSense meters like attention, meditation etc.) which are calculated based on frequency bands. From that eSense meters, attention value is mostly used while developing applications during this thesis. Another eSense value comes with SDK is blink value that indicates how strongly user is blink with value between 0 to 100. To detect double blink and blink values, algorithm developed depending on observations because blink value coming from SDK seems not accurate after some observations. Instead of getting blink value directly from SDK, this value used like binary value to indicate blink is occurred or not and algorithm

runs in order to check either double blink or blink is occurred. In Chapter 5 System design and implementation part, implementation of designed system for controlling car and software components with brainwaves covered in detailed way. Car prototype constructed on wood chassis and Arduino Uno used together with motor shield including Bluetooth module named HC-05. In order to detect head movements of user, another small hardware prototype constructed with Arduino Nano, MPU 6050 gyroscope and Bluetooth module HC-05 and placed on top of the MindWave Mobile device. After observations, Arduino code developed in order to detect head movements in the directions of forward, backward, left and right. Mpu6050 is powerful device as means of getting sensitive values in three dimensional axes, additional directions can be added as needed. Four direction seemed enough and whenever user moves the head to defined direction, one letter will send through Bluetooth module to Android application as forward represented as F, backward as B, left as L and right as R. In the android application, observer/observable pattern is used while developing algorithm that observes any changes Bluetooth message coming from head movement hardware. Whenever user moves head, android application observes and catches the direction and if the current attention value falls into predefined interval, the Bluetooth message will send to prototype car in order to move that direction. The bigger attention value the faster car prototype will move to that direction for 1.5 seconds long. Another android application named keyboard application provides a solution for writing word with brainwaves. After successful connection with MindWave Mobile device, navigation for row selection starts and wait for user to blink. If the user blinked once, navigation continues with column selection and waits user to double blink to select specific letter. Selected letter will be written to textbox and application continues with row selection. Both applications provide simple and cheap solution for brainwave controlled devices as for hardware and software manner. MindWave Mobile has one dry sensor only which can give only specific information about brain that implies constructing multiple command is hard issue for controlling devices. For that reason, small hardware placed on top of MindWave Mobile to control car with head movements together with using brainwaves which proposes simple and cheap solution for controlling devices with only one sensor EEG device. Chapter 6 Conclusion and future work gives ideas about what

can be the step next to investigate to build more complex systems with using brainwaves. Deductions from previous research investigated in this section to show appropriate usage of MindWave Mobile device for controlling devices.



2. Literature Review

Extracting meaningful data from portable EEG device and make use of this meaningful data in order to control devices is the most popular BCI research area. There are lots of ways to control devices which vary from device to device. Most of the applications are based on training and classifying EEG data for personal usage.

Controlling devices with brainwaves includes car, quadcopter, wheelchair etc. In the work of (Yu *et al.*, 2012) used Emotiv Epoc EEG headset to control Ar Drone which is a quadrotor aimed for disabled people to see future areas with drone. Another research done by (Campbell *et al.*) also used Emotiv Epoc EEG headset for making calls on smartphone by observing P300 wave of brain which is known as Event Related Potential(ERP) is about process of decision making. In another work by (Campbell *et al.*) classified EEG signals to control robots as means of human satisfaction with using Emotiv EEG device. Another interesting usage of Epoc EEG is to control wheelchair with head movements by (Rechy-Ramirez and Hu, 2014) with a successful outcome in which idea of usage head movements related with this thesis.

In this section, previous researches and conclusions about MindWave Mobile device are investigated and reviewed below as subsections.

2.1. Attention sensitive web browsing

Based on NeuroSky's eSense Meter calculations, one of research made which provides web browsing to user using brainwaves. Research study of (Bose *et al.*, 2016), basically suggests to use user's attention level to control web browser rather than using gaze tracking or time spent on web page. According to this study, they used attention level in three different ways:

First one is controlling mechanism, basically control user interface elements like menus, buttons etc.

- Depending on the attention value on one area, web developers can improve

webpage layout or can insert some advertisements on concentrated area.

- This one is related with second one which basically offers creating attention sensitive websites.

As stated by (Bose *et al.*, 2016), they are suggesting that it is good to know which sections or websites are more interesting based on user experience with attention value. They believe that it is more helpful to develop attention sensitive webpages in order to increase engagement. They made research for portable EEG devices to get momentary attention level of user in real time and transmit data mobile device using Bluetooth. Depending on their research, it is better to use EEG based solution to control device, determine user's interest and get feedback from user rather than user's emotion or gaze tracking.

2.2. Attention for controlling web browser

In the first way of controlling web page, they offered to use basic control such as backward and forward navigation buttons, menu navigation and link selection. They did not include new URL entry for reason below:

“We intentionally do not include new URL entry, since pressing keys in a virtual keyboard with the help of the EEG attention level can be quite cumbersome. If totally hands free functionality is required, the URL entry can be performed through voice using a suitable Voice API” (Bose *et al.*, 2016)

For portable EEG device, they used NeuroSky API which provides eSense meter such as Attention, Meditation and also blink value provided by SDK. They are aware that other EEG kits such as Emotiv provides more functionality in order to control things with calculating intention of user to push/pull or left/right.

Since they used NeuroSky EEG device, they created a threshold value of attention for controlling functions such that user navigates to next item like Windows' 'tab' key function. Their threshold value based on time, not based on attention value. But they faced the problem that fluctuation of attention value is high therefore they

needed some user familiarization without training. Depending on the user, there is need calibration to determine user's attention value threshold and they suggested this calibration can be performed by asking the user to perform a simple task or stay still for few seconds while wearing the EEG headset.

Depending on study of (Bose *et al.*, 2016), the idea behind controlling web browser with attention is that navigation across menus, buttons and other assets will be done by attention level and selection made by blink level of user. Navigating between elements basically done by threshold value of attention like; if attention level of user remained over the threshold for 1 sec, selection stays on the current item; otherwise selection will be moved to next item. They basically used two Activities: Main Activity which is home screen and Browser Activity. Also, they distinguished double blink from blink and used for returning to main activity and also opening current selected item in the web browser. When doing this way, they have used NeuroSky API which provides blink value ranges 0 to 100. They plotted blink level of one user over serial trial shown in Figure 2.1.

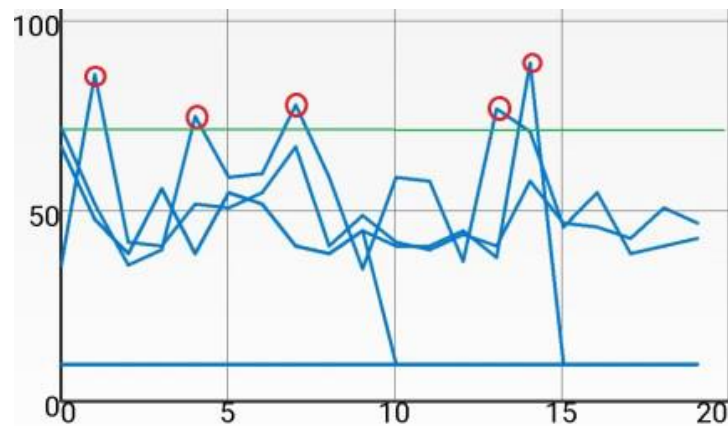


Figure 2.1 Blink levels of one user, double blinks circled in red (Bose *et al.*, 2016)

Likewise, as said by (Bose *et al.*, 2016), the difference between the current and previous blink values of 20 can distinguish between a casual and deliberate blink depending on plotting user's attention level while browsing through a Google news

article, recorded over three iterations. They concluded that for most users, the attention level consistently stayed over 30 when they were paying attention to the article.

According to their work, attention for responsive web browser, second suggestion proposed that attention level also used for designing web content more interesting way according to user intentions such as inserting appropriate advertisement. In order to do so, that has mapped the attention level to section or block element that the user is reading on the current webpage. Using JavaScript, this section is captured via scroll position. Along with using EEG sensor, the script is executed in the context of webpage to perform the tracking. They basically used some mathematical formula for scrolling and they mapped the attention level and page scroll percentage readings, using timestamp as the key. They saved user's attention level and scroll level separately for each user. The good thing is, they later verified that system correctly recorded the actual sections where the user was paying attention by asking the user if the reading reflected their interest. They concluded to send aggregated data to web content developers for gathering feedback and make web contents in more user interesting way using web server.

Their third suggestion is close to the second one; attention sensitive web architecture. With calculating attention of users, web developers can make websites more attention sensitive. They created basically a simple web architecture in order to use further. They describe the way of implementing the code as below (Bose *et al.*, 2016):

- Create class APIWrapperEEG class to receive and process events from the EEG device
- Annotate APIWrapperEEG class @JavascriptInterface.
- Instantiate APIWrapperEEG on the application's Main Activity creation.
- Find out page load finish event callback, Register APIWrapperEEG instance, with Content View on the callback using addJavaScriptInterface.

- We also provide an EEG.js JavaScript file containing all helper methods which the developer can include and use in their web pages. These are basically wrapper functions and events for the APIWrapperEEG Object.

Their idea of using NeuroSky's eSense values is good in order to control devices such as computer or mobile devices. However, it is hard to keep attention level stationary even if for 1 second. Whenever you are trying to focus some thought or some events, unexpected sound or movements decrease attention level suddenly. For that reason, it is better to use attention or meditation level for controlling selection speed or movement speed of assets. Also, it is better to analyse blink threshold with using raw EEG data of user, and calculate appropriately by extracting raw data in order to determine whether user blinked or double blinked etc.

2.3. Password application using MindWave Signals

Another possible usage of MindWave device is covered by (Senzio and Yamada, 2014) that offers making use of attention/meditation level of brain when thinking specific thing(object, color etc.). Neurosky's TGAM chip provides attention/meditation level as built-in therefore it is appropriate to use these levels for research. In (Senzio and Yamada, 2014) , they made a comparison between an expected pattern and generated ones in order to do specific actions with determining output signal is correct or no with GUI application shown in Figure 2.2 Mind pattern configuration and comparison. In the work by (Senzio and Yamada, 2014) EEG signals such as attention and meditation updated per second. In order to test generated configurable patterns, they have used three basic patterns for meditation values. Comparing with threshold value, the filtering algorithm determines if the expected pattern occurred or not within the expected time. As reported by (Senzio and Yamada, 2014) , it is easy to develop password-based applications with unique configurable patterns depending on each user within expected time. For example, if user X is able to produce patterns C->B->A in expected time, application give authorization for user X.

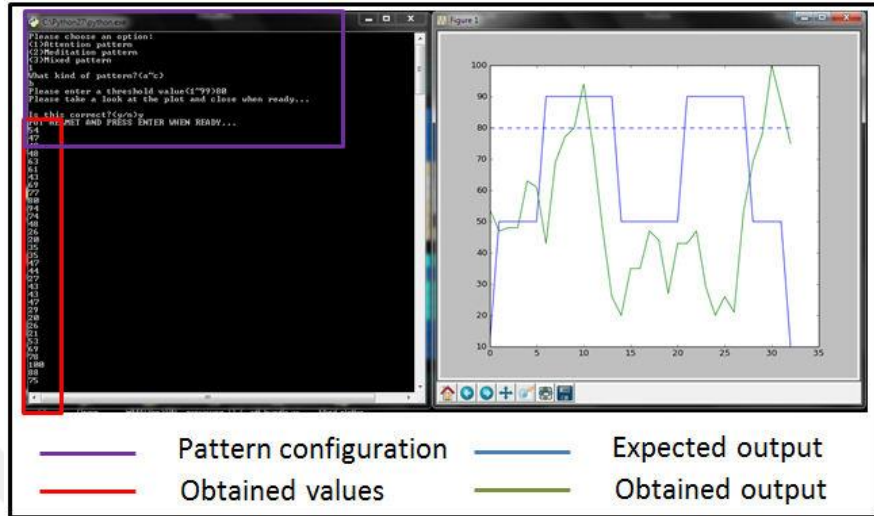


Figure 2.2 Mind pattern configuration and comparison (Senzio and Yamada, 2014)

According to work of (Senzio and Yamada, 2014) , architecture of the system is follows: EEG headset sends output values (that means TGAM-1 coded values) to microcontroller unit via RF transceiver and microcontroller unit decrypts these values. The microcontroller unit gets values from EEG headset with the same baud rate. Figure 2.3 Mind pattern processing system description (Senzio and Yamada, 2014) describes work flow and architecture of system.

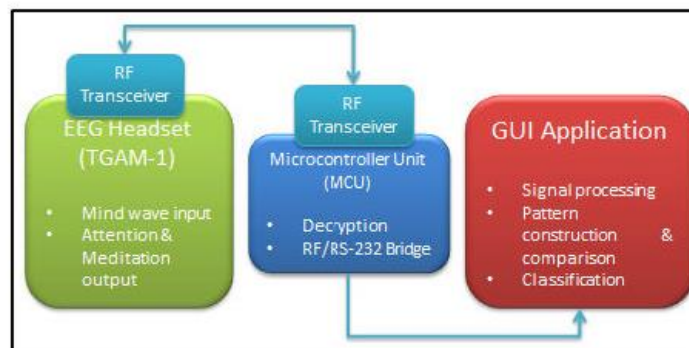


Figure 2.3 Mind pattern processing system description (Senzio and Yamada, 2014)

Work of (Senzio and Yamada, 2014), analyses and compares various patterns for users as shown in Figure 2.4.

PATTERN	AVERAGE SUCCESS RATE
A	64%
B	65%
C	15%
B,A	40%

Figure 2.4 Overall average success rate (Senzio and Yamada, 2014)

This approach may not be practical in all situations because Figure 2.4 shows pattern C was extremely difficult to recreate. With comparing to others, table shows trained users has better performance than untrained users. Also, by looking at the success rate of pattern C, it is clearly seen that not effective result has been gathered in case of short time frame and low sampling rate. A key limitation of this research is that adaptability is hugely dependent on human factors. If we consider trained users, research performed good results for generating MindWave patterns which includes meditation values and leads up to development purposes for password application.

2.4. Brain- Computer Interface for Mobile Devices

In the research of (Dobosz and Wittchen, 2015) indicated another possible usage of MindWave device for people with total motor impairment to control mobile devices. The program mainly consists of two phases; first phase aims to analyse the EEG signals and detect eye blinks second one is interpreting and do appropriate action.

Based on (Dobosz and Wittchen, 2015) , they first created mobile application which collects user's data(attention, meditation and blink value) and save in it csv file in order to analyse later. The data yielded by this study provides different options for different actions such as, switching option can be made by blink values (namely single or double blink) and choosing options can be made by attention level either reaching threshold value or stay focused in specific time interval. After analysing collected information, they observed that the data appear to suggest that

- Meditation and attention values are varying in time with very low and very high level.
- With the normal functioning (i.e. use mobile phone) attention level generally has value between %40 and %50.
- Attention level increased to %75 and higher values when someone focuses on a specific activity or tries to be concentrated.
- Also, they observed that it is hard to achieve higher attention level when someone is tired or tries to be relaxed. They seem that attention level will never greater than %50 - %60 in this situation.
- For the eye blink values, is seemed that blink strength value generally varies between 38% and 60%, but sometimes can be higher and its value can be over 80%.

Based on above observations, they concluded that either keeping action level with high values in specific interval or achieving high meditation level is both hard. Another conclusion based on observations is that, measuring blink strength is not a good option in given interval because it is hard to get. Rather than blink strength they decided to use whether user blinked in specific time slot, for average 100-400 milliseconds, in order to control system.

Another part of research in (Dobosz and Wittchen, 2015) is basically making experiments with people. They examined 8 people with varying ages between 25 – 44. For those experiments, each user did not perform any activity and each experiment is repeated five times. To give specific activity to each user, randomly selection made in the list below:

- Call the third person from the contact list.
- Play the third message from the list of voice messages.
- Send a predefined SMS or email to the third person from the contact list.

Any objective listed above was considered “success” if user was able to finish the task in one minute. They concluded the results for each experiment in Table 2.1 Result of experiments (Dobosz et al., 2015).

Number	Methods of interaction	Success	Comment
1	switch: single blink choice: focus 75%	60%	Sometimes incorrect option was chosen. The best time of completed objective was 25 seconds.
2	switch: double blink choice: focus 75%	85%	Proper option was chosen in most of times, but not every time. 19 seconds was the best time in a single experiment.
3	switch: interval - 1s choice: focus 75%	10%	Proper option cannot be chosen, because option switching interval is too short.
4	switch: interval - 3s choice: focus 75%	82%	Objective is not achieved. Proper option is chosen in most of times during the tests. The best time is 35 seconds.
5	switch: interval - 5s choice: focus 75%	16%	It is hard to keep high attention level longer than 3 seconds. This option may work for someone, who is able to keep high attention level longer after training.
6	switch: interval -3s choice: focus 5%	0%	Focus level is too low, and highlighted option is chosen every time without specific interaction with the user.
7	switch: interval - 4s choice: focus 95%	0%	Required focus level is too high. Option of switching interval is too long.

8	switch: interval - 5s choice: focus 15%	0%	Required focus level is too low. Option of switching interval is too long.
9	switch: interval - 3s choice: focus 70%	74%	Expected option is chosen. Attention level is appropriate.
10	switch: double blink choice: focus 85%	68%	Expected option is chosen in the most of tests. Objective is achieved.

Table 2.1 Result of experiments (Dobosz et al., 2015)

Table 2.1 Result of experiments (Dobosz et al., 2015), shows that 5 out of 10 experiments which success rate is higher than 50% is considered “achieved”. After these results, they concluded that (Dobosz and Wittchen, 2015):

- The best focus level (i.e. attention) is approximately 75%.
- Another conclusion that the best switching option methods are double-blink and automatic switching option with interval equal to 3 seconds.
 - Double blink is a good method, because it is not a normal human behaviour like regular eye blink and can be forced by the user at specific time.
- Time interval equals 2 seconds or less may be too low in a real situation. The average user may have problems with achieving high attention level in such short period of time.
- On the other hand, time interval equal to 4 or 5 seconds may be too long, because the user may have problems with keeping high attention level for that period of time.
- An interval equal to 3 seconds seems to be a reasonable value for this application as it was proved during the tests.
- Unfortunately, any pattern or rule representing such situations cannot be distinguished; it simply leads to the conclusion that BCI is not precise.
- The results of experiments show that the best configuration of setting uses attention level and value of interval time in the automatic mode.

The findings of (Dobosz and Wittchen, 2015) research showed different options in order to control mobile device with MindWave and mostly indicated to usage of double blink and attention level is precise way to do it. Examining different options clearly shows the best choice for switching/choosing actions with success rates. Research of (Dobosz et al., 2015) encouraged me that the usage of double blink, blink and attention level is an appropriate way to control any of mobile devices with MindWave.

2.5. Brainwave Manipulated Wagon

A recent paper with the title “Brainwave Manipulated Wagon” by (Chen *et al.*, 2014) examines the role of BCI device in order to control robotic car. Based on (Chen *et al.*, 2014) , they developed and tested the idea of classifying MindWave EEG signals and sending specific commands to robotic car. In this work, authors basically aimed to show that low cost EEG device would help people with physical disabilities such as paralyzed who could not move their hands. They built up robotic car instead of full completed wheelchair device because of time pressure.

In the design part, user starts with the training phase with simply staring at the lamp on the screen. After collecting data and training process, classifying phase is started. The robotic car is basically receiving classified commands through serial port i.e. TX and RX. Their system block diagram, Figure 2.5 System block diagram (Chen *et al.*, 2014) , consists of basically:

- C#, MySQL for data retrieval and classification.
- GUI for user interface.
- Arduino, XBEE modules for robotic car.

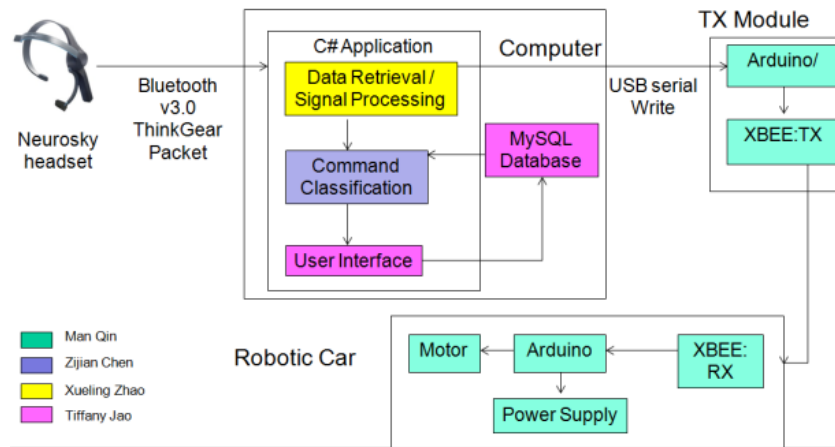


Figure 2.5 System block diagram (Chen *et al.*, 2014)

In this study, they pointed out that being able to use attention value is important because they designed algorithm accordingly. They built up a GUI with small lamp to measure user's attention value according to NeuroSky's user guide which claims that attention value can be controlled through a visual focus, such staring at a point on the screen, or focusing on imagining the action user hoped to accomplish.

To differentiate attention levels, they considered to come up with two states, concentrated and not concentrated, when classifying the user data. After user data gathered as means of attention when concentrating the bulb, algorithm sorts the collected data using merge sort. By averaging the middle third of the training data, algorithm calculates the classifying point. They preferred to choose this approach because they claimed it will eliminate low values of attention which may occur suddenly in case of not fully concentrated in training phase. Also their findings lend support to the claim that using only the threshold to distinguish between two states may not yield a stable result. For instance, sometimes the test subject has a hard time sustaining the concentrated state in long intervals, even though the subject is still staring at the blinking light (Chen *et al.*, 2014) . In order to make more accurate classifying result, they decided to include two other criteria; (Chen *et al.*, 2014).

“The first criteria is that, the algorithm will only classify the attention level as high when the input attention value is larger than 90% of the classifying point. In this case, input attention value will

still be considered as high, even if it drops below the classifying point by a little bit. Otherwise, the input attention value will be considered as low attention level. The second criteria is that, if the user is at the concentrated state originally, two consecutive low attention inputs will change the state from concentrated to not concentrated. This criteria address the problem of when the user only has a short instance when they are unable to sustain the concentrated state, but they are still trying to do so and shortly recover after that instance.”

During the experiments, they noted several important consequences; one of them is, if the user fully staring at the bulb at the training process, the classifying point will be high value which makes hard to switch concentrated state in order to control which requires more attention. Another consequence is that it is hard to switch not concreted state from concentrated state. They stated that, it will take at least two seconds to change the state because the algorithm requires two low attention levels to be considered as not concentrated (Chen *et al.*, 2014)

To illustrate the idea for having multiple commands, they tried to utilize Event Related Potentials(ERP) which is brain response to events such as cognitive, specific sensory or motor events. In order to differentiate band powers to measure ERP, they used Naïve Bayes classifier which is a probabilistic classifier based on determining current classification using previous classifications. With this approach, they faced some challenges about expecting what correlation will have with one sensor EEG. That is, they claimed the reason of Naïve Bayes classifier failed will be unclear because the uncertainty of whether it is caused by having only one sensor or they did not have big enough data. They realized that in order to improve accuracy, they have needed much more number of experiments and dataset.

The findings from the research illustrate how NeuroSky can be used in order to control robotic car. So far, they were able to turn LED light on and off with analysing alpha waves and attention values. In order to control robotic car, they predicted that attention value is not enough because there needed multiple commands rather than switching on/off. They concluded the challenges of using NeuroSky is that it only has one sensor and due to the its placement, it is hard to detect ERP signals in FP1. Another challenge about NeuroSky is, that the sample rate is fixed at 512 Hz, calculated values

outputted per second which is not fast enough in case of analysing and minimizing time delays in the system. Therefore, their findings made conclusion that if more commands needed rather than on/off or move/stop, they need EEG headset with multiple sensors placed on multiple areas of brain.

2.6. Brainwave Based Authentication

EEG based authentication is another possible consequence of extracted brainwave signals which could give unique information about each people. The thesis by (Fladby, 2008) serves a great and comprehensive introduction about extracting EEG signals in order to differentiate users, basically authentication of users. In (Fladby, 2008) first it examined two methods named Dynamic Time Warping(DTW) and feature extraction in order to see possibility of distinguishing clients and tasks based on EEG signals. It is noted that due to the SDK and EEG device limitation, NeuroSky MindWave, it is not possible to experiment Event Related Potentials(ERP) because device do not provide enough information and necessary functions. The equipment used in the work of (Fladby, 2008) is the first version of MindWave device which runs with 5v device and uses serial port to send signals to computer. (Also , the literature on (Fladby, 2008) mentions that placement of MindWave which is Fp1 gives an idea about subconscious thinking and personality such as everyday planning, decision making, emotions, social- and moral reasoning)

One of the first step of constructing experiment presented in (Fladby, 2008) is deciding tasks which will be performed during analysis. The collected data appears to suggested that the tasks are not compatible with experiments because in anomalies occurs easily when the user is talking. They concluded eight tasks can be used for experiments as means of authentication that can be considered subconscious nature of tasks at FP1. Eight tasks used during are (Fladby, 2008) :

task1 Relax - client is told to sit comfortably and relax in a normal fashion

task2	Color - client is told to think about the red color
task3	Rotate - client is told to mentally rotate a house
task4	Password - client is told to think about the password “BrainWaveS”
task5	Music - client is told to think about a song they know
task6	Words - client is told to generate random words in their native language starting with the letter “M”.
task7	Count - client is told to count upwards in their native language, fast and starting with 1.
task8	Read - client is told to read from a provided random text.

Table 2.2 Eight tasks used in experiments

They stated that all of eight tasks are easy to perform but it is hard to user get concentrated on specific task in time. The EEG signals sampled frequency at 128 Hz. Twelve clients were used during experiments with varying age range from 20-45. Also, clients used in experiments selected both right and left handed because the main purpose of experiments was to deal with signal matching rather than classification. For each client, experiments done by three sessions in which each of tasks was recorded 3 times lasting 20 seconds with short breaks. Approximately, each participant experimented three sessions with total 40 minutes. During experiments, they used NeuroView application which comes with NeuroSky SDK to record signals with N sample. Also, they only recorded raw data in a text file which contains two columns separated with a semicolon as shown in Figure 2.6 .

```

time;rawdata;
0;0.223945;
0.0078125;0.267891;
0.015625;0.248359;
0.0234375;0.287422;
0.03125;0.21418;
0.0390625;0.223945;
0.046875;0.228828;
0.0546875;0.184883;
0.0625;0.219063;
0.0703125;0.248359;
0.078125;0.306953;
0.0859375;0.282539;
0.09375;0.21418;
0.101563;0.263008;
0.109375;0.238594;
0.117188;0.287422;

```

Figure 2.6 Captured raw data in text file (Fladby, 2008)

Each text file is named in the form of <clientId>_<task>_<session>_<recordingNr>.s<type> Each task was recorded 3 times for 30 seconds in each session which is equivalent 72 records for each client. After all experiment finished, they gathered 864 signals totally.

For the signal processing part, they used first 16 seconds with 2048 sample because they concluded that it took few seconds to concentrate on specific task therefore they removed the first 4 seconds from each record. In order to differentiate frequency bands with names, they used Discrete Fourier transform (DFT). As a result, they obtained six frequency bands Delta, Theta, Alpha, Beta -Low, Beta-High and Gamma. After getting six frequency bands, they used their own filtering based on Inverse Fast Fourier Transform (IFFT) to remove to frequency domain above 50 Hz. For the feature extraction, they used 25 feature for each signal. Features used in experiments are shown in Table 2.3.

feature1	MSV - Mean sample value
feature2	ZCR - Zero Crossing rate
feature3	VAZ - Values above zero
feature4	PF - Peak Frequency
feature5	PFM - Peak Frequency Magnitude
feature6	MSP - Mean spectral power
feature7	MPA - Mean phase angle
feature8	Pdelta - Delta band power
feature9	PFdelta - Delta band peak frequency
feature10	PFMdelta - Delta band peak frequency magnitude
feature11	Ptheta - Theta band power
feature12	PFtheta - Theta band peak frequency
feature13	PFMtheta - Theta band peak frequency magnitude
feature14	Palpha - Alpha band power
feature15	PFalpha - Alpha band peak frequency
feature16	PFMalpha - Alpha band peak frequency magnitude
feature17	PbetaLow - BetaLow band power

feature18	PFbetaLow - BetaLow band peak frequency
feature19	PFMbetaLow - BetaLow band peak frequency magnitude
feature20	PbetaHigh - BetaHigh band power
feature21	PFbetaHigh - BetaHigh band peak frequency
feature22	PFMbetaHigh - BetaHigh band peak frequency magnitude
feature23	Pgamma - Gamma band power
feature24	PFgamma - Gamma band peak frequency
feature25	PFMgamma - Gamma band peak frequency magnitude

Table 2.3 Features used in experiments (Fladby, 2008)

After collecting data and constructing features, they created struct in MatLab which will hold all information about signal like below:

- $signal_i = (client_j; task_k; session_m; rec_n; feature_o)$

where i, j, k, m, n and o to refer a signal consisting of client, task, session, recording, and features respectively.

In the analysis part of signals, at the first step, they calculated minimum, maximum, mean and standard deviation of each feature and they concluded that the EEG signal activity in delta and gamma is stronger than the others. At the second step, they checked whether their samples and features follow a normal distribution or not. To do so, they used chi-square goodness-of-fit-test. After these calculation, they concluded and guided by idea that signals are more stable in the mid-range frequency bands like theta alpha, beta Low and beta High. Likewise, they concluded for each client that only 35 feature test out of 300 had a probable normal distribution (Fladby, 2008).

After analysis part, in order to see how features related with each other they computed correlation functions. They stated that if two or more features have a high correlation values, it takes advantage of creating a distance metric. They found that

there is a high correlation between beta Low and beta High for all 12 clients at all. Also, they concluded that most of clients had highest activity in the delta band.

The work of (Fladby, 2008) claims the hard part is finding similarity of two EEG signals. They used distance metric to find similarities of two sequence with four categories. They stated as hardest part because there is no best way to compute distance metric for calculating best results. Subsequently, they calculated dynamic time warping based distance metric to find matching patterns with warping techniques with simulating human ability. They used DTW algorithm which has two input in time series and one output. Since it took long time to calculate the distance between all signals, they instead calculated best case scenario which depends best performance in each session per client by calculating best value of distance between three recordings of each task

To sum up their work, they concluded that the activity of EEG signals is strongest in the delta band. Because they observed sudden improvements in the signal when recording, they decided to use Dynamic Time Warping technique which did not give them good results. They only achieved EER of 34.30% in an unrealistic “best-case-scenario” with selecting best performing result which should apply lower EER values for DTW. They overcome this problem by transferring signals to frequency domain together with extracted features from domains. Due to the fact that they did not find any correlation between a specific task and feature, they are unable to distinguish tasks. The best EER result they found is 34.41% with all-vs-all comparison is using feature based metric. The major deduction they made stated as follows:

“We have to ask ourselves, why do we get an EER lower than 50% (the worst case)? Is it because we actually detect client specific similarities and differences, or is it in fact session based such that two consecutive signals are similar because of the equipment? The results strongly suggest that the similarities are session based. The reason is that one sensor with only 128Hz sample frequency fails to extract enough client specific information in order to extract features with high entropy. The only reliable information we can extract with one sensor is the power in each frequency band, which is not enough to distinguish between clients or tasks.” (Fladby, 2008).

This research was concerned with using NeuroSky MindWave device in authentication application; however, the results showed us by using only one sensor is not good enough to construct client based authentication with tasks in real life. The findings from the research show that the limitations of one sensor EEG device, more specifically MindWave NeuroSky, as means of client and task based authentication systems.



3. Brainwaves

3.1. What is Electroencephalography (EEG)

Electroencephalography (EEG) is an electrophysiological monitoring method to record electrical activity of the brain. It is typically non-invasive, with the electrodes placed along the scalp, although invasive electrodes are sometimes used in specific applications. EEG measures voltage fluctuations resulting from ionic current within the neurons of the brain. In clinical contexts, EEG refers to the recording of the brain's spontaneous electrical activity over a period of time, as recorded from multiple electrodes placed on the scalp. Diagnostic applications generally focus on the spectral content of EEG, that is, the type of neural oscillations (popularly called "brain waves") that can be observed in EEG signals.

3.2. History of EEG

Milestones of EEG devices started with the introduction of galvanometer. Galvanometers were the first instruments used to detect and measure small amount of electric currents (Donald and Silva, 2010). It also shows the direction of flow of electric current. Sensitive galvanometers were used to detect signals from long submarine cables, and to discover the electrical activity of the heart and brain. ("Galvanometer," 2016). The introduction of the galvanometer has been associated chiefly with the name of Nobili in Florence; this instrument was refined in 1858 by William Thompson (Lord Kelvin) in England. These galvanometers would faithfully demonstrate continuous electrical currents and their variations in intensity but failed in the detection of instantaneous electrical phenomena. (O'Leary and Goldring, 1976)

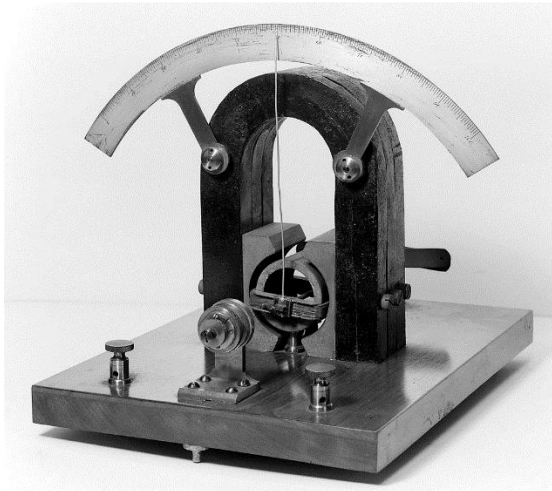


Figure 3.1 An early D'Arsonval galvanometer showing magnet and rotating coil

After foundation of galvanometer, two scientists Carlo Matteucci from University of Bologna and Emil Du Bois-Reymond in Berlin made a research and they constructed main components of an electro physiologically based physiology of the nervous system.

“Matteucci began in 1830 a series of experiments which he pursued until his death in 1865. Using a sensitive galvanometer of Leopoldo Nobili, he was able to prove that injured excitable biological tissues generated direct electrical currents, and that they could be summed up by adding elements in series, like in Alessandro Volta’s (1745-1827) electric pile. Thus, Mateucci was able to develop what he called a "rheoscopic frog", by using the cut nerve of a frog’s leg and its attached muscle as a kind of sensitive electricity detector. His work in bioelectricity influenced directly the research developed by Emil du Bois-Reymond (1818–1896), a student of the great German biologist Johannes Peter Müller (1801–1858) in Berlin, who tried the duplicate Matteucci’s experiments and ended up discovering the nerve's action potential. In 1844, for these studies, Matteucci was awarded with the Copley medal by the Royal Society.”(“Carlo Matteucci,” 2016)”

3.3. Electrical Activity of Brain

The scientist named Richard Caton (1982) shown in Figure 3.2 who was interested in electrophysiologic phenomena discovered the electrical activity of brain and lead up to discover Alpha waves by Hans Berger.



Figure 3.2 Richard Caton (Wikipedia, 2016b)

In July 1875 Caton reported to the British Medical Association in Edinburgh (Caton, 1875) that he had used a galvanometer to observe electrical impulses from the surfaces of living brains in animal subjects.(Smith, 1970) (Finger, 1994). After Caton died, Hans Berger cited Caton's work emphasizing his importance on the report of discovery of Alpha waves. He wrote in (Berger, 1929; Finger, 1994):

“Caton has already published experiments on the brains of dogs and apes in which bare unipolar electrodes were placed either on the cerebral cortex and the other on the surface of the skull. The currents were measured by a sensitive galvanometer. There were found distinct variations in current, which increased during sleep and with the onset of death strengthened, and after death became weaker and then completely disappeared. Translated by Cohen, 1959.”

3.4. Human EEG Studies

In 1924 the milestones of capturing human EEG were started. Hans Berger (1873–1941) in Figure 3.3 recorded the first human EEG in 1924 as shown in Figure 3.4. Expanding on work previously conducted on animals by Richard Caton and others, Berger also invented the electroencephalogram (giving the device its name), an invention described "as one of the most surprising, remarkable, and momentous developments in the history of clinical neurology".(Millet, 2002)

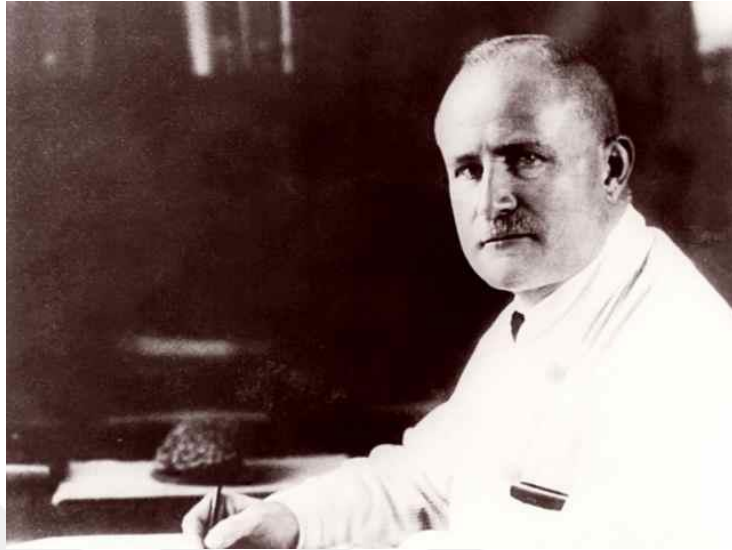


Figure 3.3 Hans Berger (Neurociencias, 2016)

At those days, there were several patients with skull bone defects due to World War I, in Germany and those patients were used for analysing brain waves. Using Edelmann string galvanometer, oscillations were observed and it was assumed it was coming from underlying brain. After one year, Berger realized that skull defects of brain did not provide advantage for getting brainwaves because of thickening of Dura, postoperative and adhesions. He found it is better to use scalp which interacts skull. With using double-coil galvanometer, he recorded alpha waves in a good way between 1926 and 1929. Although he was recorded alpha waves, he was in doubt for accuracy of recorded brainwaves.

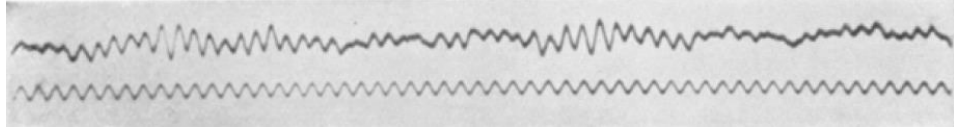


Figure 3.4 The first human EEG recording obtained by Hans Berger in 1924. The upper tracing is EEG, and the lower is a 10 Hz timing signal (cassiopaea.org, 2013).

Ever since from those years, depending on research by (Adelman and Smith, 1987) applications of EEG on humans and animals include the areas below:

- Monitor alertness, coma and brain death;
- Locate areas of damage following head injury, stroke, tumour, etc.;
- Test afferent pathways (by evoked potentials);
- Monitor cognitive engagement (alpha rhythm);
- Produce biofeedback situations, alpha, etc.;
- Control anaesthesia depth (“servo anaesthesia”);
- Investigate epilepsy and locate seizure origin;
- Test epilepsy drug effects;
- Assist in experimental cortical excision of epileptic focus;
- Monitor human and animal brain development;
- Test drugs for convulsive effects;
- Investigate sleep disorder and physiology.

3.5. **How Brainwaves can be measured**

As per definition of EEG, it is a medical imaging technique which reads electrical activity of a brain with conducting metal electrodes which touches the skin. In medical usage, several electrodes placed on the scalp with varying numbers as 64, 128 or more. The more electrodes put on scalp the more information could be gathered during recording and analysis. Conductive gels are widely used together with scalp in order to improve quality of conduction.

As our brains have electrical activity as means of current flows when the neurons are activated, EEG measures that current which is flowing throughout synaptic excitations of the dendrites. Differences of electrical potentials are caused by summed postsynaptic graded potentials from pyramidal cells that create electrical dipoles between soma (body of neuron) and apical dendrites (neural branches). Brain electrical current consists mostly of Na^+ , K^+ , Ca^{++} , and Cl^- ions that are pumped through channels in neuron membranes in the direction governed by membrane potential (Atwood and MacKay, 1989). Since electrical signals go through in the brain and faces with skull and other things, the signals can be weaker. In order to measure signals with EEG, electrodes on the scalp hugely amplified in order to be catch.

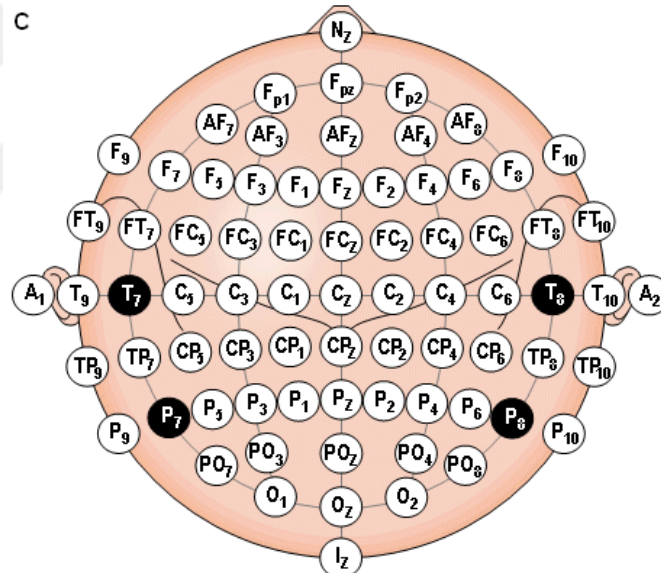


Figure 3.5 Example of placement of electrodes (Plonsey and Malmivuo, 1995)

Figure 3.5 shows several electrode positions on the head in which names has abbreviation's such as A = Ear lobe, C = central, Pg = nasopharyngeal, P = parietal, F = frontal, Fp = frontal polar, O = occipital. NeuroSky MindWave is placed only at Fp1 region of head that is the Frontal lobe of the brain.

EEG devices measure signals coming from brain part called cerebrum which consist of left and right cerebral hemispheres called cerebral cortex. Cerebrum

considered as a part of the central nervous system and largest part of human brain. The nervous system, it is the centre of movement initiation, conscious awareness of sensation, complex analysis, and expression of emotions and behaviour. Cerebral cortex is divided into 4 parts mainly called “lobes” and each of the lobes responsible for different tasks as described below (Schmidler, 2016) and Each of lobes can be seen in Figure 3.6 :

- The frontal lobe extends from the tip of the front of the hemisphere to the central sulcus. The back areas of the frontal lobe specialize in motor functions, including language and voluntary movement; the front areas are involved in learning, planning and other higher psychological processes like our personality and behaviour.
- The occipital lobe is at the back of the hemisphere and is involved in interpreting visual stimuli, that is, what we see.
- The parietal lobes are at the top and outside areas between the occipital lobe and the frontal lobe and is involved in sensory functions of the skin including pain, temperature, and touch. It also interprets size, shape, distance, vibrations and texture. Other areas are also important in cognitive and intellectual processes.
- The temporal lobe controls the hearing centers, language comprehension, storing and recalling memories and related areas including some speech centers. Other areas of the brain also affect memory. The front and bottom areas of the temporal lobe are involved in smell and functions of the limbic system.

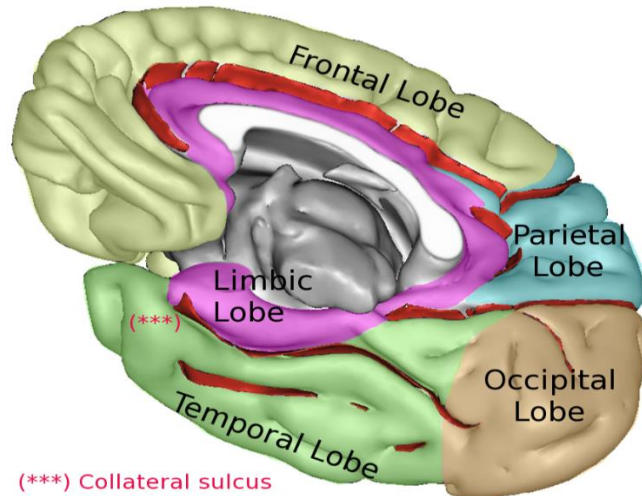


Figure 3.6 Lobes of cerebral cortex (Sebastian023, 2012)

3.6. Brainwave Classification

EEG devices capture brainwaves as raw data which includes all frequency bands. Each of frequency band represents specific characteristics of current condition of user that is unique state of some behaviour such as feeling tired, sleepy etc. To differentiate each of frequency bands most of the time Fast Fourier Transform(FFT) method is used; that is basically converts a signal from its original domain to a representation in the frequency domain(Wikipedia, 2016a). NeuroSky MindWave Mobile also uses FFT algorithm on the TGAM chip providing each frequency band with NeuroSky SDK. Each of frequency band described in Table 3.1 and constructed from (Hillman, 2014) :

Wave	Frequency	Meaning
Gamma waves	40 Hz to 100Hz	These are involved in 'higher processing' and are the waves we want to generate when learning new information or engaging in sports. Gamma waves are also associated with communication across different areas of the brain. Those with learning disabilities will often have lower levels of

		<p>gamma waves than average, whereas too much can lead to anxiety and stress. Gamma waves are also ideal for binding the senses making us highly alert and on edge. Meditation has been shown to help encourage gamma waves.</p>
Beta Waves	12Hz to 40Hz	<p>Beta waves are high frequency and low amplitude: meaning they are rapid and shallow. These types of waves are similar to gamma waves, being involved in learning, focusing and thinking logically, though they are somewhat less intensive when compared to gamma waves and occur at 12Hz-40Hz. Again they can cause stress in high amounts, whereas low amounts might be associated with daydreaming, ADHD or low motivation. You can increase beta waves by using stimulants such as energy drinks, caffeine or nootropics.</p> <p>Beta waves can also be broken down into three categories of their own: low-beta (12-15Hz), beta (15-22Hz) and high-beta (22-38Hz). These are also known as Beta1, Beta2 and Beta3 respectively. The lower ends of beta brainwaves are the most common and tend to dominate our waking lives. While high frequencies may increase focus and awareness, they reduce creativity and emotional awareness and they drain us of energy.</p>
Alpha Waves	8Hz to 12Hz.	<p>Alpha waves are the slow we experience in normal waking life when we're relaxed or absent minded. These are the brainwaves likely present when you unwind with a book or get ready to fall asleep, occurring at 8Hz to 12Hz. Alcohol, marijuana and antidepressants can all also contribute to alpha waves. Generally, more alpha waves mean fewer beta and gamma waves and vice versa.</p> <p>While we might normally associate alpha waves with relaxation, they can also be associated with states of productivity, awareness and even 'flow states' (which border alpha and theta waves).</p>
Theta Waves:	4Hz to 8Hz	<p>Theta waves occur between 4Hz and 8Hz and are associated with daydreaming and sleep. Theta waves are also present during trance, meditative or hypnotic states, as well as "hypnagogia" which is the period just before we fall asleep and certain restorative points during sleep. Theta brainwaves are thought to contribute to creative thoughts, as our brain explores loosely connected ideas and topics in an unstructured way.</p>
Delta Waves:	0.5 to 3Hz	<p>Occurring between 0.5 and 3Hz, delta brainwaves are the lowest frequency recorded in human beings. They also have high amplitude. Delta waves are associated with the deepest levels of (dreamless) sleep, as well as intensive meditation.</p>

They suspend our awareness of the external world and are thought to be connected to empathy.

Table 3.1 Types of brainwaves and their meaning (Hillman, 2014)



4. MindWave Mobile

MindWave Mobile is the low-cost portable EEG device produced by NeuroSky Company that will capture common brain waves as well as raw data and eSense values. It basically consists of headset, and ear-clip and a sensor arm. Ear-clip basically used for grounding EEG electrode which is above the eye, more basically of the FP1 position. MindWave Mobile headset parts are shown in Figure 4.1. MindWave Mobile uses single AAA battery.

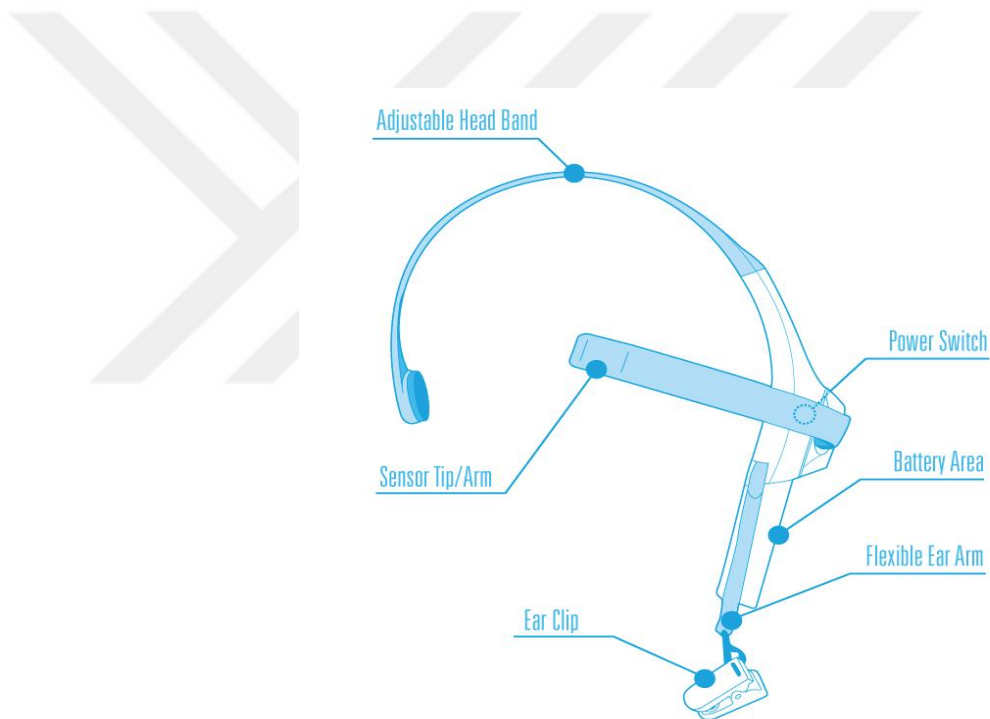


Figure 4.1 MindWave Mobile headset (Neurosky.com, 2016)

4.1. Technology Overview and details

MindWave Mobile uses ThinkGear™ technology, which measures the analogue electrical signals, commonly referred to as brainwaves, and processes them into digital signals. It includes the sensor that touches the forehead, the contact and reference points

located on the ear pad, and the on-board chip that processes all of the data and provides this data to software and applications in digital form. Both the raw brainwaves and the eSense Meters (Attention and Meditation) are calculated on the ThinkGear™ chip.

Some technical details about MindWave Mobile are listed below (Neurosky):

- Uses the TGAM1 module
- Automatic wireless pairing
- Single AAA Battery (Not included)
- 8-hours battery run time
- Bluetooth v2.1 Class 2 (10 meters range). Bluetooth dongle not included.
- Static Headset ID (headsets have a unique ID for pairing purposes)
- iOS and Android support

MindWave Mobile measures:

- Raw-Brainwaves
- Processing and output of EEG power spectrums (Alpha, Beta, etc.)
- Processing and output of NeuroSky proprietary eSense meter for Attention, Meditation.
- EEG/ECG signal quality analysis (can be used to detect poor contact and whether the device is off the head)

Bluetooth properties of MindWave Mobile listed below:

- BT Version: 2.1
- BT Output Power: Class 2
- BT Minimum Voltage: 1.0V
- BT Range: 10m range
- BT Power Consumption: 80mA (when connected and transmitting)
- Low Battery Indicator 1.1V
- UART(Serial): VCC, GNC, TX, RX

- UART Baudrate: 57,600 Baud

4.1.1. Bluetooth Pairing

MindWave Mobile uses Bluetooth connection in order to communicate with computer, tablet, phone etc. Any device that wants to communicate with MindWave Mobile headset, it should “paired” using Bluetooth protocol rather than connecting MindWave Mobile directly. According to MindWave Mobile : User Guide (Neurosky, 2015), Bluetooth pairing with MindWave Mobile should be following:

- Put the MindWave Mobile headset into "Pairing Mode" by holding the On/O switch past the "On" position for 3 seconds.
 - Release switch when the light starts flashing blue.
 - If you continue for more than 6 seconds, the MindWave Mobile headset will clear all previously remembered pairings.
- Refer to the Bluetooth pairing instructions that came with your iOS, Android, PC, or Mac device to search for and pair to the MindWave Mobile headset.
- If prompted, enter "0000" for the authentication key.
- MindWave Mobile headset can "pair/remember" up to 3 computers/tablets/phones at the same time.

If MindWave Mobile paired and connected properly, it should flash blue light shown in Figure 4.2.



Figure 4.2 MindWave Mobile successful connection

4.2. ThinkGear™ Chip Details

MindWave Mobile device comes up with ThinkGear™ chip that provides interface to capture user brainwaves. ThinkGear™ is basically the core module of MindWave Mobile device. As shown in Figure 4.1 , sensor tip touches user's face and ear clip attached to ear for grounding. ThinkGear™ chip inside MindWave Mobile has the ability to process all of the data that comes from sensor as well as capturing raw brainwaves. Additional data like Attention and Meditation values (which are called “eSense Meters”) are also calculated in ThinkGear™ chip which differs MindWave Mobile device from other portable EEG devices.

MindWave Mobile uses MindSet™ communication protocol in conjunction with ThinkGear™ which basically describes:

- How to connect to the Bluetooth serial data stream to receive a stream of bytes.

- How to parse the serial data stream of bytes to reconstruct the various types of brainwave data sent by the MindWave.
- How to interpret and use the various types of brainwave data that are sent from the ThinkGear™ (including Attention, Meditation, and signal quality data) in a BCI application

4.3. ThinkGear Data Values and Packet Structures

In order to get appropriate fields of brainwave data from the MindWave Mobile device, it must be known how to parse coming data and their meanings. To do so, packet structure and data values will be explained according to “ThinkGear Serial Stream Guide” published by (Neurosky, 2014) in this section.

4.3.1. POOR_SIGNAL Quality

POOR_SIGNAL tag is good information that tells user whether MindWave Mobile device is conducting properly or not with user’s skin. This value is unsigned one-byte integer which varies 0 to 255 and outputs every 1 second and it is enabled by default. The values are;

- If POOR_SIGNAL quality value is 0, then it is ready to use and it indicates there is no noise between MindWave Mobile and user skin.
- If POOR_SIGNAL is other than 0, this means some sort of noise contamination is detected. The higher values of this value signs that more noise is detected.
- If POOR_SIGNAL is equal to value 200, this means ThinkGear electrodes aren't contacting a person's skin.

According to “ThinkGear Serial Stream Guide” published by (Neurosky, 2014) poor signal may be caused by a number of different things. In order of severity, they are:

- Sensor, ground, or reference electrodes not being on a person's head (i.e. when nobody is wearing the ThinkGear).
- Poor contact of the sensor, ground, or reference electrodes to a person's skin (i.e. hair in the way, or headset which does not properly fit a person's head, or headset not properly placed on the head).
- Excessive motion of the wearer (i.e. moving head or body excessively, jostling the headset).
- Excessive environmental electrostatic noise (some environments have strong electric signals or static electricity buildup in the person wearing the sensor).
- Excessive non-EEG biometric noise (i.e. EMG, EKG/ECG, EOG etc.)

A certain amount of noise is unavoidable in normal usage of ThinkGear, and both NeuroSky's filtering technology and eSense™ algorithm have been designed to detect, correct, compensate for, account for, and tolerate many types of non-EEG noise. If POOR_SIGNAL is detected, some of eSense meters such as Attention and Meditation will not be updated, basically they will stay same until POOR_SIGNAL value reaches 0. When planning to develop more sensitive applications like medical or research, it is better to run algorithm when POOR_SIGNAL is equal to 0.

To sum up you can refer the Table 4.1.

POOR_SIGNAL VALUE	MEANING	IMPORTANCE
POOR_SIGNAL = 0	It is ready to use and it indicates there is no noise between MindWave Mobile and user skin	When considering some applications, a certain amount of noise is negligible. In some critical applications (medical, research),

POOR_SIGNAL > 0	Some sort of noise contamination is detected. The higher values of this value signs that more noise is detected.	calculations should start when the POOR_SIGNAL value equals to 0. Also eSense values Attention and Meditation will not be updated unless POOR_SIGNAL value equals to 0.
POOR_SIGNAL =200	ThinkGear electrodes aren't contacting a person's skin.	

Table 4.1 POOR_SIGNAL values and meanings

4.3.2. eSense™ Meters

One good advantage that comes with MindWave Mobile is that it has ThinkGear chip and calculates some values with raw EEG data. Calculating some values on the chip is a good property by means of not to charge software loads on developers other than API calls.

eSense meter values (i.e. Attention, Meditation) has a scale starting from 0 to 100. Based on “ThinkGear Serial Stream Guide” this value range is divided and considered as:

- If eSense value varies from 1 to 20 it is indicating “strongly lowered” levels of the eSense. These levels may indicate states of distraction, agitation, or abnormality, according to the opposite of each eSense.
- If eSense value varies from 20 to 40 it is indicating “reduced” levels of the eSense.
- If eSense value varies from 40 to 60 at any given moment, it is considered as considered “neutral”, and is similar in notion to “baselines” that are

established in conventional EEG measurement techniques (though the method for determining a ThinkGear baseline is proprietary and may differ from conventional EEG).

- If eSense value varies from 60 to 80 it is considered as “slightly elevated”, and may be interpreted as levels being possibly higher than normal (levels of Attention or Meditation that may be higher than normal for a given person).
- If eSense value varies from 80 to 100 it is considered as “elevated”, meaning they are strongly indicative of heightened levels of that eSense.
- If eSense value equals 0, this means ThinkGear chip is not able to calculate corresponding eSense value. This probably indicates that excessive amount of noise detected by ThinkGear and POOR_SIGNAL value updated according to that noise level.

To explain why eSense meter values vary within those range, you can refer excerpt from “ThinkGear Serial Stream Guide” published by (Neurosky, 2014) :

“The reason for the somewhat wide ranges for each interpretation is that some parts of the eSense algorithm are dynamically learning, and at times employ some “slow-adaptive” algorithms to adjust to natural fluctuations and trends of each user, accounting for and compensating for the fact that EEG in the human brain is subject to normal ranges of variance and fluctuation. This is part of the reason why ThinkGear sensors are able to operate on a wide range of individuals under an extremely wide range of personal and environmental conditions while still giving good accuracy and reliability. Developers are encouraged to further interpret and adapt these guideline ranges to be fine-tuned for their application (as one example, an application could disregard values below 60 and only react to values between 60-100, interpreting them as the onset of heightened attention levels).”

To sum up value ranges and meaning of eSense meter values, you can look at the Table 4.2

eSense METER VALUE	MEANING
---------------------------	----------------

eSense value = 0	ThinkGear chip is not able to calculate corresponding eSense value. This probably indicates that excessive amount of noise is detected by ThinkGear and POOR_SIGNAL value updated according to that noise level
1 < eSense value <= 20	Indicates “ strongly lowered ” levels of the eSense. These levels may indicate states of distraction, agitation, or abnormality, according to the opposite of each eSense.
20 < eSense value <= 40	Indicates “ reduced ” levels of the eSense.
40 < eSense value <= 60	It is considered as “ neutral ”, and is similar in notion to “baselines” that are established in conventional EEG measurement techniques (though the method for determining a ThinkGear baseline is proprietary and may differ from conventional EEG).
60 < eSense value <= 80	It is considered as “ slightly elevated ”, and may be interpreted as levels being possibly higher than normal (levels of Attention or Meditation that may be higher than normal for a given person).
80 < eSense value <= 100	It is considered “ elevated ”, meaning they are strongly indicative of heightened levels of that eSense

Table 4.2 eSense value ranges and meanings

4.3.3. ATTENTION eSense

eSense values vary from 0 to 100 as explained in eSense Meters section. Attention value is unsigned one-byte value that shows the level of user’s “focus” on some activity. It is a good property for developing application based on user’s attention. It is updated once a second. If the user is distracted, lacks of focus or has some anxiety then this value will be low. It is considered as concentration level of user with a specific value from 0 to 100.

NeuroSky MindWave Mobile comes with a program named “Brainwave Visualizer” and it basically shows EEG data’s in a nice graphics including eSense meters such that Attention and Meditation. When user tries to test Attention output, program suggests picking a point on screen to stare in order to get concentrated. Figure 4.3 shows attention values that represents concentration level of user.



Figure 4.3 eSense Attention Meter

4.3.4.MEDITATION eSense

As described in ESense meter section, Meditation value is unsigned one-byte and also varies from 0 to 100 and mainly calculates user’s mental “calmness” or “relaxation” level. Physical level of calmness will not affect directly to Meditation value as much as mental relaxation. If relaxing muscles of body helps your mind to relax as well it is easy to observe your Meditation value will be high.

Depending on observations, taking breathe and closing eyes will increase meditation level. Distractions, wandering thoughts, anxiety, agitation, and sensory stimuli may lower the Meditation meter levels. In Figure 4.4 eSense Meditation level is shown.



Figure 4.4 eSense Meditation level

4.3.5. RAW Wave value

ThinkGear chip has powerful functionality in terms of calculating eSense values and also with raw values. Raw value consists of 2 bytes and represents a single raw brainwave sample. This value is a signed 16-bit value and ranges from -32768 to 32767. The first byte of the value represents the high-order bits of the two's-complement value, while the second byte represents the low-order bits. In order to construct full raw wave value, there exist two ways:

1. First, simply shift the first byte left by 8 bits, and bitwise-or with the second byte like:
 - a. $\text{short raw} = (\text{Value}[0] \ll 8) | \text{Value}[1]$; where Value [0] is the high-order byte, and Value[1] is the low-order byte.
2. Second, instead of bitwise operations, user can evaluate full raw value with arithmetic operations:
 - a. $\text{raw} = \text{Value}[0] * 256 + \text{Value}[1]$;

- b. if (raw >= 32768) raw = raw - 65536; where raw is of any signed number type in the language that can represent all the numbers from -32768 to 32767.

By default, the output of raw wave value is enabled and outputted 512 times a second which approximately equals once every 2ms.

4.3.6.ASIC_EEG_POWER

This value outputs the current magnitude of 8 types of brainwaves. It is 3-byte unsigned integer number in little endian format, no unit and outputted once in a second.

The eight brainwaves in different power bands listed:

1. Delta (0.5 - 2.75Hz)
2. Theta (3.5 - 6.75Hz)
3. Low-alpha (7.5 - 9.25Hz)
4. High-alpha (10 - 11.75Hz)
5. Low-beta (13 - 16.75Hz)
6. High-beta (18 - 29.75Hz)
7. Low-gamma (31 - 39.75Hz)
8. Mid-gamma (41 - 49.75Hz).

4.3.7.Blink Strength

With the new API's, it is possible to calculate user's blink strength. It varies from 1 to 255 and shows the intensity of user's blink. It is reported whenever user blink's and it has no unit. According to "ThinkGear Serial Stream Guide" published by

(Neurosky, 2014) , this data value is currently only available via the TGCD and TGC APIs. It is not directly available as output from any current ThinkGear.

4.4. Consumer BCI's comparisons and accuracy

There is rapidly growing industry on portable EEG devices aiming multi-purpose usage together with balancing prices. Therefore, lots of portable EEG devices exist since early 2005. Table 4.3 shows EEG devices with their functionalities constructed by (alphatrainer.com, 2016).

Feature	Emotiv EPOC (Research)	MindWave Mobile	TrueSense Kit (OPI)	Muse	Emotiv INSIGHT
Raw EEG	No / Yes	Yes	Yes	Yes	Yes
Electrodes	14	1	2	4	5
Locations	AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4	FP1	--	AF3, AF4, TP9, TP10	AF3, AF4, T7, T8, Pz
Sensors type	Wet	Dry	Dry/gel	Dry	Dry
Sampling rates	128Hz	512Hz	512Hz	100-600Hz	128Hz
Protocol	USB Dongle	Bluetooth	ZigBee	Bluetooth	Bluetooth
Power	12 hours	6-8 hours (AAA bat.)	18 hours	10 hours	4 hours
Off Line recording	N/A	N/A	Memory chip	N/A	microSD card
Extra Sensors	Gyroscope	None	Accelerometer, temperature	Accelerometer	Accelerometer,

					magnetometer
SDK	OSX, Windows	Android, IOS, Windows, OSX	Linux, Windows, OSX	Android, IOS, Linux, Windows, OSX	Android, IOS, Linux, Windows, OSX
Price	300/750 USD	100 EURO	40 EURO	269 EURO	300 USD

Table 4.3 Comparison list of portable EEG devices (alphatrainer.com, 2016)

To compare MindWave Mobile with others, it comes with Bluetooth feature and provides lots of SDK to widen the usage area. It has one dry sensor placed on Fp1 and interprets brainwaves accurately. In order to make more complicated applications as means of controlling robots, of course one sensor is not enough in that case usage of MindWave Mobile can be meaningless.

There exist lots of applications with MindWave Mobile which has great outcomes as means of monitoring stress levels, some neurofeedback applications used in ADHD patients and simple controlling mechanisms with attention levels. In one study, attention levels measured by MindWave Mobile when users play online game and made a comparison for accuracy of attention value provided in MindWave Mobile concluded that SDK values are accurate.(Rebolledo-Mendez *et al.*, 2009). Another study also measures attention values of school children in an e-learning settings in the BRAVO project with defined threshold value of attention level.(Marchesi *et al.*, 2013)

When comparing price and functionality balance, MindWave Mobile seems reasonable build some applications based on neurofeedback, controlling devices with concentration level, but for the complex issues one sensor is not enough to get related information about brain.

One of the research published by NeuroSky company itself put forward the claim that measurements of MindWave Mobile device is close to medical EEG device named Biopac which is a wet system that proves the accuracy of MindWave Mobile. They compared raw EEG signals with Biopac system besides they performed FFT to make

another comparison. They concluded that results close to each other which shows NeuroSky provides accurate result when comparing to medical EEG devices as showed in Figure 4.5.

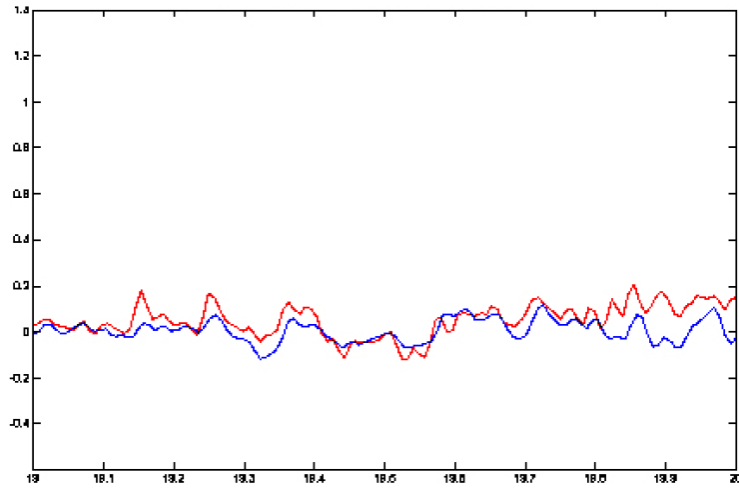


Figure 4.5 Comparison of raw EEG power bands Biopac (red) with NeuroSky(blue) (I. NeuroSky, 2009)

5. System design and implementation

5.1. Aim

The aim of this thesis is to give an applicable solution for controlling devices which can be hardware based system and also give a solution for controlling software components with brainwaves. Blinking state of a user is used in order to develop both solutions, that has own algorithm for extracting blink values from EEG signals.

Additional hardware added on top of MindWave Mobile device in order for controlling wheelchair prototype (considered as hardware based system). This hardware based system constructed with Arduino Nano, MPU-6050 gyroscope sensor and HC-05 Bluetooth module. Whenever user moves head to predefined directions, appropriate command will send through Bluetooth module to application. The idea behind the system is that when the user moves head and if the attention level is appropriate then move command will send to prototype car. The study about controlling hardware based system namely wheelchair, can be applied as controlling car, is an attempt to address the issue of giving ability to paralyzed people to drive their wheelchair. That is a solution for paralyzed people in which can't use their hand in order to control wheelchair or anyone who can't use hand. It is a simple and cheaper solution for even paralyzed people who can use their hand can't give comfortability to use wheelchair.

The arguments against usage of NeuroSky MindWave device for controlling devices shows that due to the one sensor it is not possible to collect various information about user. Depending on research and literature reviews, head movements give flexible solution for controlling car with combining brainwaves rather than training user data which is not enough to build reliable solution in real time.

Another perspective of using EEG device is to show ability about controlling software components with brainwaves of user. MindWave device is making use of simple keyboard application with depending on basically users blink values. Able to

use keyboard with brainwaves provides a simple solution for disabled person. Also, keyboard application inspires any other application that needs to be controlled with brain waves.

5.2. Wheelchair Prototype with MindWave

One of Android application developed using MindWave is Wheelchair prototype which can be applied for controlling car prototype. The aim for developing such application is that provide a simple solution for controlling hardware based wheelchair prototype in most cheaper way with one sensor EEG device.

5.2.1. System design

When designing car prototype, the car chassis with 4 DC motor together with Arduino Uno is used. To build whole system, the hardware' for car listed below:

- Car chassis with 4 DC motor (Shown in Figure 5.1)
- Arduino Uno (To control wheelchair car)
- HC-05 Bluetooth Module (To get data from Android application)
- Adafruit Motor Shield V1.0 (To control motors)
- Battery Holder for 12 V (For motor powers)
- 9V battery (For Arduino Power)

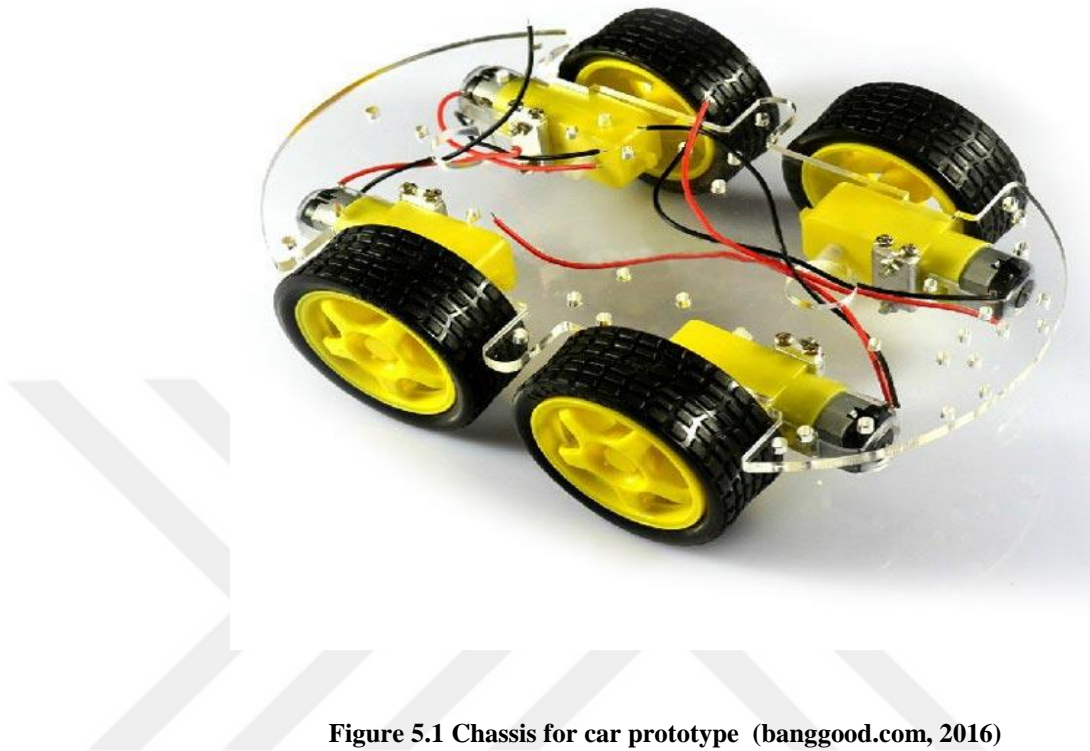


Figure 5.1 Chassis for car prototype (banggood.com, 2016)

Additional hardware' for integrating brain movements with MindWave listed below:

- HC -05 Bluetooth Module (For sending head movements to Android Application)
- MPU-6050 Accelerometer and Gyro Module (For head movements)
- Arduino Nano (To process messages coming from Mpu-6050 and to send processed messages to Android Application)
- 9V Batter Holder (Power for Arduino Nano)

To build car prototype, first step started with integrating motor shield with Arduino Uno. Adafruit Motor shield comes with ability that fully integration with Arduino Uno when placing Motor shield on the top of the Arduino Uno. As seen in Figure 5.2.

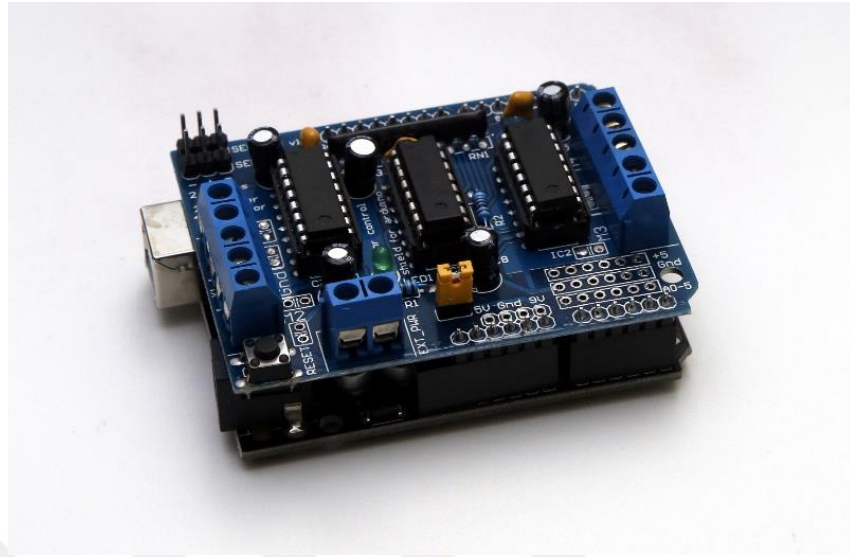


Figure 5.2 Arduino Uno and Adafruit motor shield stacked together (Lee, 2014)

After that, motor wires coming from chassis attached to the dc motor connectors on the motor shield. For simplicity, each motor named starting 1 to 4 and stickers glued on the chassis. Afterwards, HC-05 module has been attached to motor shield as following pins:

- **VCC** pin of HC-05 connected to Motor shield 5v pin.
- **GND** pin of HC-05 connect to Motor shield GND pin.
- **TXD** pin of HC-05 connected to Motor shield 13. pin
- **RXD** pin of HC-05 connected to Motor shield 2. pin.



Figure 5.3 HC-05 Bluetooth pins

As seen in Figure 5.3 and Figure 5.4, pin connections has been done according the specifications above. There needed additional soldiering for pin 2 on motor shield since by default it is not coming with female pin.

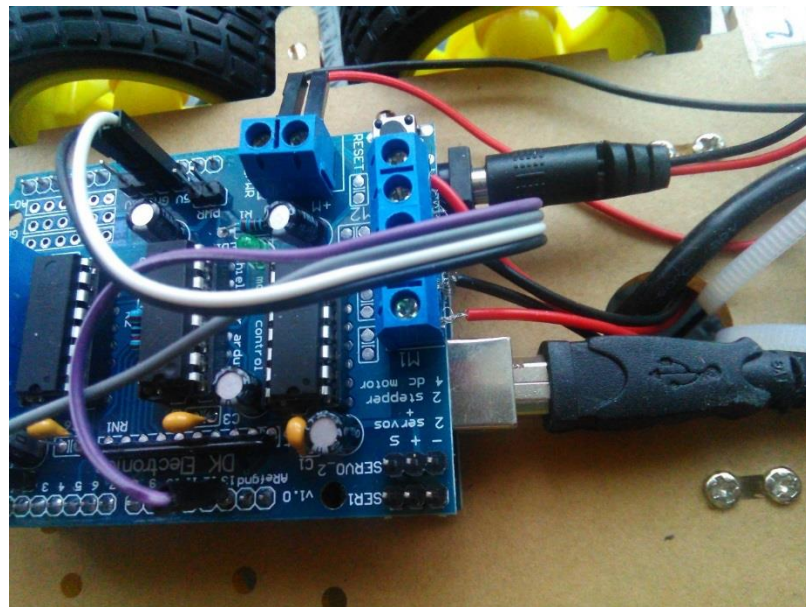


Figure 5.4 HC-05 Bluetooth pins connected on motor shield pins

After connection of Hc-05 and motors, heart of the car ready to fit on the chassis board and needs to be placed in good way. Figure 5.5 shows the car chassis after connections has been done.

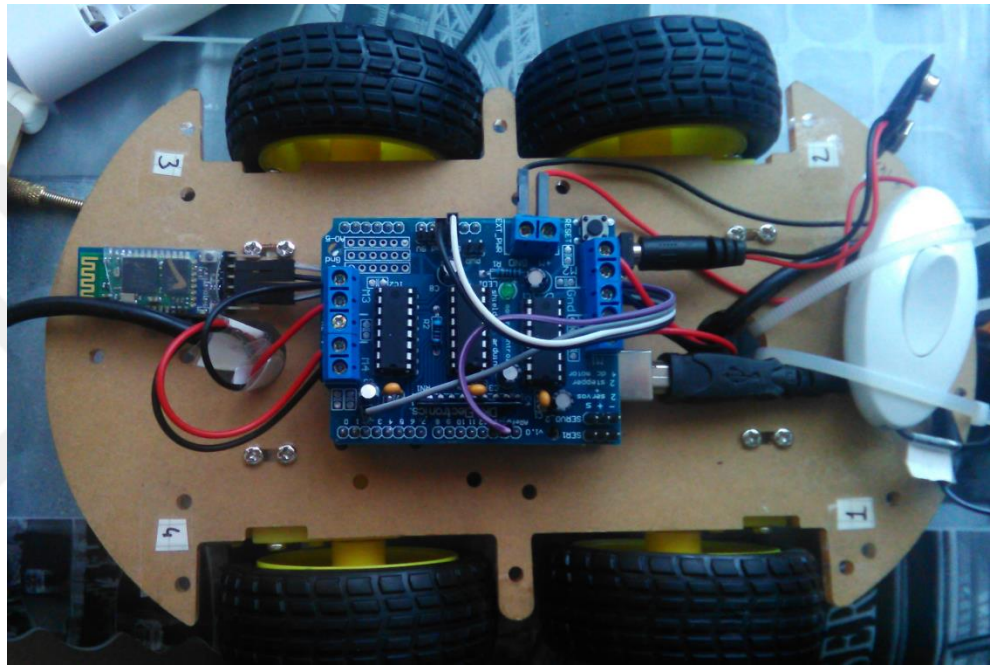


Figure 5.5 Car chassis after putting hardware

There exist extra power pin named EXT_PIN on Motor shield in order to power up four dc motor. EXT_PIN connected to 12V shown in Figure 5.6 which holds 8 rechargeable NiMH 1.2 V AA batteries with 2600 mAh.



Figure 5.6 Battery pack for powering motors on EXT_PIN pins

Figure 5.7, Figure 5.8, Figure 5.9 and Figure 5.10 shows different perspectives for completed car chassis with all connections has been made. After connecting all wires together, simple word box placed to protect hardware from outside. To open Arduino Uno switch has been placed and one switch placed for 12 V battery pack to power motor as well. Bigger switch used to power motor shield with 12

V and small switch used to power Arduino Uno with 9v. The front of the car is the side where HC-05 is placed (side that 4. And 3. Motors placed).



Figure 5.7 Shows wheelchair at the upper side



Figure 5.8 Shows car at the right side

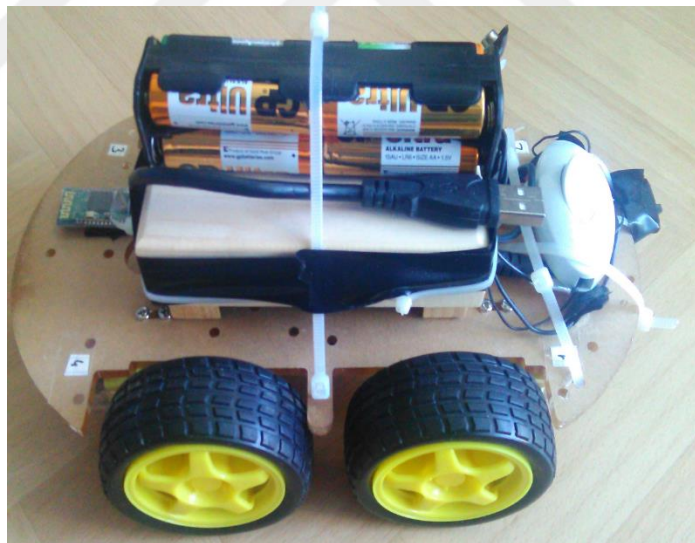


Figure 5.9 Shows car at the left side

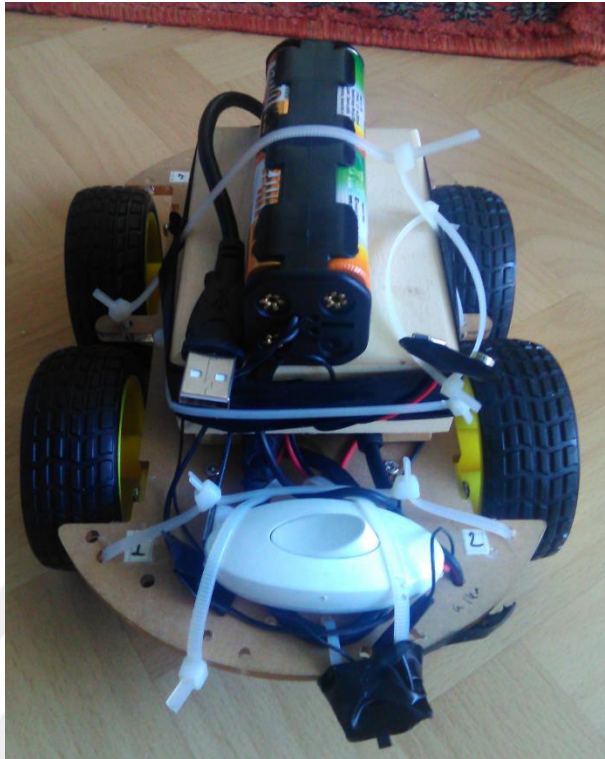


Figure 5.10 Shows the car at the back side

Circuit plan of car prototype is shown in the Figure 5.11.

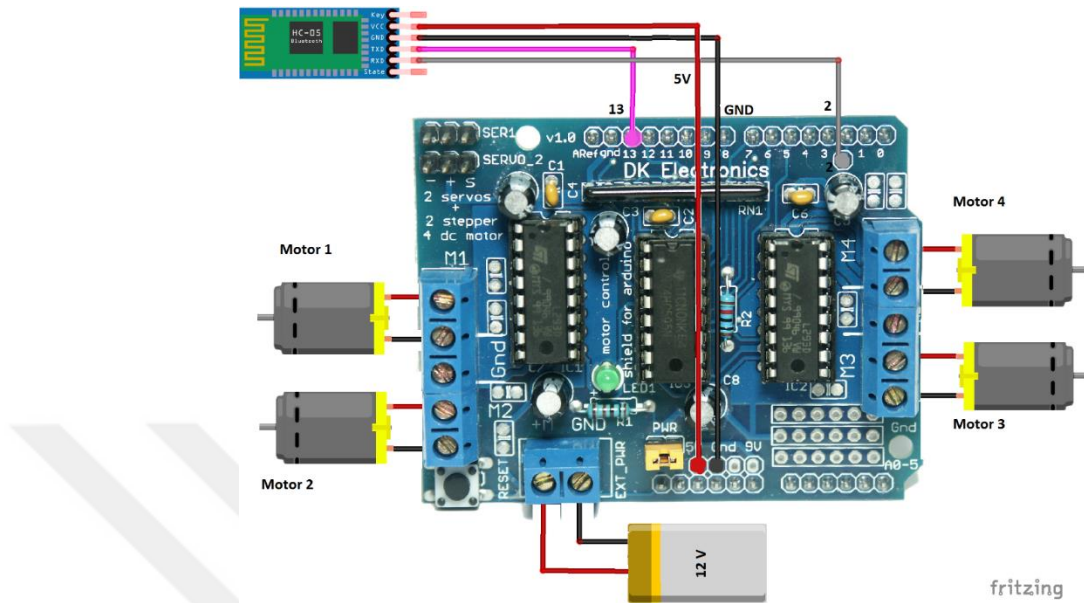


Figure 5.11 Circuit plan of wheelchair prototype

Another part for implementing wheelchair is adding components for head movements on top of MindWave device. In order to build such system MPU-6050 (see APPENDIX 1) device which is powerful and accurate sensor used together with Arduino Nano and HC-05.

All the components placed on mini bread board and connections made as follows:

- **VCC** pin of HC-05 connected with Arduino Nano VIN pin.
- **GND** pin of HC-05 connected with Arduino Nano GND pin.
- **TXD** pin of HC-05 connected with Arduino Nano D3 pin.
- **RXD** pin of HC-05 connected with Arduino Nano D4 pin.
- **VCC** pin of MPU-6050 connected with Arduino Nano VIN pin.
- **GND** pin of MPU-6050 connected with Arduino Nano GND pin.
- **SCL** pin of MPU-6050 connected with Arduino Nano A5 pin.
- **SDA** pin of MPU-6050 connected with Arduino Nano A4 pin.
- **INT** pin of MPU-6050 connected with Arduino Nano D2 pin.

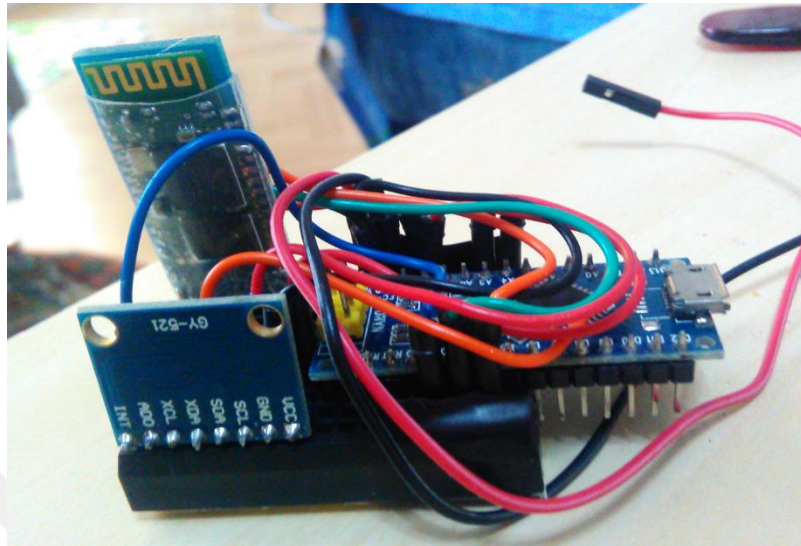


Figure 5.12 Completed circuit for detecting head movements from right side

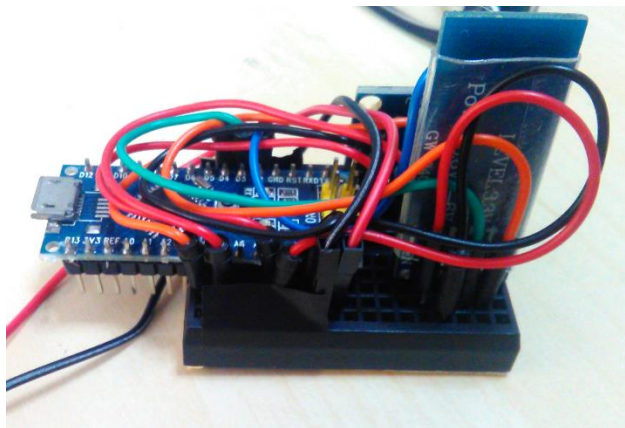


Figure 5.13 Completed circuit for detecting head movements from left side

Figure 5.12Figure 5.13 and Figure 5.13 shows the completed circuit for head movements. The whole tiny circuit placed on top of the MindWave device as shown in Figure 5.14 and Figure 5.15 from different sights.



Figure 5.14 MindWave Mobile with MPU-6050 sensor from left side view



Figure 5.15 MindWave Mobile with MPU-6050 sensor from back side view

For the simplicity, circuit plan of head movement with MPU-6050 sensor shown in Figure 5.16 which drawn with Fritzing tool.

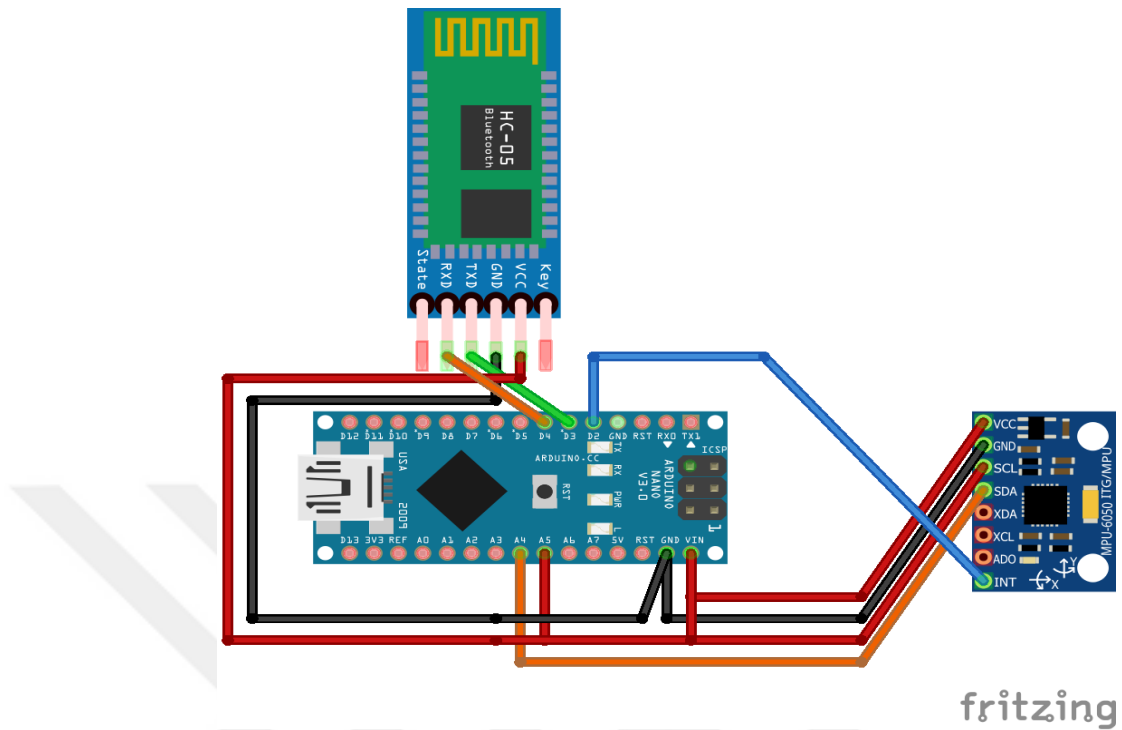


Figure 5.16 Circuit plan of head movement prototype

5.2.2. Implementation

In order to implement car prototype with MindWave Mobile (edited version with head movement) Android application developed to make easier to carry rather computer. Corresponding Android application works with minSdkVersion and compileSdkVersion 23 and uses ThinkGear Android API named “ThinkGear.jar” to build applications.

The main application consists of 3 packages in order to run business logic and 2 helper classes which corresponds to images/textbox operations. Structure of wheelchair android application shown in below:

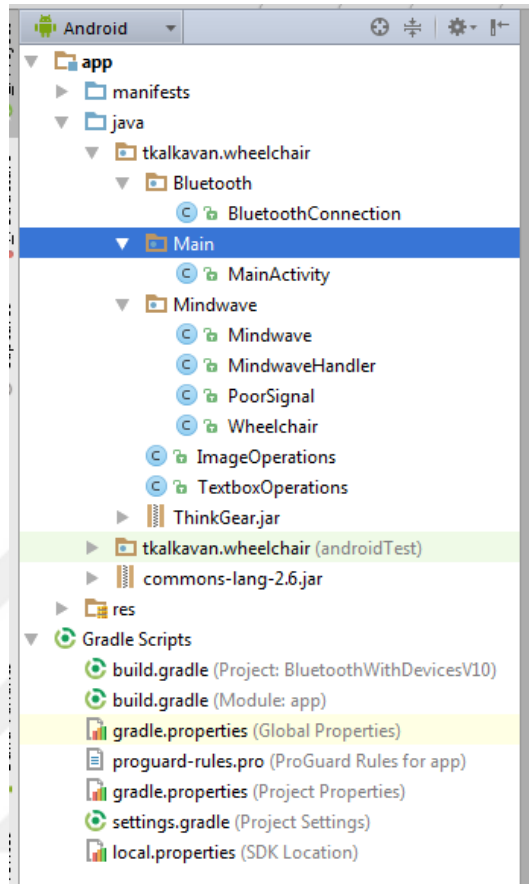


Figure 5.17 Wheelchair android application project structure

Each of package consist of several classes when the all applications business logic works. Package names gives clue about what can be the classes; to look more detailed way each class can be described as follows:

- **BluetoothConnection.java:** It can be considered most important class in this project for the reason that it handles all Bluetooth connections constructing simple piconet (which is an ad-hoc network) which supports up to 7 devices communicate with each other. The mechanism behind communication multiple devices with multiple Bluetooth connection is similar with creating network sockets in classical network application. Since Android API's supports Bluetooth piconet connections, it easily can be used for communication between multiple devices. Mainly, the class uses BluetoothServerSocket and BluetoothConnection objects in order to build Bluetooth piconet together with helper classes.

Developed code built on top of the code of Piconet class captured from (jonnysgomes, 2013) and some of codes from is directly used from (developer.android.com, 2016) .

- **Mindwave.java:** Includes appropriate fields for holding eSense values (attention, meditation etc.) and calculates blink values as described in ThinkGear Data Values and Packet Structures section.
- **MindwaveHandler.java:** It is considered as most important class since all application flow directed to this classes. This classes handles connections coming from BluetoothConnection classes and makes decision about wheelchair movement. After initialization of main application, business logic started this class including initializing wheelchair object, MindWave object etc.
- **Wheelchair.java:** This class contains basic information about wheelchair like current state, current direction, speed. Wheelchair object is derived from this class in order to be used in MindwaveHandler class.
- **PoorSignal.java:** In the current version of wheelchair application, this class is not directly used because of time issues. It first designed for calculating average poor signal value for given seconds and if it is equal to 0, then all application can have started safely. The idea behind such algorithm is that, when user not properly fitted MindWave device on the head, it sometimes gives results changing 0 to 26 suddenly in seconds which is not optimal for controlling wheelchair. Due to the time issues, current version is not implementing this class, rather main application looks directly poor signal value to make application work in that time.
- **ImageOperations.java:** Handles image operations to show in the main screen of application.
- **TextboxOperations.java:** Handles textbox operations such as set text, append text to specific text boxes.
- **MainActivity.java:** Application starts with this class. It creates necessary UI components. Also, creation and initialization of MindwaveHandler object and BluetoothConnection object occurs this class.

As application flow started in MainActivity class, it first created MindwaveHandler object named “mindwaveDevice” and initialized this object with method initDevice as seen in Figure 5.19 . initDevice method responsible for initializing MindwaveDevice, Wheelchair objects and also adding corresponding observers to the both BluetoothConnection and Wheelchair objects as described later. MindwaveHandler class has objects from another classes can be seen in Figure 5.18

```
public class MindwaveHandler extends Thread{

    Context context;
    Mindwave mindwaveDevice;

    TextboxOperations textboxOperations=new TextboxOperations();
    ImageOperations imageOperations=new ImageOperations();

    private Wheelchair wheelchairDevice;
    private TGDevice device;
    private BluetoothConnection bluetoothConnection;
    //Provides calculation for poor signal,as needed
    private PoorSignal poorSignal;
```

Figure 5.18 Variables in MindwaveHandler class

Also, at the same time it creates new BluetoothConnection object named “bluetoothConnection” and sets mindwaveDevice object with setBluetoothConnection method.

```
public void initDevice()
{
    //this.setBluetoothConnection(new BluetoothConnection(this.context));

    this.setDevice(new TGDevice(BluetoothAdapter.getDefaultAdapter(), mindwaveHandler));
    this.setWheelchairDevice(new Wheelchair(this.context));
    this.initPoorSignal(5000);

    getBluetoothConnection().addObserver(new BluetoothObserver());
    getWheelchairDevice().addObserver(new WheelchairObserver());
}
```

Figure 5.19 initDevice method in MindwaveHandler class

Afterwards, MindwaveHandler class is ready to run business logic in order to control wheelchair. Once the wheelchair application is started and no connection made with each device, the screen can be seen in Figure 5.20 .

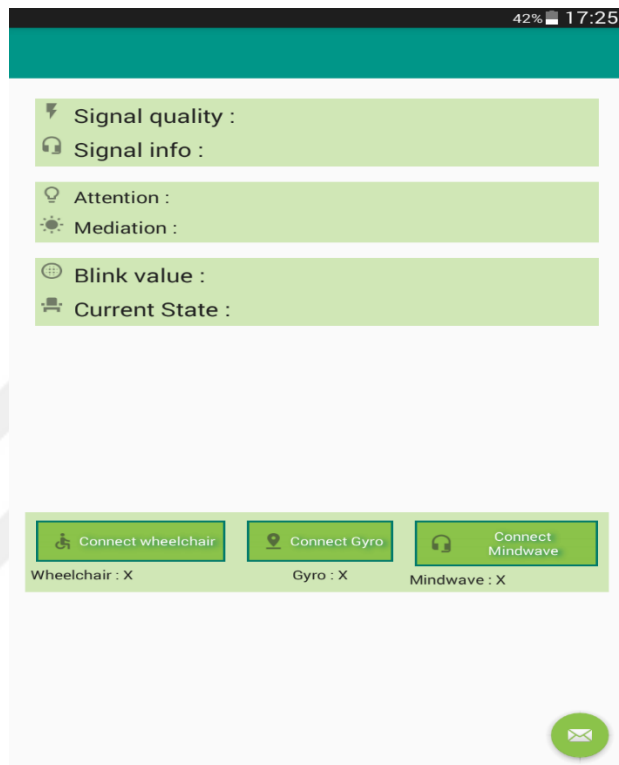


Figure 5.20 Wheelchair application started

When user clicked the connect button for each device and if the connections are successful, the screen become as shown in Figure 5.21.

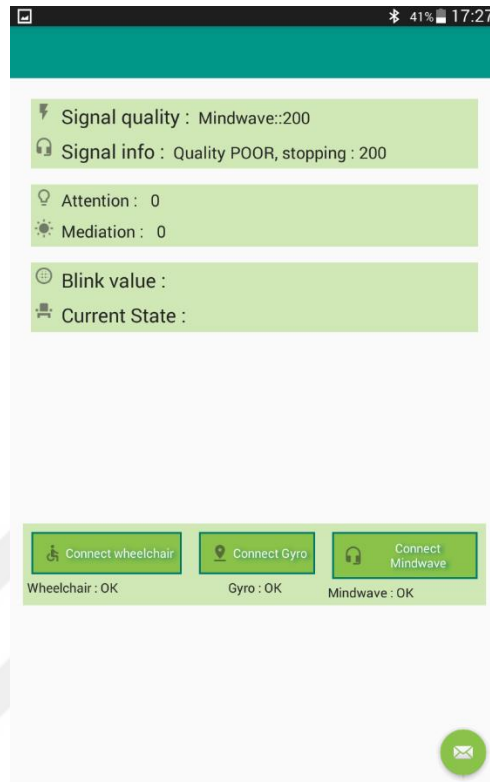


Figure 5.21 Wheelchair application after connections has been made

When all connections have been made, application looks poor signal value of the MindWave device, that gives information about whether conducted property or not. In order to proper work of application, poor signal value need to be equal 0. If it is equal to 0, that means wheelchair is ready to move; signal info says “Quality is poor” otherwise can be seen in Figure 5.22.

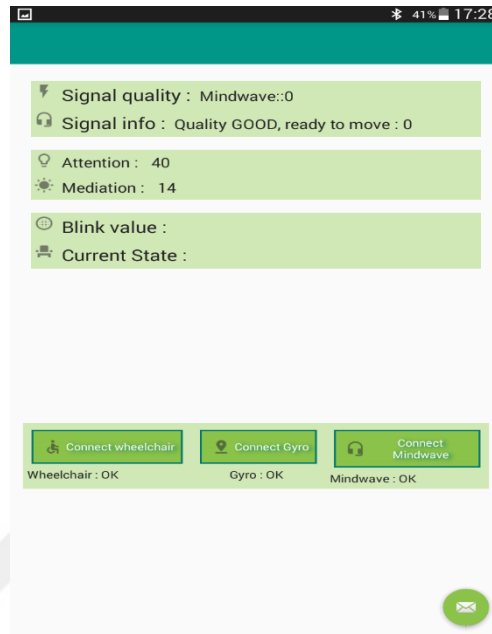


Figure 5.22 Wheelchair device ready to move

The idea behind wheelchair application is that when the user reached specific attention level interval, it means that wheelchair is ready to move any of direction. In that time, if user moves head to any of direction wheelchair will move to that direction in specific time slot. That will give the user flexibility to not stay attentive in a long time period, instead making one move in given time slot. If the user stay concentrated instead of one move user gain a control in continuous way.

In order to do so, Observer/Observable pattern used both in BluetoothConnection and WheelChair classes. In the initMethod in Figure 5.19 , shows the adding observers to classes.

When the user moves the head in the direction defined front/right/left/back, MindWave Device with gyroscope send Bluetooth message with Bluetooth connection and BluetoothConnection class holds this message in a string named “gyroMessage”. This variable used as observable and any change of this string will notify corresponding observers, in this case BluetoothObserver class placed in the MindwaveHandler class

as inner class. In the BluetoothConnection class shows how “gyroMessage” listened by observers by setGyroMessage function.

```
public void setGyroMessage(String gyroMessage) {  
    synchronized (this) {  
        this.gyroMessage = gyroMessage;  
    }  
    setChanged();  
    notifyObservers();  
}
```

Figure 5.23 Observable variable gyroMessage in setGyroMessage

Whenever gyroMessage has been set; that is whenever user moves to head in directions, it is observed by BluetoothObserver class in which then gets current direction and determines the following operations based on variable named readyToMove which is set “true” by WheelchairObserver class when the currentState equals to “moving” or “false” when the currentState equals to “stopped”:

If readyToMove equals “true”, wheelchair object’s current direction by

- setCurrentDirection(direction) method and calls “moveCar” method to send move command to wheelchair car by getting wheelchair device objects attributes with methods getCurrentDirection, getTime and getSpeed.
- If readyToMove equals “false”, stopCar method is invoked, that is send stop command to wheelchair by only sending “S” parameter.

That algorithm implies even if user moves the head randomly, the wheelchair is not moving any of direction until user get concentrated.

currentState variable of wheelchair device is determined in Handler method in MindwaveHandler class, that is continuously listening MindWave device and get values from that. Since movement of wheelchair depends on attention values, Handler method always get attention values firstly by checking if the signal is great or not and then decides the speed of the wheelchair as described in Table 5.1:

If attention ≥ 35 and attention < 55	Wheelchair objects speed is set to “135” and current state is set to “moving”
If attention ≥ 55 and attention < 75	Wheelchair objects speed is set to “145” and current state is set to “moving”
If attention ≥ 75 and attention < 100	Wheelchair objects speed is set to “145” and current state is set to “moving”

Table 5.1 Speed of wheelchair depending on attention values of user

Wheelchair objects speed and currentState is set depending on values in Table 5.1 and time for all movements is fixed, that is 1 seconds for all.

The sequence diagram for wheelchair application can be seen in Figure 5.24

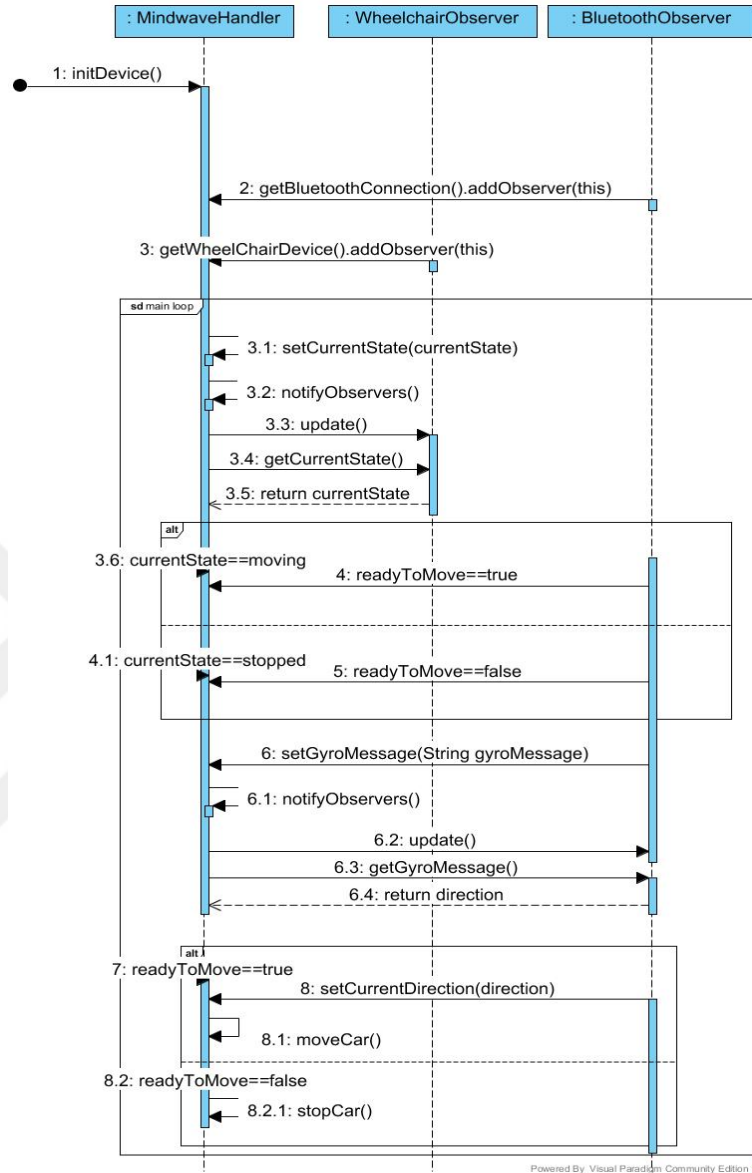


Figure 5.24 Sequence diagram of movement of wheelchair

As an example of implementation, Figure 5.25 shows wheelchair is moving left and right direction with various speed depending on attention values.



Figure 5.25 Wheelchair moving left/right directions

Another example of implementation, Figure 5.26 shows wheelchair is moving forward and backward direction with various speed depending on attention values.

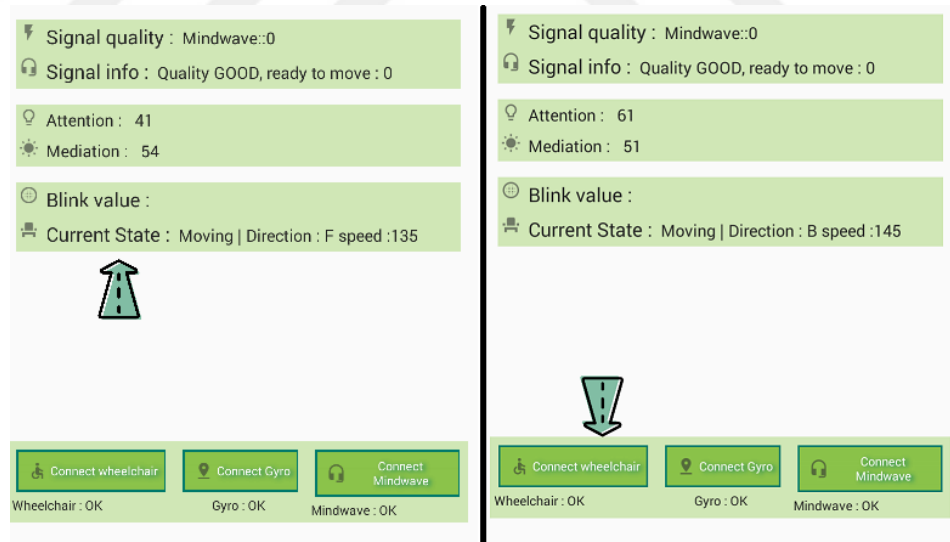


Figure 5.26 Wheelchair moving forward/backward directions

5.3. Keyboard Application with MindWave

Another implementation of MindWave device is making use of simple keyboard application with basically users blink values. Able to use keyboard with brainwaves provides a simple solution for disabled person. Also, keyboard application inspires any other application that needs to be controlled with brain waves.

5.3.1. System design and implementation

Application structure of keyboard application can be seen in Figure 5.27.

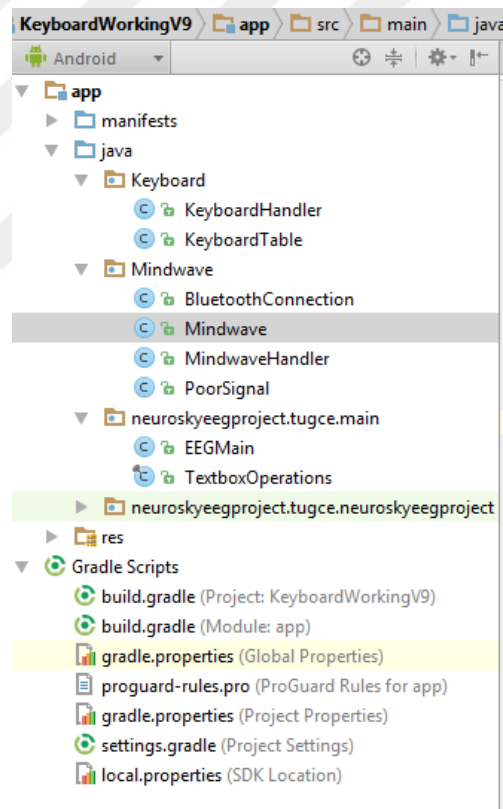


Figure 5.27 Project structure of keyboard application

For keyboard application, there exist 3 package with classes and each of the class described below:

- **KeyboardHandler.java** : Responsible for keyboard related action; mainly navigation through rows and columns. All the business logic that is associated with keyboard issues is invoked in this class. Starting and stopping of navigation is basically runs with Thread object.
- **KeyboardTable.java** : This class responsible for creating dynamic keyboard in which all properties defined in EEGMain class. It gets values such as number of column, number of row and letters used in table and builds dynamically created table in the main application UI. In order to do that, this class contains BuildTable method with some additional properties like background color, text size etc.

Other classes same as used in Wheelchair application and described in 5.2.2 Implementation section in 5.2 Wheelchair Prototype with MindWave chapter.

Main workflow:

Application started when MindWave connection is ready that is connection with device is successful. In the EEGMain class new objects derived from KeyboardHandler, KeyboardTable and MindwaveHandler classes created with corresponding properties such as number of columns etc. After creation of this objects and initializations, object called mindwaveDevice derived from MindwaveHandler sets its keyboardHandler object with initKeyboardHandler method. After setting keyboardHandler, all application workflow runs in MindwaveHandler class. Initially, when an application runs, user waited for connecting MindWave Mobile via Bluetooth to start row navigation of keyboard application. In order to be ready for row navigation, signal quality of MindWave Mobile has to be equal 0 (which states device is perfectly fit), “Quality GOOD, ready to write” message has been shown in “Signal Quality” textbox and row navigation started as shown in Figure 5.28.



Figure 5.28 Keyboard application started with row navigation

After row navigation started, selection of a row made by users single “BLINK”. When the user performs single blink in a strong way, row has been selected and column navigation started.

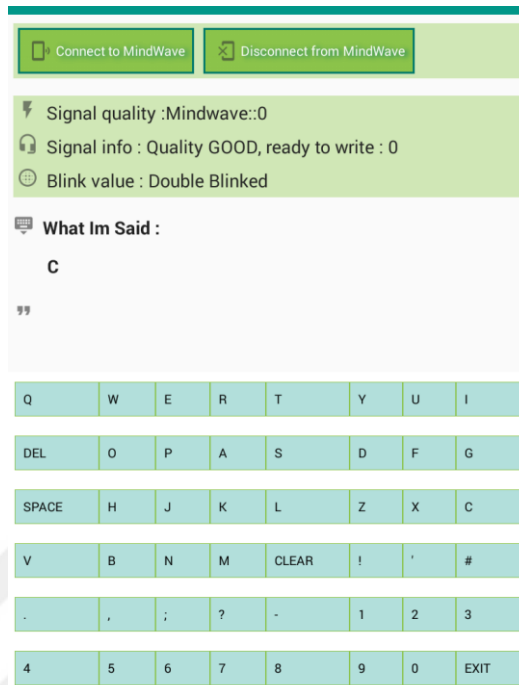


Figure 5.29 Selection of letter with double blink

As column navigation started, letter selection made if the user performs “Double Blink”. It continues highlighting letters in selected row and waits for to perform “Double Blink” of user. Figure 5.29 shows user double blinked on the letter “C” and in the “What I’m said” section shows the selected letter. After selection of letter, navigation of row continues from scratch and wait for another single blink performed by user to select another row. Figure 5.30 shows application flow as simple sequence diagram for keyboard application after connection done with MindWave Mobile device.

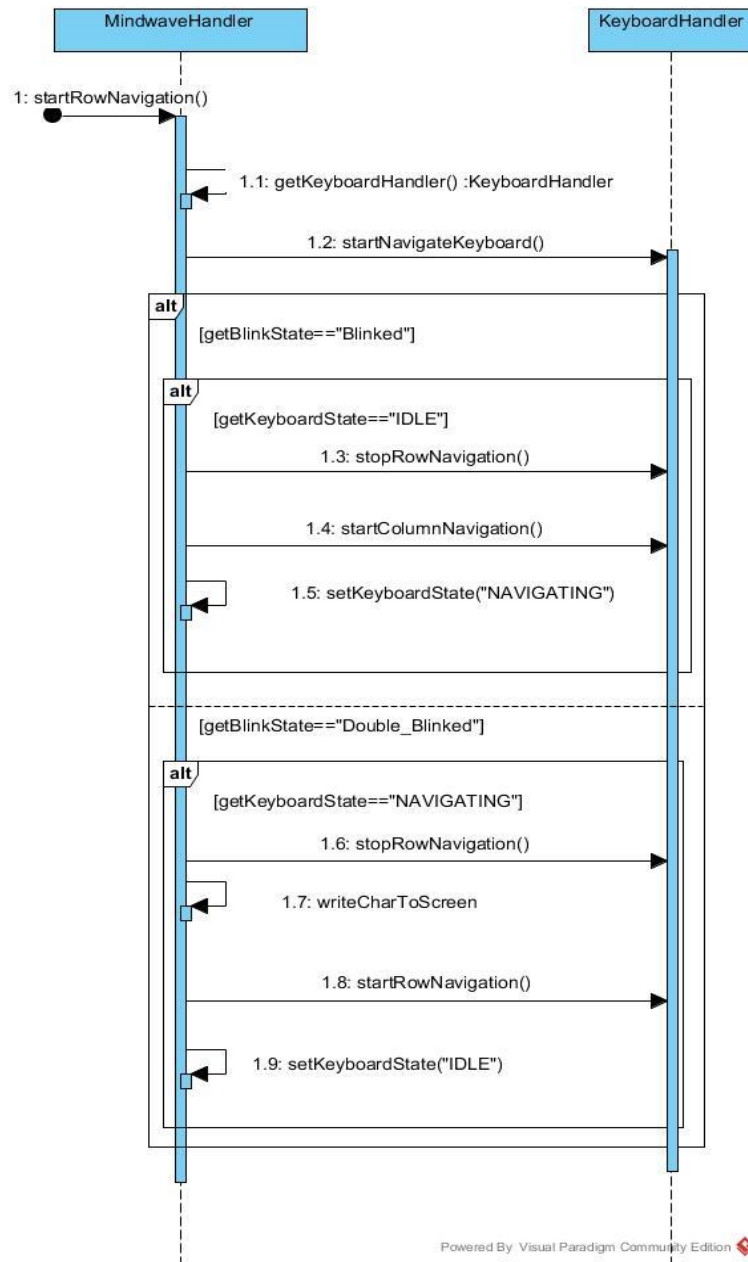


Figure 5.30 Sequence diagram for keyboard application

5.4. Extraction of blink values

As discussed chapter MindWave Mobile , NeuroSky SDK provides to get blink strength value between 0-255. Blink strength value is not direct output of the hardware of MindWave rather it is calculated on TGAM chip and transferred through API. However, depending on trials made through this thesis and work of (Tonkin, 2011) ,a

new algorithm developed that improves detection of blink/double blink values in a way extraction that directly from raw EEG data comes from MindWave.

5.4.1. Eye blink detection

Electroencephalogram is used for recording the brain activity using electrodes and most commonly in non-invasive way. In the brain, voltage fluctuations occur between neurons due to the ionic current flows and in the medical context of EEG these voltage fluctuations represented and named as electrical signals of brain. Even though the purpose of EEG to record cerebral activity of brain¹, it also records non-cerebral electrical activities. The non-cerebral electrical activities that recorded by EEG device is called artifacts, besides EEG data always polluted by artifacts. Most common biological artifacts contain:

- Cardiac artifacts(ECG)
- Muscle artifacts (EMG)
- Ocular artifacts
- Eye-included artifacts (eye blinks, eye movements and extra-ocular muscle activity)

Eye blink artifacts are generated by fast movement of the eyelid along the cornea, as it happens during an eye blink. By friction between lid and cornea, this movement results in charge separation, with a dominantly dipolar charge distribution, and the dipole moment pointing in up-down-direction. On the other hand, EOG artifacts are produced by eye movements, and generated by a fricative mechanism similar to the one underlying blink artifacts but involving retina and cornea rather than cornea alone. ("User Tutorial:EEG Measurement Setup," 2012)

¹ Cerebral activity, which is electrical activity in cerebral cortex that is responsible for memory, attention, perception, awareness, thought, language, and consciousness.

As a result of the quite large potential difference between the cornea and retina, eye-induced artifacts occurs and it is easy to observe them by looking at the EEG data. Since eye-induced artifacts include both eye blinks and eye movements, time slot between brainwaves can be used to differentiate what type of eye blink artifact is occurred. For instance, blinking eyes can occur several times per minute on the other hand eye movements is occurs very high frequency such that several times per second.

Eye blink artifacts mainly recorded as positive peak and lasting generally few of seconds and visible in the frontal probes of EEG devices. Also, eye blink artifacts wave form has quite large amplitude as easily seen in Figure 5.31

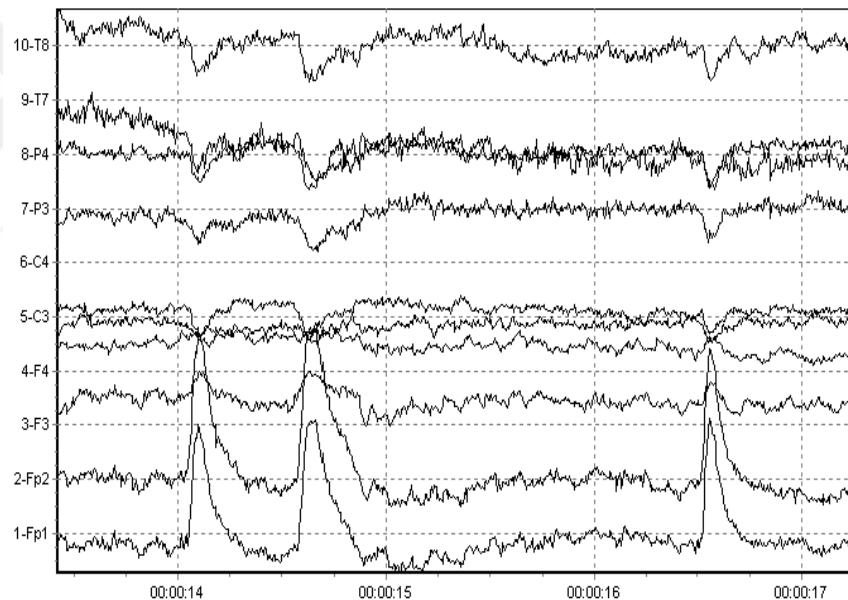


Figure 5.31 Eye blink artifact ("User Tutorial:EEG Measurement Setup," 2012)

In the eye movement artifacts, frequency and time domain looks similar but it is different as means of frequency domain which is lower and amplitude is likely to be larger than blinking. EEG data of eye-movements can be observed in Figure 5.32 .

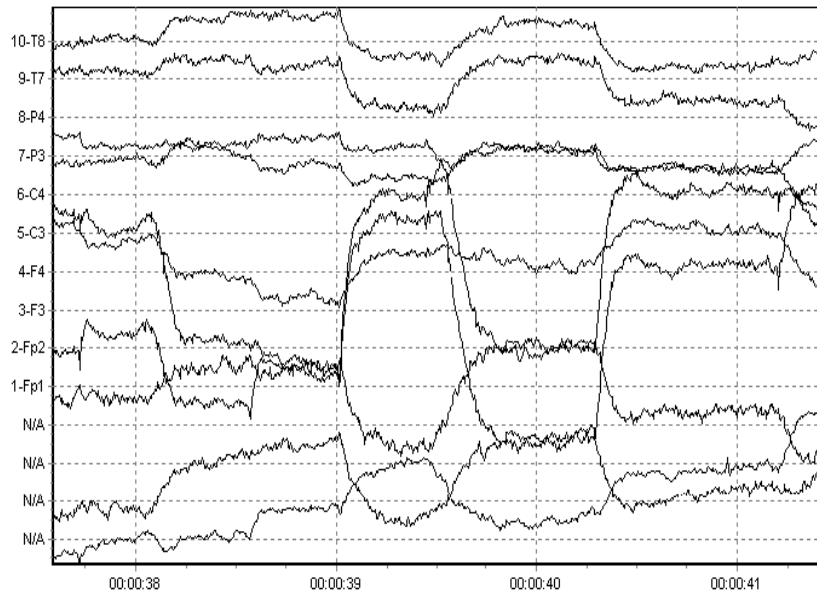


Figure 5.32 Eye movement artifact ("User Tutorial:EEG Measurement Setup," 2012)

5.4.2. Observations

To extract eye blink threshold values depending on the theory that occurs spike in the EEG data, observations made in Openvibe program with using MindWave device. To illustrate the idea of capturing eye blinks from EEG data, various samples collected as means of viewing and estimating threshold values of eye blink artifact together with time slot. During the experiments, it has been tried that both strongly and weakly closing eyelids to see difference states and thresholds.

In the Figure 5.33 , several eye blinks occurred in the times and it is observed that approximately all blink values have the same values as in raw EEG data. Time values represented as seconds and values along the y lines represents the raw EEG data. As seen in Figure 5.33 , there exist 7 eye blinks and all blinks approximately has same strong as means of closing eyelids and has raw value approximately between 500-650 in positive side.

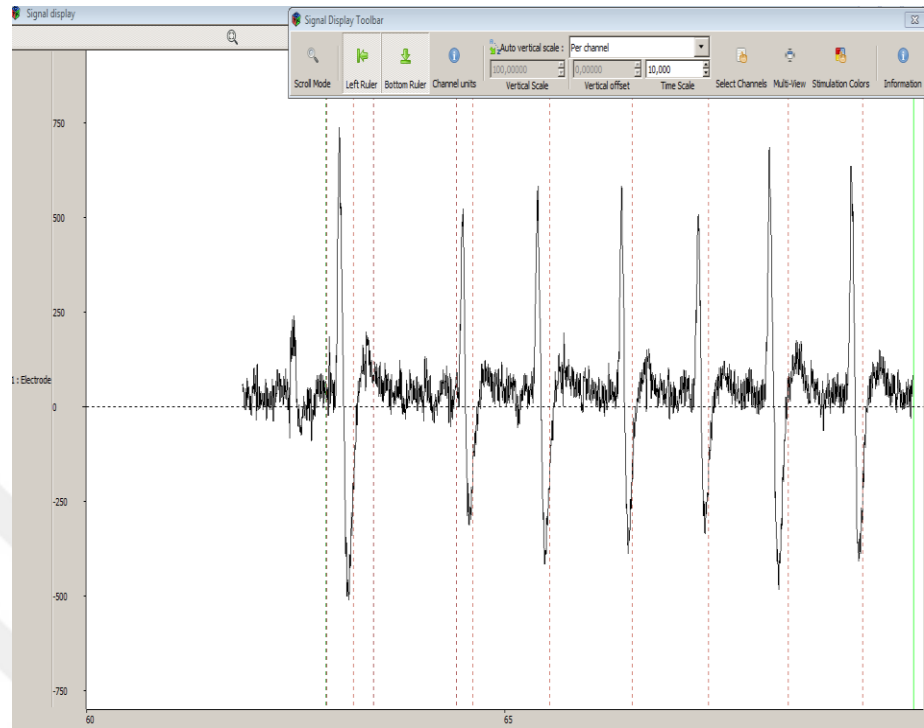


Figure 5.33 Single blink values with respect to time

Another observation can be seen in Figure 5.34 to see how strongly closing eyelids effects the raw EEG data. In the first 2 eye blink values occurs when any of user close his/her eyes in a strong way. In that time, raw EEG values reaches even the number of 1000 which is approximately 2 times bigger than as normal eye blinks. Another normal strongly blinks observed in the raw EEG values in between 250 to 700.

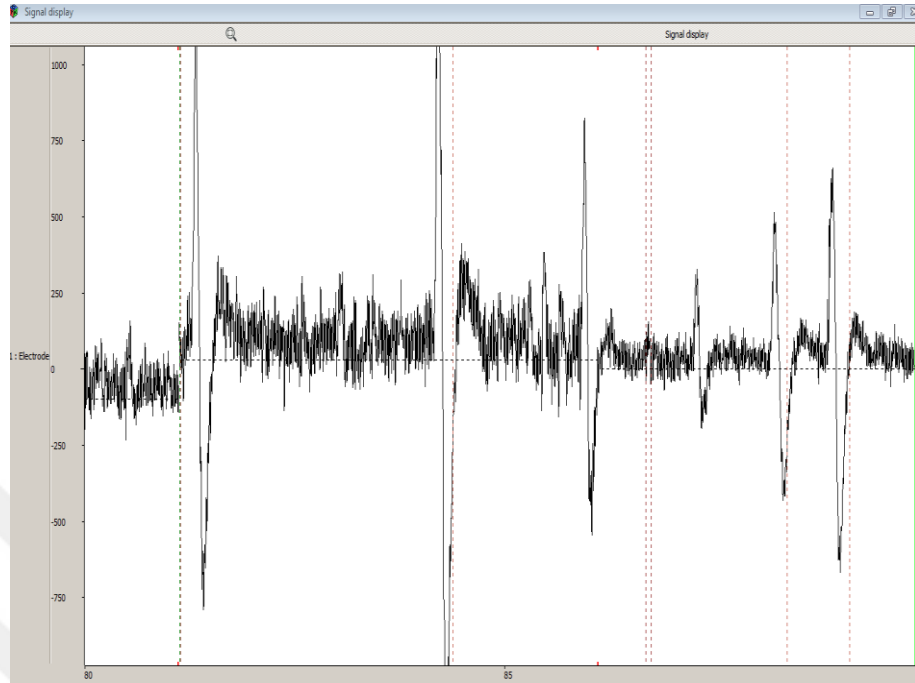


Figure 5.34 Several eye blinks observations including strongly closing eyelids

In order to detect double blink and even triple blink, time values observed consecutively. Figure 5.35 illustrates the occurrence of double blink values with respect to time that is followed right after first closed eyelids in approximately 300-400 milliseconds. Figure 5.35 gives an example of two double blink and one triple blinking raw EEG values with respect to time that has raw value interval approximately +400 and -400 in the 300-400 milliseconds. These values guided to detect double blinks in average time slot 400 milliseconds.

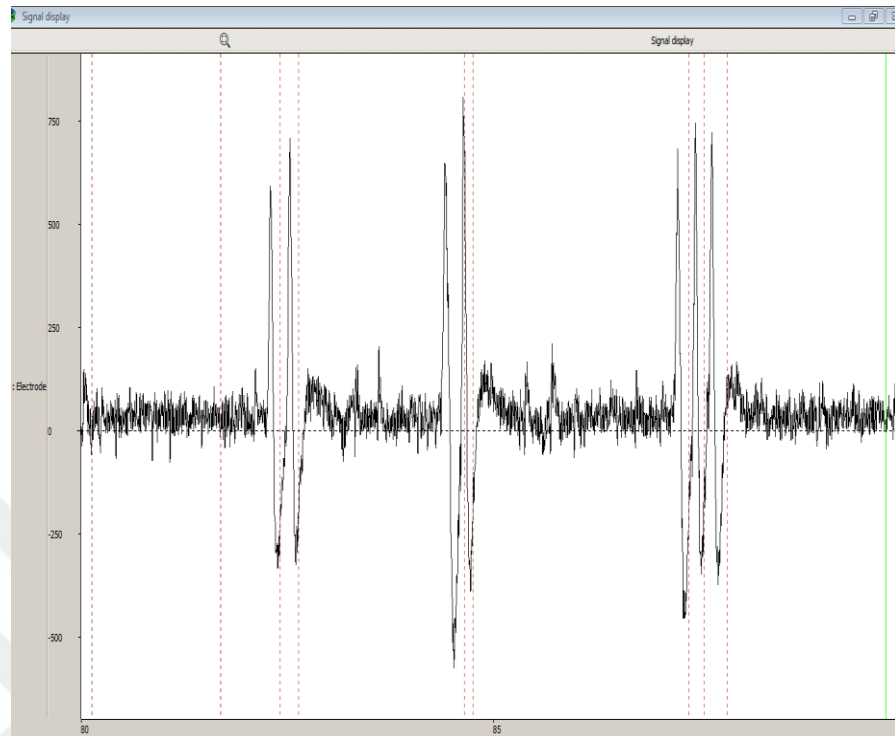


Figure 5.35 Double/Triple blinking with respect to time

5.4.3. Algorithm

By substituting the results as described in Extraction of blink values , appropriate algorithm developed. In the algorithm, detection of blinking values occurred in checkBlinking method which has two parameters described below:

- **int wave** : Coming raw EEG data from main application flow, approximately in every 2 ms. It is mentioned more detailed in RAW Wave value section in ThinkGear Data Values and Packet Structures chapter.
- **boolean apiBlinkCheck** : This value become true, when the NeuroSky SDK value , TGDevice.MSG_BLINK, has value greater than 40. This provides more powerful control when detecting eye blinks instead of using only SDK value which will give eye blink strength. With using this value, we can control if blink is occurred or not, it is not our concern to get eye blink strength from the NeuroSky SDK which sometimes give inconsistent values in case of not strongly closing eyelids.

```

public String checkBlinking(int wave,boolean apiBlinkCheck)
{
    //String result="NONE";
    blinkTime = timer.getTime();

    if (wave > 32767) {
        //Normalize the raw values, depending on Mindwave Specifications
        wave -= 65535;
    }
    //If raw wave is greater than 425, possible blink may occurred,start timer
    if (wave > 425 && blinkTime == 0 && isTimerStarted == false) {
        timer.start();
        isTimerStarted = true;
    }
    //If raw wave is less than -425, possible blink occurred, add 1 to blink value
    else if (wave < -425 && blinkTime > 10 && blinkTime < 350) {
        if (isTimerStarted == true) {
            currentTime = blinkTime;
            timer.stop();

            timer.reset();
            this.setBlinkCount(this.getBlinkCount()+1);
            isTimerStarted = false;
        }
        //Reset blink time when specific time is passed
    } else if (blinkTime > 500) {
        if (isTimerStarted == true) {
            timer.stop();
            timer.reset();
            isTimerStarted = false;
        }
    }
}

```

Figure 5.36 Possible occurrence of eye blink algorithm

Figure 5.36 shows the possible event of eye blink algorithm in checkBlinking method. First if statement deduced directly from NeuroSky specifications which described in RAW Wave value section in MindWave Mobile chapter states that:

“b. if (raw >= 32768) raw = raw - 65536; where raw is of any signed number type in the language that can represent all the numbers from -32768 to 32767.” Page 44

When raw value is above 425, it signs there is artifact in EEG data which means it could be eye blink. When this condition happens, timer started in order to count time interval and check if there is negative fluctuation in raw EEG data. When negative artifact has been observed, in second else if block that means user blinked. It is important to measure time interval because to differentiate time blink counts to check whether double blinked or single blinked. Detection of blink number happens in switch statement which is right after finishing if statements described above. If statements only count “possible” blinks of user within specific time, algorithm continues with

switch statement to define final decision about single blink/ double blink using states like in state machines.

When the program starts, current blink state sets “IDLE” by default. Note that possible values of blinkState value is: “IDLE” or “BLINKING”. When the blinkCount greater than 0, it means there is possible blink, algorithm stores this time lastBlinkTime and sets the blinkState to “BLINKING”. When user blinked, current blinkCount increased as one, enters the case “IDLE” state of switch statement, gets the current time as lastBlinkTime and switches to “BLINKING” state.

In the “BLINKING” state, algorithm checks blinkCount value and passed time interval since lastBlinkTime to determine result as “DoubleBlinked” or “Blinked”.

If the blinkCount equals to 2 and time interval since last blink is less than 400 milliseconds, in which signs consecutive eye blink occurred, result determined as “DoubleBlinked” and BlinkState is set to “IDLE” to make algorithm ready for another computation of blink as seen in Figure 5.37 Detection of eye blink as means of counter and time values.

```

switch (this.getBlinkState()) {
    case "IDLE":
        if (this.getBlinkCount() > 0) {
            lastBlinkTime = System.currentTimeMillis();
            this.setBlinkState("BLINKING");
        }
        break;
    case "BLINKING":
        //If blink count is equal to 2 in specific time (approximately in 400 ms)
        if (this.getBlinkCount() == 2
            && System.currentTimeMillis() - lastBlinkTime <= 400
            && System.currentTimeMillis() - currentTime > 30
            && apiBlinkCheck == true) {
            //If blink count =2 within time interval, it means double blink
            this.setBlinkState("IDLE");
            this.setBlinkCount(0);
            this.setBlinkResult("DoubleBlinked");
            //If blink count is equal to 1 and specific time passed (approximately
        } else if (this.getBlinkCount() == 1
            && System.currentTimeMillis() - lastBlinkTime > 400
            && System.currentTimeMillis() - currentTime > 30
            && apiBlinkCheck == true) {
            // blink count =1 and last time greater than threshold, it means
            this.setBlinkState("IDLE");
            this.setBlinkCount(0);
            //TextboxOperations.setTextViewByName("showBlink", "Blinked");
            this.setBlinkResult("Blinked");
        }
        //If any case occurs with blink counts, reset it.
        else if (this.getBlinkCount() > 2) {
            this.setBlinkResult("");
            this.setBlinkCount(0);
            this.setBlinkState("IDLE");
            // TextboxOperations.setTextViewByName("showBlink", "");
        }
        break;
}

```

Figure 5.37 Detection of eye blink as means of counter and time values

Similarly, If the blinkCount equals to 1 and time interval since last blink is greater than 400 milliseconds that signs time is up for possibility of any blink during the time interval, result determined as “Blinked” and BlinkState is set to “IDLE” to make algorithm ready for another computation of blink. Details of algorithm for determining eye blinks shown in Figure 5.33 and also sequence diagram of checkBlinking method shown in Figure 5.38 Sequence diagram of checkBlinking method.

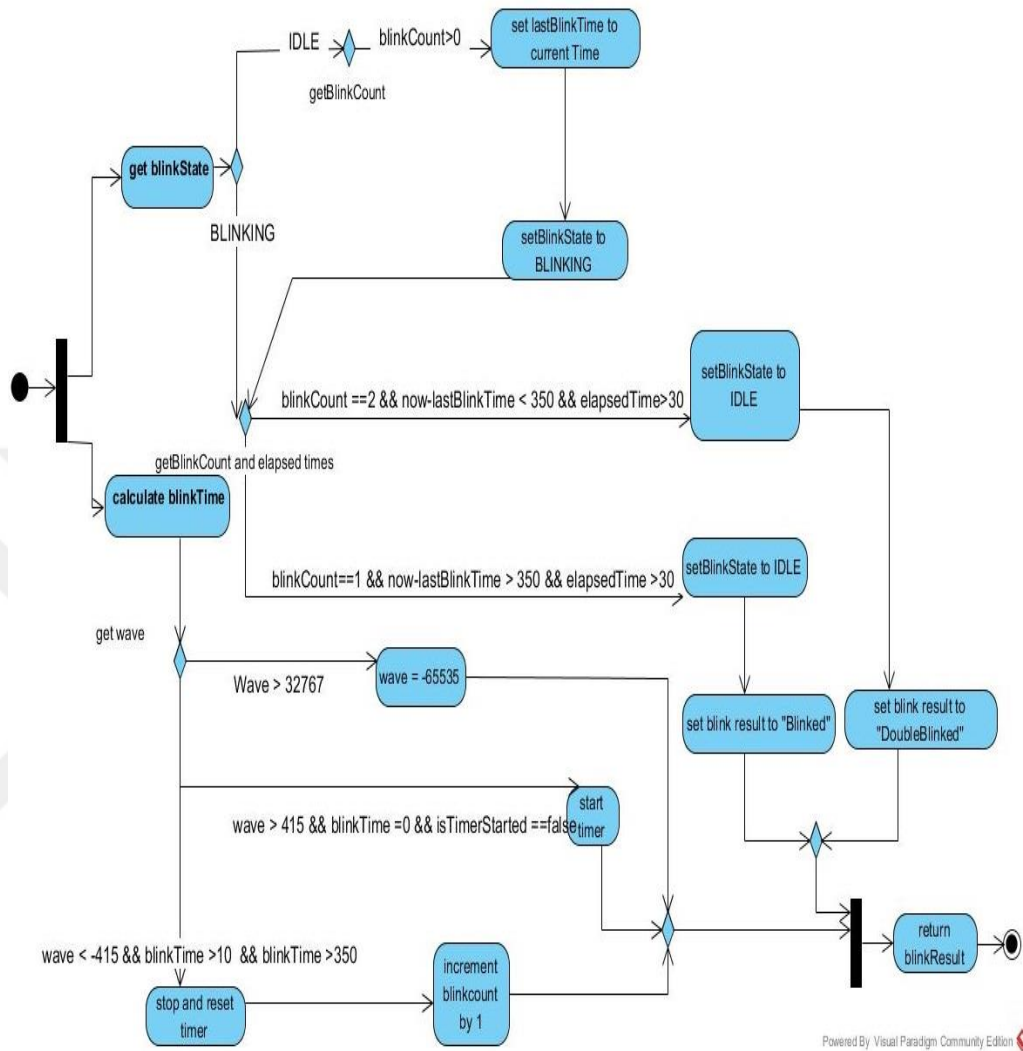


Figure 5.38 Sequence diagram of checkBlinking method

6. Conclusion and future work

This thesis studies the both theoretical and practical possibilities of practising portable EEG device; namely MindWave Mobile to provide a solution for controlling devices with brain waves. Plenty of research investigated in a comparative way to see advantages/disadvantages of using MindWave Mobile for controlling devices both hardware and software manner.

Plenty of research made through this thesis in order to construct efficient and cheap system to control devices with brainwaves. One research work by (Dobosz and Wittchen, 2015) concluded that double blink is best choice in order to switch one option from another in the application because it is not regular human behaviour like blink together with attention value. Another work by (Bose *et al.*, 2016), it is concluded that NeuroSky's eSense values are accurate to use, but it is hard to keep concentrated on specific task. This study guided to use attention values in that time rather than analysing previous attention values. Another study by (Chen *et al.*, 2014) used attention values used for switching concentrated state to not concentrated state with taking two consecutive attention value. The study by (Chen *et al.*, 2014) showed that it is possible to toggle of application component with using attention values but for multiple commands more values needed. Studies by (Bose *et al.*, 2016), (Chen *et al.*, 2014) and (Dobosz and Wittchen, 2015) yielded to use attention level together with blink/double blink values as means of controlling hardware and software systems with multiple commands. Keyboard application is one solution for software based system using MindWave Mobile device. Keyboard application starts with navigating through row selection and waits for user blink. After selecting row, navigation continues with column selection, namely letter. If user double blinks, current letter selected and outputted.

This thesis also provides ability to work in Android supported systems rather than simple computer application which gives ability to carry devices in anyway. Aim of the thesis is provide a cheaper solution for controlling Android devices and also wheelchair prototype for disabled person who cannot use hand directly. After making

all Bluetooth connections with devices (MindWave, Arduino Nano and prototype car) application starts and prototype car ready for commands. Application waits attention level to reach some threshold values to accelerate the car. If attention level reach appropriate level and if the user move head to any of defined direction (forward, backward, left and right) the prototype car moves that direction for 1.5 second. Depending on work by (Bose *et al.*, 2016) and (Chen *et al.*, 2014) instant attention value used to move car in real time more accurately. Head movements of user triggers car to move that direction if the attention value is appropriate. Simple Arduino Nano circuit stickled with MindWave Mobile device to detect head movements of user. Circuit includes Bluetooth module in order to send direction of movement. This solution shows applicable solution for providing multiple commands for controlling hardware device with MindWave Mobile.

By depending on results gathered related works shows the accuracy of MindWave Mobile is nearly equal to medical EEG device and values outputted accurate therefore suitable to develop any application on top of SDK provided. Also, solution for wheelchair can easily be applied to control car in a similar way.

In this sense, it is believed to provide solution for controlling both software application components and prototype of car using Android supported device in hardware manner. This gives ability to carry any of devices more portable way instead of using computers.

Among all discussions about EEG devices, related works section in thesis showed the possible usage of MindWave Mobile device in a controlling of devices and general picture showed that due to the one sensor it is not possible to give multiple command in an “easy” way. To make a combination and give multiple commands to devices Android Nano and gyroscope sensor added on top of the MindWave Mobile device which can give opportunity to work even smaller angle movements in order to drive car which can be used as wheelchair prototype for disabled users to control their wheelchairs as well as controlling car. Provided ideas during this thesis gives

opportunity on behalf of both controlling devices with hardware based and also controlling software components with brainwaves to show flexibility of usage.



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CURRICULUM VITAE

Tuğçe Kalkavan was born in 1990, İzmir – Turkey. She graduated from Yaşar University, Computer Engineering Department with a GPA of 3.55 in 2008. Her professional career started in 2008 as a Research Assistant at Yaşar University Computer Engineering Department in İzmir.

After 9 months of work experience in a Yaşar University, she decided to start her Master of Science (MS.c.) education in Yaşar University in order to utilize her academic development in a professional academic environment through the most efficient support of related courses and practical projects.

7.APPENDIX 1

MPU 6050

MPU-6050 is called IMU sensor (abbreviation for Inertia Measurement Unit) that contains both MEMS accelerometer and MEMS gyroscope sensor in a single chip. It is able to capture all axis x, y and z and able to give 6 values of output as three comes from accelerometer and 3 comes from gyroscope. It uses the I2C bust to interface with other devices such as Arduino. Figure 7.1 shows the MPU-6050 sensor.



Figure 7.1 MPU-6050 sensor (arduino.cc, 2016)

Besides, it has following properties:

“The MPU-60X0 is the world’s first integrated 6-axis MotionTracking device that combines a 3-axis gyroscope, 3-axis accelerometer, and a Digital Motion Processor™ (DMP) all in a small 4x4x0.9mm package. With its dedicated I2C sensor bus, it directly accepts inputs from an external 3-axis compass to provide a complete 9-axis MotionFusion™ output. The MPU-60X0 MotionTracking device, with its 6-axis integration, on-board MotionFusion™, and run-time calibration firmware, enables manufacturers to eliminate the costly and complex selection, qualification, and system level integration of discrete devices, guaranteeing optimal motion performance for consumers. The MPU-60X0 is also designed to interface with multiple noninertial digital sensors, such as pressure sensors, on its auxiliary I2C port. The MPU-60X0 is footprint compatible with the MPU-30X0 family.

An on-chip 1024 Byte FIFO buffer helps lower system power consumption by allowing the system processor to read the sensor data in bursts and then enter a low-power mode as the MPU collects more data.

Communication with all registers of the device is performed using either I2C at 400kHz or SPI at 1MHz (MPU-6000 only)” (InvenSense, 2013)

