DESIGN AND DEVELOPMENT OF A BRAIN COMPUTER INTERFACE CONTROLLED ROBOTIC ARM

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**A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Bachelor of Engineering (Hons) Electronics Engineering**

**Faculty of Engineering and Green Technology
Universiti Tunku Abdul Rahman**

May 2015

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DESIGN AND DEVELOPMENT OF A BRAIN COMPUTER INTERFACE CONTROLLED ROBOTIC ARM"** was prepared by **KHOW HONG WAY** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons) Electronics Engineering at Universiti Tunku Abdul Rahman.

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Date   : _____

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Specially dedicated to

My beloved mother and father

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ABSTRACT

An electroencephalogram (EEG) signal is a brain signal recorded from human scalp by using electrodes. Brain computer interface (BCI) is a system that allows human to communicate with electronic device by using brain signal. The aim of this project is to design and develop a BCI controlled robotic arm using EEG signal. In this project an EPOC (a headset consists of 14 electrodes) is used to detect and collect EEG signal from human scalp. Every facial expression made by human beings generates a specific EEG signal, the BCI robotic arm is designed to be controlled by human expressions. The robotic arm created in this project is able to make 4 moves (Make a fist, release fist, flexion of elbow and extension of elbow). Each move is controlled by one expression (Left smirk, right smirk, raise brow, and look left/ right). The performance of the BCI robotic arm is determined by testing it on 10 subjects. The average accuracy of the system is above 92%. We have analyzed the effect of decreasing the number of electrodes on the proposed BCI system. It has been concluded that 7 electrodes are ehough to control the robotic arm. The accuracy of the BCI system with reduced number of electrodes (7 only) for 10 subjects is above 90%.

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CHAPTER 1

INTRODUCTION

1.1   Background

The human brain consists of billions of neurons (brain cells). When they are working or active, they produced current flow. These neurons cause a current flow when active. The neurons are electrically charged or are polarized by membrane that transport protein which pumps ions (Na+, K+, Ca++, and Cl-) through channels in neuron membranes. This electrical activity is recordable on the scalp surface is known as electroencephalogram (EEG).

Hence EEG signal is defined as the electrical activity along the scalp which appears in the form of a brain wave. To acquire EEG signal, several small and flat metal discs called electrodes are attached to the scalp. As the neuron current has to penetrate through skin, skull, and several other layers, the electrical signals are very weak on surface so the signals detected by the scalp electrodes are amplified and then transmitted to a computer, and then displayed a graph of brain wave. These EEG recordings can be classified into several frequency bands: Delta (0.5~4Hz), Theta (4~8Hz), Alpha (8~11.5Hz), Beta1 (11.5~15Hz), Beta2 (15~35Hz), and Gamma (30~100Hz). EEG is widely used in medical area nowadays, for example like diagnosing epilepsy, checking for problem with loss of consciousness, studying sleep disorder and etc. EEG can play an important role in enhancing human life quality using the brain signal for Brain Computer Interface (BCI) controlled devices. Because the brain signals are different according to the activities of a human, BCI

allows people to communicate with a computer using their mind. By utilizing BCI, it is possible that user can have dexterous artificial limbs, control of a movable device, ability to operate computer system, better gaming experience and etc.

In this project, the objective is to design and develop a BCI controlled robotic arm using EEG signal. In fact, this BCI controlled arm is similar to artificial arm which is a big contribution for those who lost their limbs. Although EEG signal is weaker than Electrocorticography (ECoG) and Stereoelectroencephalography (SEEG) but it is non-invasive which means the user do not need to implant it within human head. To create a BCI controlled arm, the identification and collection of brain signals is necessary. By using these sampled signals, it can be used to program the action of the arm. The higher the mobility of the BCI arm the more signals need to be sampled.

1.2   Problem Statements

In this century, there are plenty of artificial limbs but most of them are either not controllable or the mobility is limited. So, disabled people cannot have a dexterous artificial limbs and not able to respond to their mind very well. To solve this problem, an artificial limb controlled by BCI will do.

1.3   Aims and Objectives

The objectives of the thesis are shown as following:

i)   To control a robotic arm using EEG signal.

ii) To design and develop a BCI robotic arm that is able to make 4 moves.

iii) To determine the minimum number of electrodes that are required by the BCI system.

CHAPTER 2

LITERATURE REVIEW

2.1   Electroencephalography (EEG)

The nerve signals in brain travel through the paths called axons that are covered by myelin. Even for the paths covered by myelin, there are some of the electric signals escape from the path and they are detectable. The EEG is a process to detect and measure this electrical activity resulting from ionic current flows within the neurons of the brain by attaching some electrodes along the scalp. In 1875, Richard Caton (1842-1926), a physician discovered the existence of electrical phenomena of brain from animals. in 1925, Hans Berger (1873-1941), a German physiologist and psychiatrist recorded the first EEG from human beings (La Vaque, 1999). Because EEG is a non-invasive (not necessary to implant any device within human body) test so the electrical signals from brain to electrodes are weak due to the multiple layers (skin, skull, and etc.) between them. Therefore, a computer will amplify the collected signals and filter out the noise. In the end, a brain wave will be displayed on computer screen.
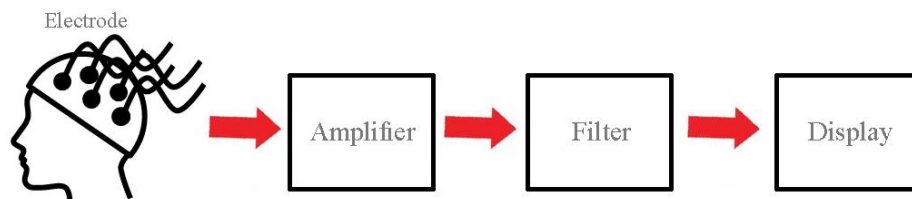
Figure 2.1: EEG system

In recent days, EEG is commonly used for medical application. Basically, it is used to evaluate people who are having brain function problem like confusion, coma, tumors, long-term difficulties with thinking, and etc. However, the EEG is also used to develop BCI applications which has a big potential on enhancing human life.

2.2   Neuron Activities

The brain is an electrochemical organ which is filled with approximately 100 billion neurons (nerve cells). A neuron consists of three parts. The first part is cell body, it is a main component of the cell and it contains nucleus, endoplasmic reticulum and ribosomes (components that build protein) and mitochondria (component that make energy). The second part of neuron is called axon. It is a long and cable-like component of the cell that carries the electrochemical message along the length of the cell. The transmission speed is higher if the diameter of axon is larger. Some types of neurons have a thin layer of myelin sheath covering the axon like an insulated electrical wire. The function of myelin is to speed up the transmission of nerve impulse down a long axon. The myelinated neurons can be found in the peripheral nerves (sensory and motor neurons) while non-myelinated neurons are found in the brain and spinal cord. The third part of neuron is dendrites. They are small, branch-like components that are located on one or both ends of the cell. The dendrites make connection to other cells and allow neurons to interact with other cells.
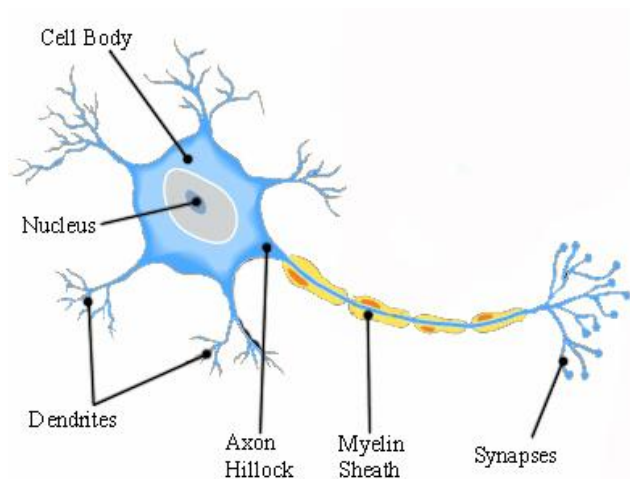
Figure 2.2: Neuron structure

The electrical activities are caused by electrically charged or polarized neurons. There are sodium ions (Na+), potassium ions (K+), calcium ions (Ca++), and chloride ions (Cl-) inside and outside of the neurons. They have their own specific channel in cell membrane which allows them to move in and out of neurons. In addition, there are large proteins within the cell that gives the inside of the cell a negative electrical charge compared to the outside. The charge is about 70 to 80 mV. In addition, there are sodium-potassium pumps located in the membrane. This pump uses energy (Adenosine triphosphate) to pump K+ from the outside to the inside and Na+ from the inside to the outside. Because K+ and Na+ are positively charged, so they can carry tiny electrical currents when they move across the cell membrane. When there is sufficient number of ions move across the membrane, the electrical current is measurable (Freudenrich and Boyd, 1998).

2.3 Brain Wave

After the EEG signal is processed by EEG system, a filtered brain wave will be produced. The produced brain wave can be categorized according to their frequency. Generally, the brain wave can be categorized into four types (Beta, Alpha, Theta, and Delta) and each type is representing the activity of a particular form (Canadian Electroacoustic Community, 2012).

The Beta wave has relatively low amplitude but it is the fastest among all. The frequency of beta wave ranges from 12.5 to 30Hz but it can be separated into three ranges: Low Beta (12.5-16Hz), Beta (16.5-20Hz), and High Beta (20.5-28Hz). This 'fast' wave represented arousal and is a characteristic of a strongly engaged mind, it happens when people are busily engaged in activities and conversation.
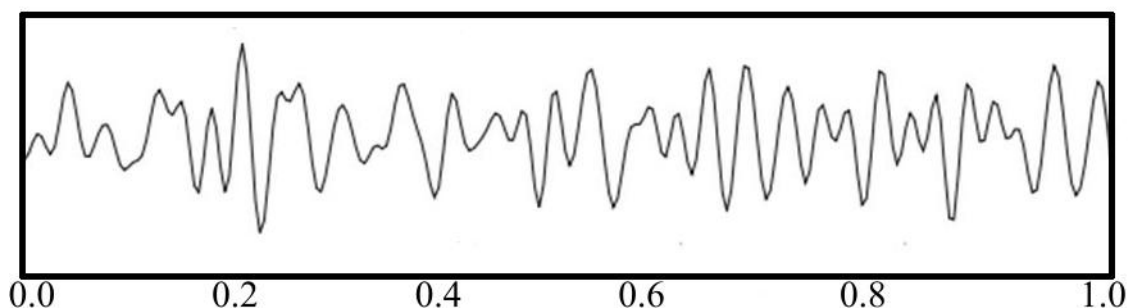
Figure 2.3: Beta wave (Cvijetic, 2013)

The Alpha wave is also known as Berger's wave because it was identified by Hans Berger. This wave represents non-arousal. It has a slower brainwave but higher in amplitude compared with Beta wave. The Alpha wave frequency ranges from 7.5 to 12.5Hz. In addition, in this state the mind is relaxed and in normal resting state. This wave occurs when people listen to music, watching TV or meditating.
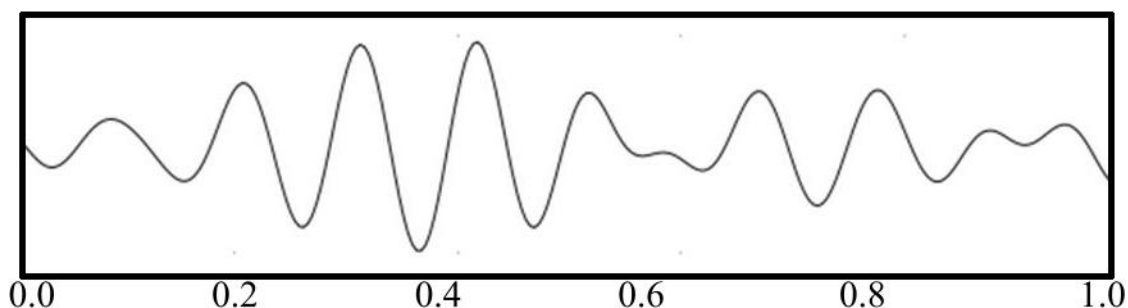
Figure 2.4: Alpha wave (Cvijetic, 2013)

The next brain wave category in order of frequency is Theta wave. The Theta wave has even greater amplitude and slower frequency compared to Alpha wave. The frequency of Theta wave normally ranges from 4 to 7.5Hz. People are in Theta state they are in a pre-sleep or semi-awake situation which is also called hypnoidal state.
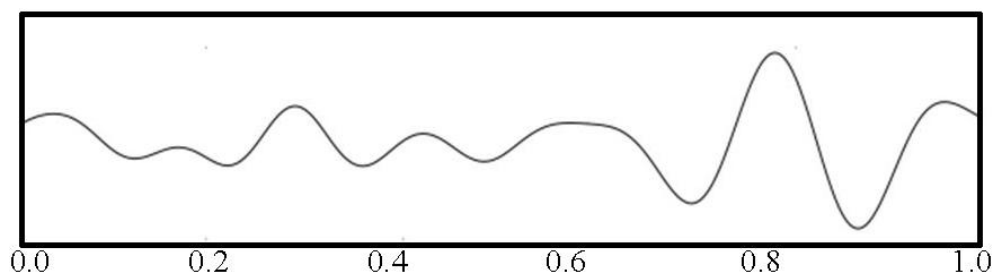
Figure 2.5: Theta wave (Cvijetic, 2013)

The last brainwave state is Delta wave. The Delta wave has greatest amplitude and slowest frequency. Typically, the frequency of Delta wave ranges from 0.5 to 3.5Hz. It is the deepest brainwave level associated with dreamless sleep. Besides, it is also important for restoration of health and immune system. The Delta wave can be found in babies normally.
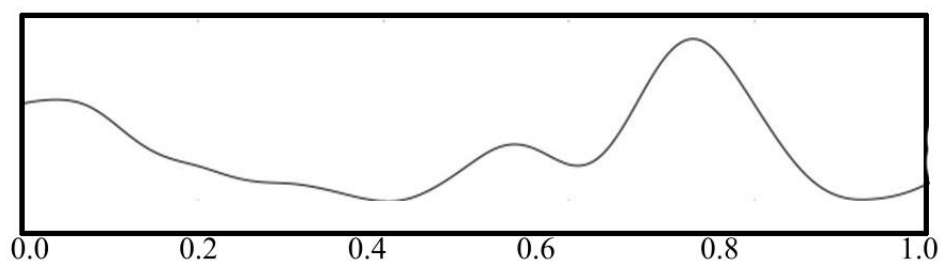
Figure 2.6: Delta wave (Cvijetic 2013)

However, there are still two categories of wave beyond those stated above: gamma and Mu wave. The frequency of Gamma wave is range from 25 and 100Hz, typically is 40Hz. It usually happens when the mental is excited state which is also

great for learning. The Mu wave has same frequency with Alpha wave (7.5 to 12.5Hz) but unlike alpha wave, it can be found at sensorimotor cortex only and shows the rest state motor neurons.
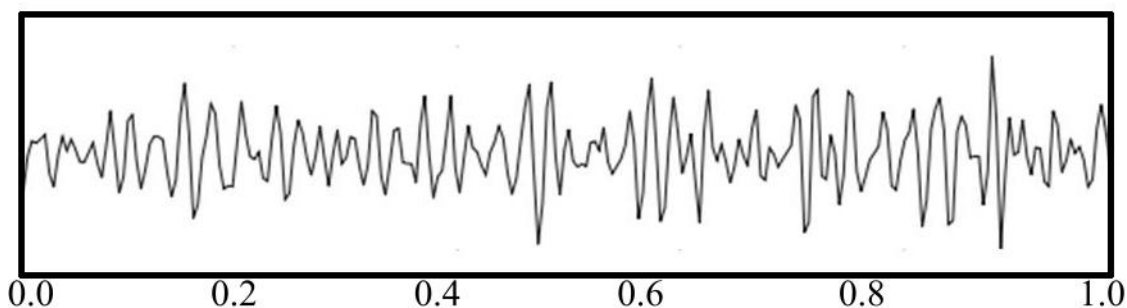
Figure 2.7: Gamma wave (Cvijetic 2013)

Table 2.1 Summary of brain waves

Waveform	Frequency (Hz)	Location	Mental State	Activities
Gamma	25 – 100+	- Somatosensory cortex	Excited	- Concentration - Higher learning
Beta	12.5 – 30	- Both side of brain - Symmetrical distributon - Most evident frontally	Active	- Awake - Thinking - Talking
Alpha	7.5 – 12.5	-Posterior regions of head - Central sites (C3-C4) at rest	Relaxed	- Listening music -Watching TV - Meditating
Theta	4 – 7.5	- Where not related to task of hand	Drowsy	- Pre-sleep/ Semi-awake
Delta	0.5 – 3.5	- Frontally in adults - Posteriorly in children	Sleep	- Sleep - Healing
Mu	7.5 – 12.5	- Sensorimotor cortex	Relaxed	- Resting of motor neurons

2.4   Brain Computer Interface (BCI)

The history of Brain Computer Interface (BCI) began with Hans Berger's discovery of EEG. After that, the research on BCI was begun in the 1970s at the University of California Los Angeles. The BCI allows human to communicate with computer system using brain. The concept of BCI is to process the input brain signal and generate output signal for device. Each action of a man generates a different electrical signal and this is why computer can react to human brain.
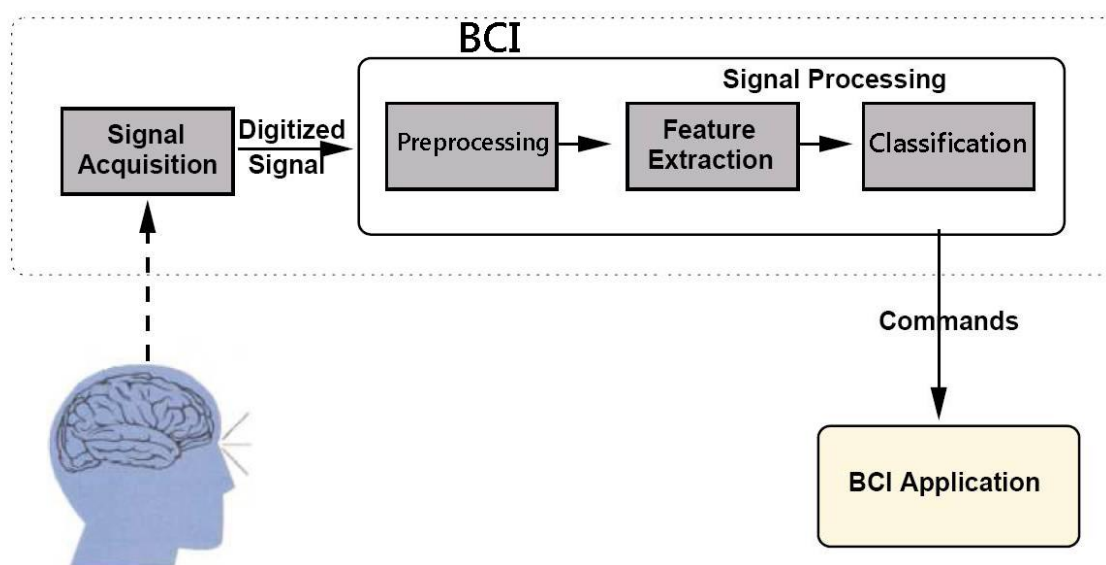
Figure 2.8: BCI system (Alomari, Samaha, & AlKamba 2013)

The easiest method to implement BCI is using EEG which is usually non-invasive method that attaches a set of electrodes on the scalp surface. However, there are multiple layers (skull, skin, and etc.) blocking the brain signals toward the electrode causing the collected signals to be weak or distorted. There is way to extract higher-resolution signal but the electrodes have to be implanted into the grey matter of the brain or on the surface of the brain which is an invasive way.

One of the most interesting parts of BCI development is the devices can be controlled by user thoughts. It is a big contribution for disabled people like those who lost their limbs. Unfortunately, there is a difficulty on using brain signals to control a device, example someone who cannot physically move their arm trying to control a robotic arm. In this situation, the subject needs some training to use the device. By taking a BCI robotic hand as an example, the subject must visualize closing his or her hand. After that, the signals of this thought (hand-closing) will be collected or sampled and then programmed into the BCI system. So, when the subject has the thought of closing hand, the robotic hand should close (Nagavivek, 2012).

Although BCI has many applications but may not work perfectly. This is because the brain is too complex that the signals of actions or thoughts are understatement or unclear. There are chemical processes involved in neuron activities but the EEG is not able to pick up. Moreover, the received signals by EEG electrodes are weak and prone to interference. Somehow a simple eyelids-blinking can generates a strong signal. But the refinements in EEG and implants may overcome this problem in the future.

2.5 EEG Electrode

The electrode is a necessary medium for transmitting brain signals to computer for EEG test or BCI device. There are two types of EEG electrodes: surface type and needle type. The surface electrode is flat disk with wire connected to the EEG system, it is an easy and commonly used way because the user needs to attach this electrode on the scalp surface only while needle electrode needs to be placed under the skin.

The placement of electrodes are usually follows the international 10-20 electrode system. The "10" and "20" are refer to the distance between adjacent electrodes which are either 10% or 20%. This measurement technique is based on standard skull landmarks. The first measurement line starts from the nasion to the inion. The line is then divided into five separate areas like in Figure 2.9.
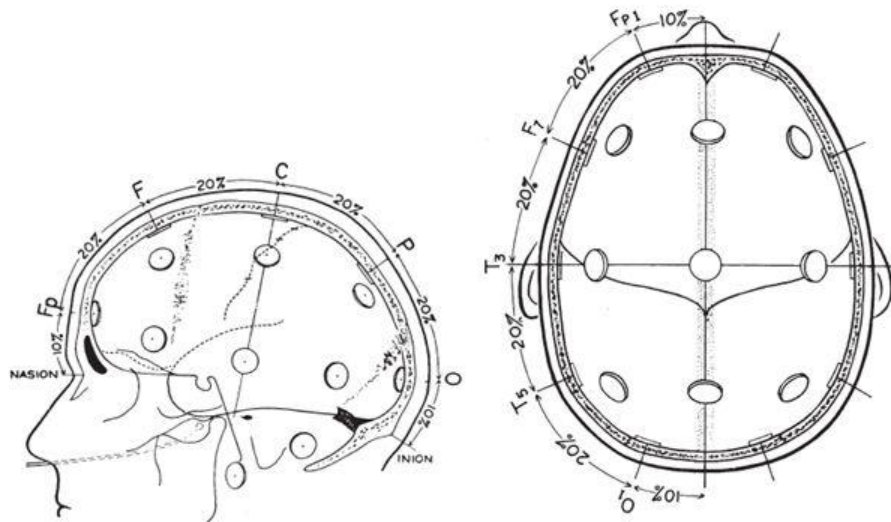
Figure 2.9: Side view and top view of electrode positions

(Jamison, Madoff, Rohmann & Woods 2005)

Furthermore, the line is labeled Fp, F, C, P, and O, each of them represent the front polar, frontal, central, parietal, and occipital areas respectively. After that, a second measurement line is placed from left preauricular through the C vertex mark to the right preauricular point and then separates it like in Figure 2.10. The label T represents temporal area. Then, a landmark (Figure 2.12) of standard electrodes position is formed (Klem, et al.,1986)
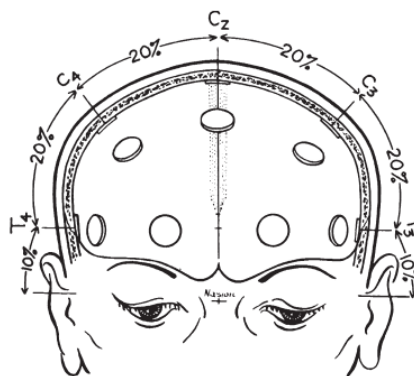
Figure 2.10: Front view of electrode positions (Jamison, Madoff, Rohmann & Woods 2005)

Figure 2.11: Standard electrode positions (Jamison, Madoff, Rohmann & Woods 2005)

Figure 2.12: Modified combinatorial nomenclature (Jamison, Madoff, Rohmann & Woods 2005)

2.6   Emotiv EPOC

The Emotiv EPOC is a wireless headset that is able to receive EEG signals from human scalp. It is a product developed by a company called Emotiv Systems which is an Australian electronic company that focus on BCI and EEG relevant technology. Furthermore, this headset consists of sixteen electrodes but only fourteen of them are EEG channels, the rest electrodes are used as references offering optimal positioning for accurate spatial resolution.

Figure 2.13: Emotiv EPOC

The EEG channel names of this headset are based on the international 10-20 electrode location system (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4). The advantages of EPOC compared to conventional EEG system are it is easy to set up and it is portable. Besides, the Emotiv Systems provide software for EPOC. With the aid of the software, EPOC users are able to study and observe EEG signals. In fact, software also allow users to apply EEG on other technologies, such as robotic and control system (Reder, EE et al 2014).

Table 2.2: Emotiv EPOC specifications (Emotiv EPOC 2014)

	EEG HEADSET
Number of channels	14 (plus CMS/DRL references, P3/P4 locations)
Channel names (International 10-20 locations)	AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4
Sampling method	Sequential sampling. Single ADC
Sampling rate	128 SPS (2048Hz internal)
Resolution	14 bits 1 LSB = 0.51 µV (16 bit ADC, 2 bits instrumental noise floor discarded)
Bandwidth	0.2 – 45Hz, digital notch filters at 50Hz and 60Hz
Filtering	Built in digital 5th order Sinc filter
Dynamic range (input referred)	8400 µV (pp)
Coupling mode	AC coupled
Connectivity	Proprietary wireless, 2.4GHz band
Power	LiPoly
Battery life (typical)	12 hours
Impedance Measurement	Real-time quality using patented system

2.7   Emotiv Software Development Kit (SDK)

The Emotiv SDK is a package of software that is provided by Emotiv Systems. This software package contains Emotiv Control Panel, EmoComposer, Emokey, and TestBench. EPOC user can interact with these by using their headset.

2.7.1   Emotiv Control Panel

The Emotiv Control Panel shows the headset setup and its mapping as well as the signal strength of each channel. It aids user to locate the electrodes on optimal

positions. Besides, it also provides three suits: Expressiv Suite, Affectiv Suite, and Cognitiv Suite.
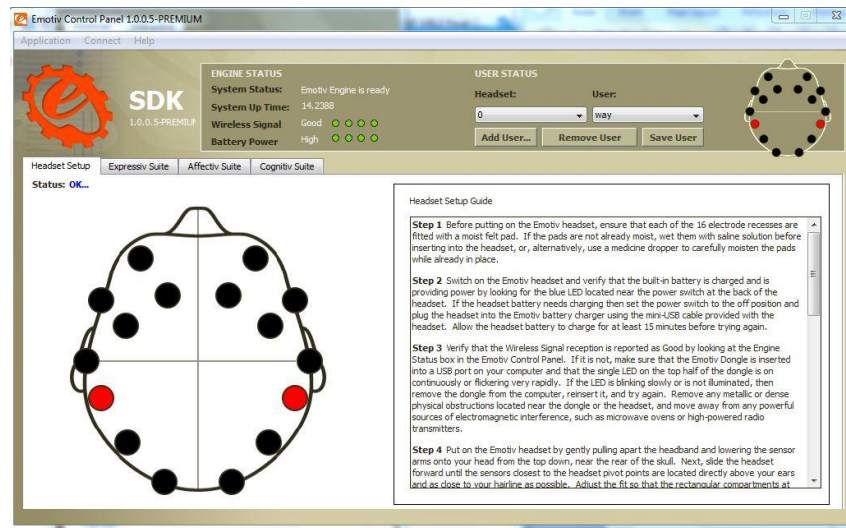
Figure 2.14: Interface of Emotiv Control Panel

The Expressiv Suite is a suite that can detect EPOC user's facial expression according to user EEG signals and uses an animated figure (face) to display user current expression. It can recognize 12 types of expressions. Besides showing the user expression, it also allows user to adjust the sensitivity of the signals. Moreover, these expression signals are possible to be applied on other applications. The interface of Expressiv Suite is shown in Figure 2.15.
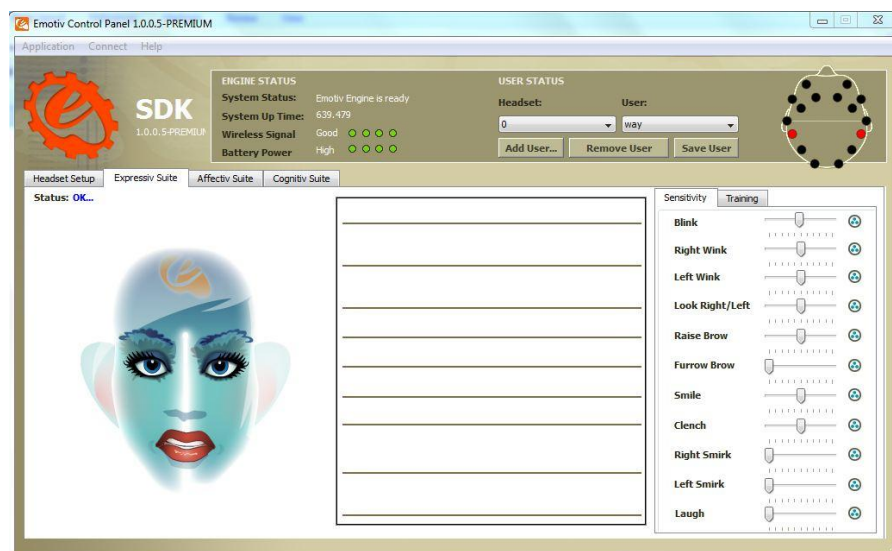
Figure 2.15: Interface of Expressiv Suite

The Affectiv Suite displays the current mental situation of the EPOC user. There are two graphs that display the level of each situation. Each situation has its own color. The interface of Affetiv Suite is shown in Figure 2.16.
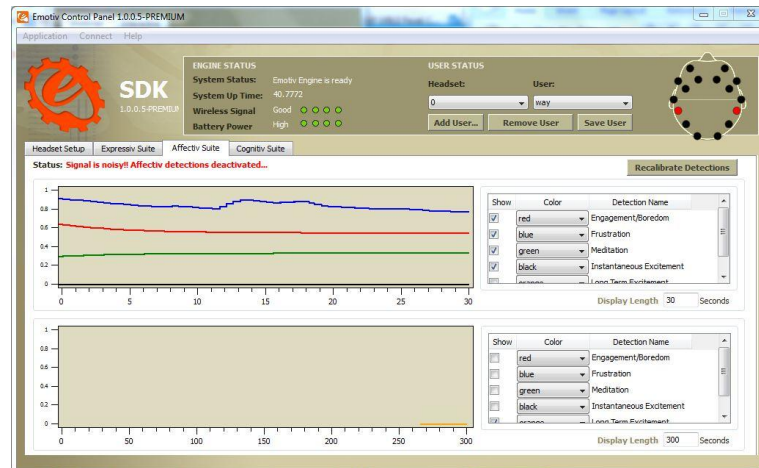
Figure 2.16: Interface of Affectiv Suite

In Cognitiv Suite, there is a 3D platform that contains a flowing cube and this cube can be controlled by user EEG signals. EPOC user can use it to sample EEG signals for each command on the cube movement. The sampling process will take 8 seconds, user is required to maintain same thought within this 8 seconds. After the sampling process, user is able to moves the cube by using the same thought he/she sampled. In addition, this suite can sample and store many types of EEG signal, user can utilize this on other applications like BCI system too.
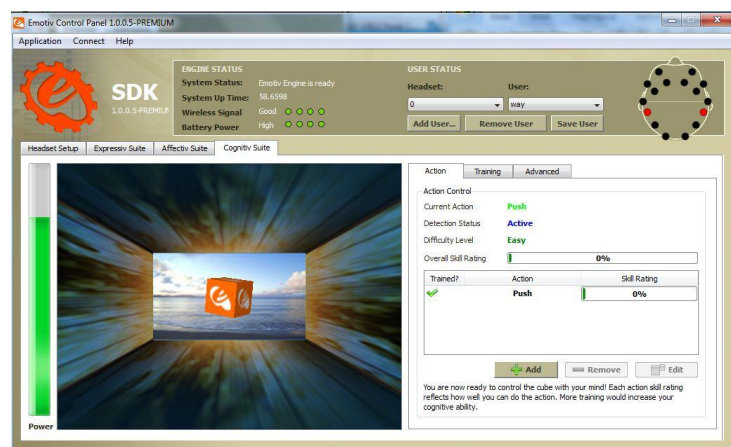
Figure 2.17: Interface of Cognitiv Suite

2.7.2   EmoKey

The EmoKey is a program that allows user to define keystrokes for sampled EEG signals. This program must be connected to either Emotiv Control Panel or EmoComposer. EPOC user can define what signal(s) will generate a keystroke and what keystroke is it. In short, it is like using human thought to do some typing some typing on computer. It is possible to use EmoKey to navigate and operate a computer or device. After defining the keystroke, user can save the key mapping for future use.
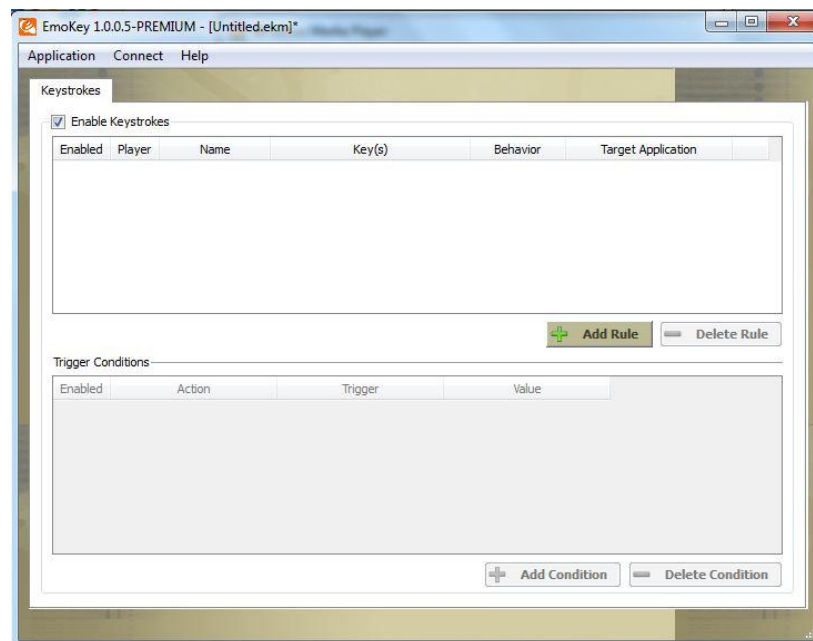
Figure 2.18: Interface of EmoKey

2.7.3   TestBench

The TestBench is a program that displays a graph of real-time raw EEG signals. It is used for observing and studying the EEG signals. The raw EEG signals are able to be recorded and saved for future playback by using TestBench. Moreover, this program also allows user to observe the magnitude of Fast Fourier Transform (FFT) and Delta, Theta, Alpha, and Beta signals.
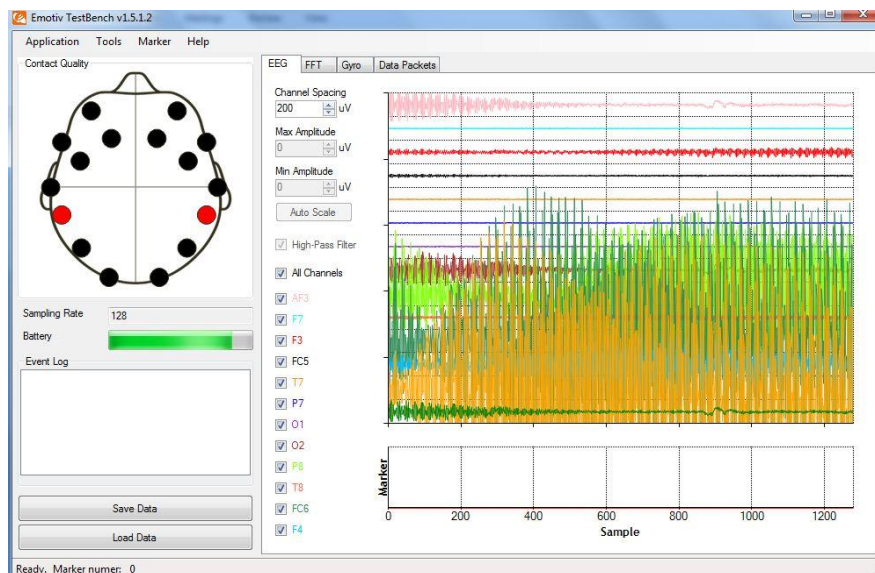
Figure 2.19: Interface of TestBench

2.8   Arduino UNO

The Arduino UNO (Arduino 2015a) is an electronic board with a built-in microcontroller that is based on the ATmega328. It is a product released by a computer hardware and software company called Arduino. Besides Arduino UNO, this company also released plenty of electronic boards like Leonardo, Due, Motor Sheild, GSM Sheild, and etc. In addition, they also provide education on their products as well as provide some examples and forum for discussion with worldwide user.

Figure 2.20: Arduino UNO (Arduino 2015a)

The Arduino UNO (Arduino 2015b) is a tool for making a computer that can perform applications designed by users. The microcontroller is programmable by user with easyby just using the software provided by the company.

Table 2.3: Arduino UNO specifications (Arduino 2015a)

Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (Recommended)	7-12V
Input Voltage (Limits)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40mA
DC Current for 3.3V Pin	50mA
Flash Memory	32KB (ATmega328) of which 0.5KB used by bootloader
SRAM	2KB (ATmega328)
EEPROM	1KB (ATmega328)
Clock Speed	16MHz
Length	68.6mm
Width	53.4mm
Weight	25g

2.9 InMoov Robot

Gaël Langevin is a French sculptor and model maker who had no real robotic engineering or Arduino experience. He started a personal project to create a life size humanoid robot called InMoov since January 2012. The InMoov robot was designed with the Open Source 3D and it is able to be printed by using any 12x12x12cm area 3D printer. Those 3D part files (.stl) are open source and they are downloadable from Gaël's website, InMoov.blogspot.com. Gaël first come out with the idea of incorporate servos and an Arduino to yield a programmable robotic hand. The hand was succeeded and able to be controlled by using keyboard and able to move at

varying speed. This project attracted Thingverse users and they start printing their own version and want to see more from Gaël. In eight months, Gaël's project had gone from a simple hand to a torso, arms, and head.

Figure 2.21: InMoov robot

The robot designed by Gaël has a moving capability just like a human. The fingers are able to move, the hand is able to twist, the elbow is able to flex and extend, and etc. Fortunately, people can make it at home because Gaël made public 3D parts of his InMoov project as non-commercial files on his website with friendly instructions, tutorial, and advice. The design of Gaël is implemented by many users in many ways like making an artificial limb, bartender that serves drinks and much more (InMoov 2015).
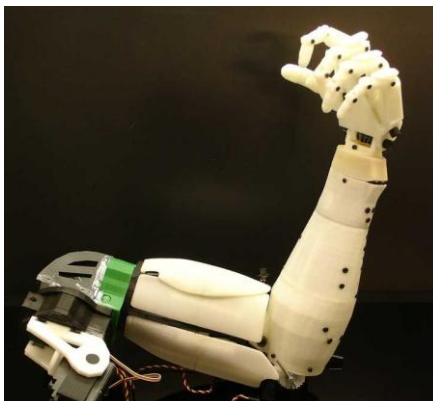
Figure 2.22: InMoov robotic arm

CHAPTER 3

METHODOLOGY

3.1   Design of the System

3.1.1   System Overview

The objective of this project is to create a BCI robotic arm that is able to make four moves (flexion and extension of elbow, and making and releasing a fist). To realize this project, a system which collects EEG signals as input and generates mechanical output is necessary. Basically, the designed system consists of five steps as shown in Figure 3.1.

Figure 3.1: Block diagram of BCI robotic arm

The first step is to sample the brain signal for specific thought from a user by using EPOC headset and Emotiv software. The robotic arm should have four moves so at least four different EEG signals should be sampled. The system is designed based on the Expressiv suite provided by Emotiv software.

After this, two Emotiv softwares: Emotiv Control Panel and EmoKey will be used to define the keystroke for each signal (George et al. 2014). The Emotiv Control Panel allows a user to create a profile and samples his/ her EEG signals while the Emokey allows user to define keystroke for each EEG signal. These keystrokes will send input to the Arduino microcontroller. In order to send commands from a personal computer to an Arduino microcontroller, a Matlab programming is necessary. Matlab is used to create a program as a medium between personal computer and Arduino. After Matlab programming is done, the Arduino microcontroller will be programmed so it can make the robotic arm move according to the keystrokes from the computer. In the end, the system should work as shown in flow chart in Figure 3.2.
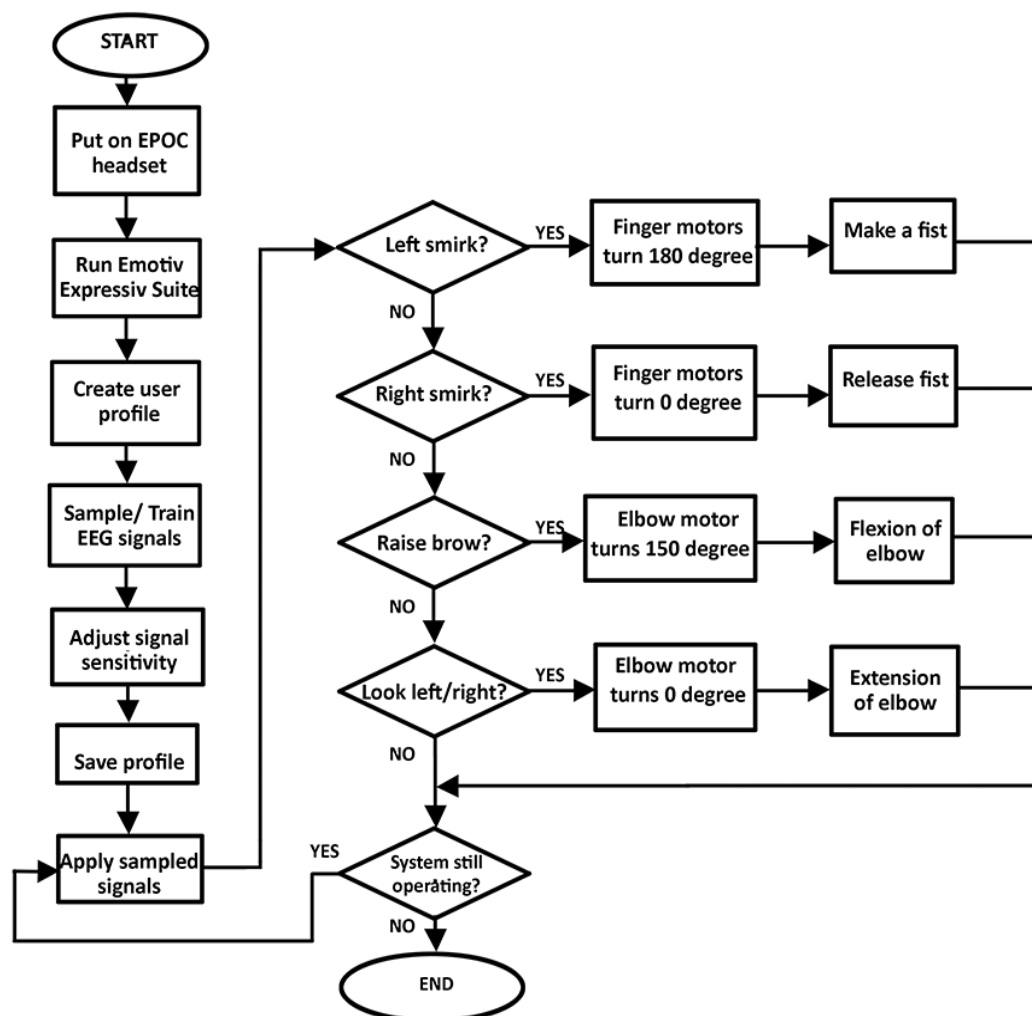
Figure 3.2: Flow chart of the BCI system

3.1.2   Sampling and Setting of EEG Signals

The Emotiv Control Panel 1.0.0.5 is a program that allows user to observes the EEG signals transmitting from a user. It also allows user to sample their EEG signals and save it for future purposes. This software provides three suits, Expressiv Suite, Affectiv Suite, and Cognitiv Suite. For this project, Expressiv Suite is chosen to control the robotic arm. To fulfill the objectives of this project, this robotic arm requires four EEG signals to drive it. The EEG signals and movements are listed in Table 3.1.

Table 3.1: List of EEG signal and the response

Signal	Movement
Left smirk	Make a fist
Right smirk	Release fist
Raise brow	Flexion of elbow
Look left/ right	Extension of elbow

The Emotiv Control Panel requires user to turn on and put on the EPOC headset and pair it with the computer otherwise this software is not able to be used if it does not detect any signal from Emotiv headset. After the headset is connected with Emotiv Control Panel, create and save a user profile so it will store all the sampled signals and settings for future use. Referring to the signals listed in Table 3.1, the left smirk, right smirk and raise brow signals have to be trained or sampled. To sample these signals, click on the 'Training' bar (Figure 3.3) on the right hand side of the software interface, select the expression to train then click on 'Start Training' and make the expression for 8 seconds. After that, click on the 'Sensitivity' bar (Figure 3.4) and adjust the sensitivity of the four signals by dragging the pointer to left or right until the accuracy is better. Save and update the user profile after everything is done.
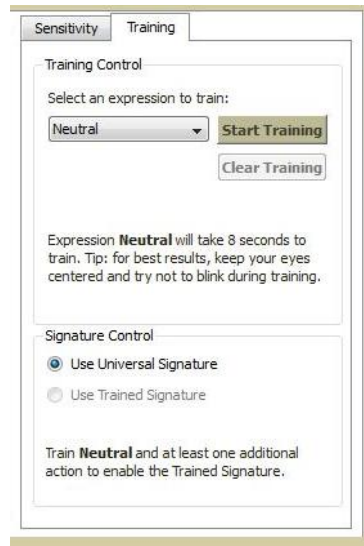
Figure 3.3: Interface of Training section
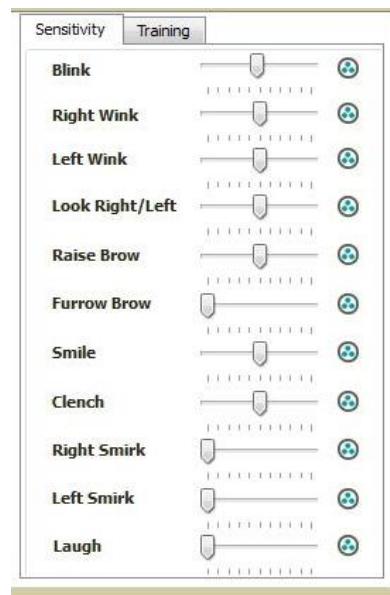
Figure 3.4: Expression signal sensitivity setting

3.1.3   Keystroke Identification

The EmoKey 1.0.0.5 can connect to either Emotiv Control Panel or EmoComposer but it will connect with Control Panel only for this project. The Control Panel must be still running and loaded with the user profile that is created in previous step. After

the EmoKey is connected to Control Panel, click the 'Add Rule' four times to add four rules. Rename the rules by double-click on the name. Again, double-click on 'Key(s)' column to define the keystroke for each response.

Next, click on one rule and add click 'Add Condition' to define a condition to triggers that rule. Double click on Action column to change the action according to the signal and response listed in Table 3.2. After that, repeat these steps until the actions of all keystrokes are defined and save this mapping. In the end, the mapping of the keystrokes should look like what Figure 3.4 shows.

Table 3.2: List of EEG signals and the response

Signal	Movement	Keystroke
Left smirk	Make a fist	1
Right smirk	Release fist	2
Raise brow	Flexion of elbow	3
Look left/ right	Extension of elbow	4
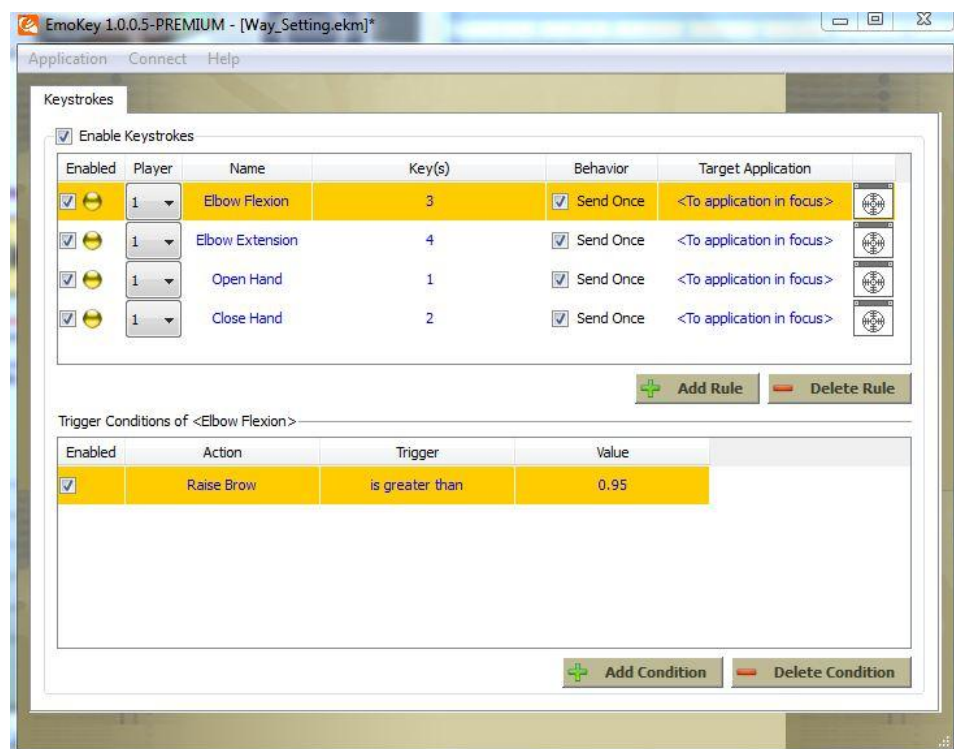
Figure 3.5: EmoKey setting

3.1.4 Interactive Program

After defining the keystrokes, user can perform some typing by using their thought with Emotiv headset which means it allows user to interact with computer. However, the computer cannot communicate with the Arduino Microcontroller directly because a medium is needed to connect both of them. To solve this problem, the Matlab software is used to create this medium.

An application (Figure 3.6) with at least four buttons (for four types of arm response) will be created and each button will be assigned into a specific hot-key. The hot-keys are the keys that are define on EmoKey. This application will be designed by using Matlab software. The design and function of the Matlab coding is shown in Figure 3.6 below. In the end, this application should be able to send input from computer to the microcontroller of the robotic arm.

Figure 3.6: Interface of MATLAB application
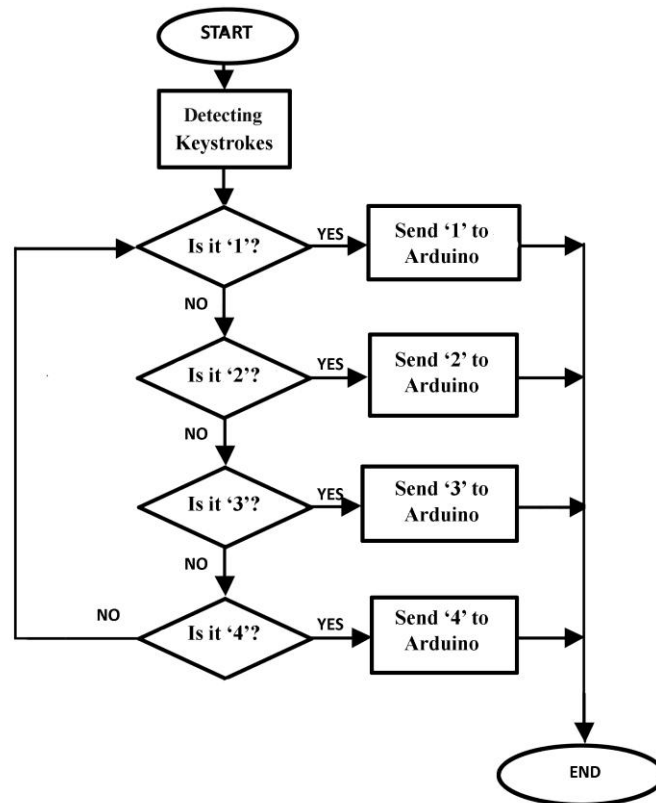
Figure 3.7: System of interactive program

3.1.5   Arduino Microcontroller

The movement of the robotic arm is drived by several servo motors and these motors are controlled by an electronic board called Arduino UNO R3. Generally, there is a microcontroller on the board and this microcontroller gives responses to all servo motors depending on the input signal. The response of the servo motors are listed in Table 3.3. In addition, this microcontroller is needed to be programmed so it can read input from computer and give output to all motors. The Arduino coding will be able to perform the process shown in Figure 3.7.

Table 3.3: Response of robotic arm

Keystroke	Action	Movement
1	Finger motors turn 180 °	Make a fist
2	Finger motors turn 0 °	Release fist
3	Elbow motor turn 150 °	Flexion of elbow
4	Elbow motor turn 0 °	Extension of elbow
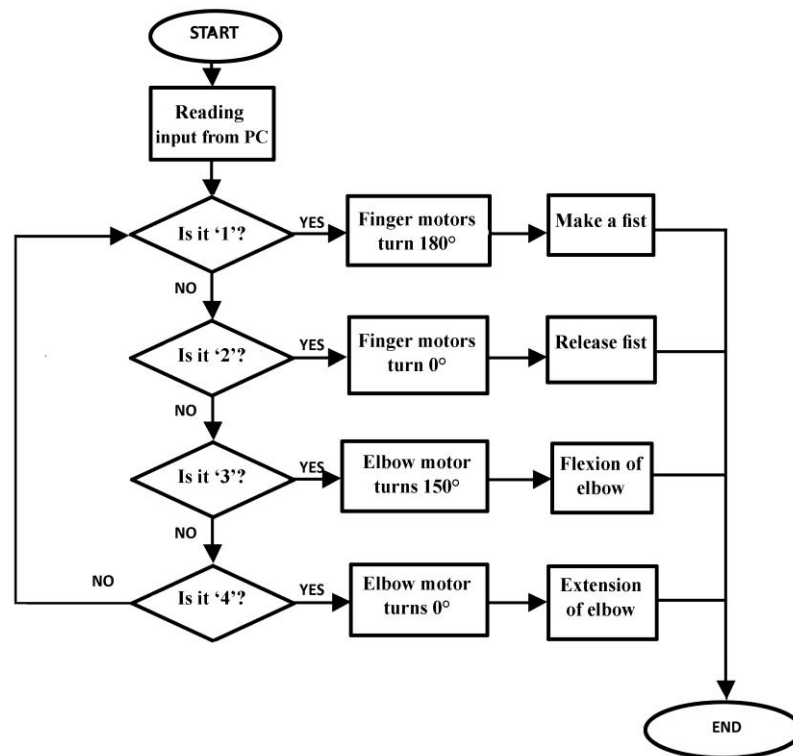
Figure 3.8: Function of Arduino microcontroller

3.1.6   Robotic Arm

The hand part of the robotic arm is printed by 3D printer based on the design of Inmoov. After the printing process and assembly, the process is followed by creating the forearm part and elbow part. The forearm and elbow is created by craft wood. Five servo motors (TowerPro SG90) were attached on the forearm wooden board and bind them with each finger of printed hand part by using fishing string. After that, the

forearm and elbow will be connected by a metal gear servo motor (RDS 3115). Last but not least, the 6V battery holder and the Arduino board will be attached on the elbow part. The Figure 3.8 shows the design of the robotic arm.
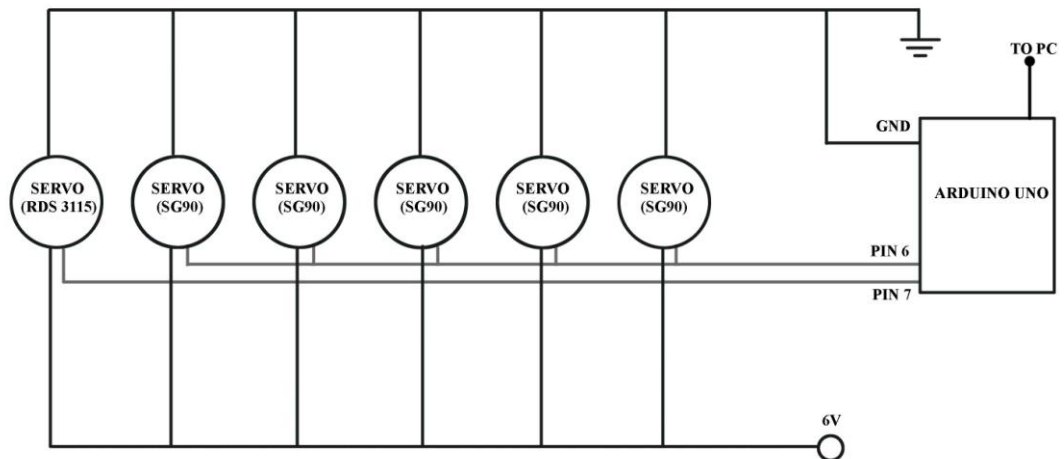
Figure 3.9: Schematic of robotic arm
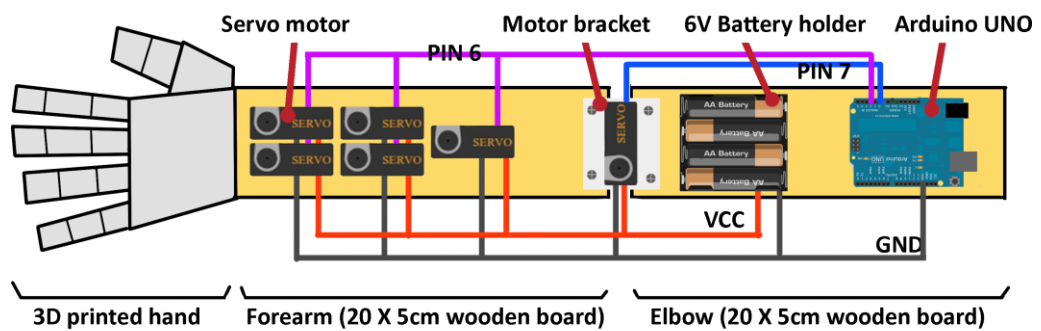
Figure 3.10: Design of robotic arm

Table 3.4: Specification of TowerPro SG90

Description	Specification
Operating Voltage	3.5 ~ 6.0V
Operating Temperature	-30 ℃ to +60 ℃
Operating Speed	0.12 sec/ 60 °
Torque	1.6kg/ cm
Dead Band Width	5 usec
Servo Dimension	23x12.2x29mm

Table 3.5: Specification of RDS 3115

Description	Specification
Operating Voltage	5 ~ 7.2V
Operating Temperature	-10 ℃ to +50 ℃
Operating Speed	0.16 sec/ 60 ° ~ 0.14 sec/ 60 °
Stall Torque (at lock)	13.5kg/ cm ~ 15kg/ cm
Dead Band Width	3 usec
Servo Dimension	40x20x40.5mm

3.2 Experiment 1: Performance of the System (Full electrodes)

The BCI system will be tested on ten subjects to review the sensitivity and accuracy of the system. Due to the malfunction of one of the electrode (AF3) of EPOC headset, all subjects are tested with thirteen electrodes only. So, any 'full set of electrode' or 'all electrode' that mentioned at following contents refer to thirteen electrodes instead of fourteen electrodes.

To determine the sensitivity and accuracy of the system, ten subjects were invited to use and test the system performance. Each subject is required to follows the following steps:

1. A short briefing is given to the subject to ensure that he/ she understands procedure fully.
2. Let the subject put on the EPOC headset with 13 electrodes.
3. Run Emotiv Control Panel and create a user profile for the subject.
4. Adjust the position by referring to the display of Emotiv Control Panel to ensure that all channels are in green condition.
5. Select Epressiv Suite from the Control Panel and let the subject trains 'Neutral' signal, followed by 'Raise Brow', 'Left Smirk', and 'Right Smirk'. The subject was advised to remain calm for the whole process.
6. Adjust the sensitivity of the signal and save the user profile after any adjustment.
7. The subject controlls the robotic arm for each move for ten times.
8. Record and analyze the data.

3.3 Reduction of Electrodes

After the BCI system is completed and tested, this project was proceeded to find out the minimum number of electrode channel that are required by this BCI system. This research is conducted by removing the electrodes one by one and observing the effect on the functionality of the system. When one electrode is removed, the system will be tested by each move for ten times and record the data to determine the accuracy. If the accuracy is above 85%, that electrode will be considered as removable electrode; if the accuracy is low, that electrode is considered important for the system. After that, put the removed electrode back and start removing another electrode for another test. This step was repeated until all electrodes had been tested.

3.4 Experiment 2: Performance of Improved System (Reduced electrodes)

The minimum number of electrodes are tested on same ten subjects again in Experiment 2 to determine and compare its' accuracy. The headset should have lesser number of electrode and all subjects requested to use it to determine the performance of the BCI. The procedure of Experiment 2 is shown as below:

1. Let the subject put on the EPOC headset with lesser electrodes.
2. Repeat same steps as in Experiment 1.

3.5   Gantt Chart

Table 3.6 Gantt chart for final year project 1

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Project proposal and selection	■	■												
Study EEG signal			■	■	■	■								
Study BCI			■	■	■	■								
Study on Emotiv EPOC			■	■	■	■								
Study and design mechanical arm					■	■	■							
Practice Emotiv sofware				■	■	■	■	■						
Items preparation						■	■	■	■	■				
Assemble robotic arm (forearm)							■	■	■	■	■			
Study Matlab and Processing Programming									■	■	■	■		
Report writing											■	■		
Presentation														■

Table 3.7: Gantt chart for final year project 2

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Deisgn interactive program	■	■	■											
Finishing robotic arm	■	■												
Troubleshooting and debugging			■	■	■	■								
Experiment 1							■	■						
Improve system								■	■					
Experiment 2									■	■				
Design Poster											■			
Report writing											■	■	■	
Presentation														■

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Data Analysis

The BCI robotic arm was tested on ten subjects and the results were collected to compute the accuracy or performance of the system. To determine the system accuracy, first we need to define the outcomes: true positive, false negative, true negative and false positive of the result. The definitions of each outcome are listed in Table 4.1.

Table 4.1: Definition of outcome

Outcome	Definition
True positive (TP)	Correct input, correct output.
False negative (FN)	Correct input, incorrect output.
True negative (TN)	Incorrect input, incorrect output.
False positive (FP)	Incorrect input, correct output.

Each subject was asked to try each action ten times, so the total number of trials will be forty. The 'correct input' means the correct expression that is required to make the robotic arm to do the desired move. To find out the value of true positive or false negative of an action, we need to refer to the result when the subject doing a correct expression for ten times. On the other hand, to find out the value of true negative and false positive of an action, we refer to the results generated by other

three actions which results from the rest thirty trials. Table 4.2 shows the result recorded from Subject 1 while Table 4.3 shows the analyzed outcome of Subject 1.

Table 4.2: Result of Subject 1

Input		Output			
No.	Expression	Elbow Flexion	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O		O	
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look Left/Right		O		
12	Look Left/Right		O		
13	Look Left/Right				O
14	Look Left/Right		O		
15	Look Left/Right		O		
16	Look Left/Right		O		
17	Look Left/Right		O		O
18	Look Left/Right		O		
19	Look Left/Right		O		
20	Look Left/Right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	

26	Left Smirk			O	
27	Left Smirk				O
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table 4.3: Outcomes of Subject 1

Action	TP	FN	TN	FP
Elbow Flexion	9/10	1/10	30/30	0/30
Elbow Extension	8/10	2/10	30/30	0/30
Close Hand	9/10	1/10	29/30	1/30
Open Hand	10/10	0/10	27/30	3/30

After the outcomes are defined, we can determine the sensitivity, specificity, and accuracy as well. The sensitivity is also known as true positive rate, it refers to the measure of the proportion of positives that are defined correctly while the specificity, also known as true negative rate refers to the measure of the proportion of negatives that are defined correctly. Basically, the accuracy defines the performance of the BCI robotic arm of the project. The formulae of sensitivity, specificity, and accuracy are shown in Table 4.4.

Table 4.4: Formulae for calculation

Outcome	Formula
Sensitivity	$$\frac{\text{Number of True Positive, TP}}{\text{Number of True Positive, TP} + \text{Number of False Negative, FN}}$$
Specificity	$$\frac{\text{Number of True Negative, TN}}{\text{Number of True Negative, TN} + \text{Number of False Positive, FP}}$$
Accuracy	$$\frac{TP + TN}{TP + FN + TN + FP}$$

4.2 Result of Experiment 1 (Thirteen Electrodes)

In the first experiment, ten subjects were requested to put on an EPOC with thirteen working channels (see Figure 4.1). The outcomes of the result, sensitivities, specificities, and accuracies of all subjects are shown in tables below.
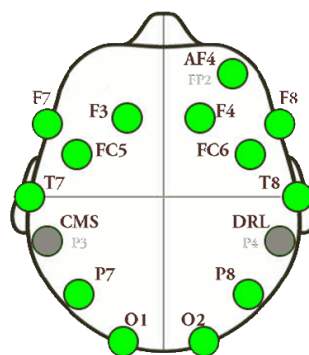
Figure 4.1: Mapping of 13 electrodes

Table 4.5: Result of Subject 1

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	30/30	0/30	0.9	1.000	0.950

Elbow Extension	8/10	2/10	30/30	0/30	0.8	1.000	0.900
Close Hand	9/10	1/10	29/30	1/30	0.9	0.967	0.900
Open Hand	10/10	0/10	27/30	3/30	1.0	0.900	0.950

Table 4.6: Result of Subject 2

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.000	1.000
Elbow Extension	8/10	2/10	28/30	2/30	0.8	0.933	0.867
Close Hand	10/10	0/10	29/30	1/30	1.0	0.967	0.983
Open Hand	10/10	0/10	30/30	0/30	1.0	1.000	1.000

Table 4.7: Result of Subject 3

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.000	1.000
Elbow Extension	10/10	0/10	30/30	0/30	1.0	1.000	1.000
Close Hand	9/10	1/10	30/30	0/30	0.9	1.000	0.950
Open Hand	10/10	0/10	30/30	0/30	1.0	1.000	1.000

Table 4.8: Result of Subject 4

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	30/30	0/30	0.9	1.000	0.950
Elbow Extension	9/10	1/10	29/30	1/30	0.9	0.967	0.933
Close Hand	9/10	1/10	29/30	1/30	0.9	0.967	0.933
Open Hand	8/10	2/10	29/30	1/30	0.8	0.967	0.883

Table 4.9: Result of Subject 5

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	30/30	0/30	0.9	1.000	0.950

Elbow Extension	8/10	2/10	29/30	1/30	0.8	0.967	0.883
Close Hand	10/10	0/10	30/30	0/30	1.0	1.000	1.000
Open Hand	8/10	2/10	30/30	0/30	0.8	1.000	0.900

Table 4.10: Result of Subject 6

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	29/30	1/30	1.0	0.967	0.983
Elbow Extension	9/10	1/10	29/30	1/30	0.9	0.967	0.933
Close Hand	10/10	0/10	30/30	0/30	1.0	1.000	1.000
Open Hand	9/10	1/10	30/30	0/30	0.9	1.000	0.950

Table 4.11: Result of Subject 7

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	30/30	0/30	0.9	1.000	0.950
Elbow Extension	9/10	1/10	27/30	3/30	0.9	0.900	0.900
Close Hand	10/10	0/10	29/30	1/30	1.0	0.967	0.983
Open Hand	10/10	0/10	30/30	0/30	1.0	1.000	1.000

Table 4.12: Result of Subject 8

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.000	1.000
Elbow Extension	8/10	2/10	29/30	1/30	0.8	0.967	0.883
Close Hand	9/10	1/10	30/30	0/30	0.9	1.000	0.950
Open Hand	9/10	1/10	29/30	1/30	0.9	0.967	0.933

Table 4.13: Result of Subject 9

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	29/30	1/30	0.9	0.967	0.933

Elbow Extension	8/10	2/10	28/30	2/30	0.8	0.933	0.867
Close Hand	9/10	1/10	29/30	1/30	0.9	0.967	0.933
Open Hand	10/10	0/10	30/30	0/30	1.0	1.000	1.000

Table 4.14: Result of Subject 10

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	30/30	0/30	0.9	1.000	0.950
Elbow Extension	8/10	2/10	27/30	3/30	0.8	0.900	0.850
Close Hand	10/10	0/10	29/30	1/30	1.0	0.967	0.983
Open Hand	9/10	1/10	30/30	0/30	0.9	1.000	0.950

Table 4.15: Summarized and average accuracy of subjects

Subject	Accuracy				
Number	Elbow Flexion	Elbow Extension	Close Hand	Open Hand	Average
1	0.950	0.900	0.900	0.950	0.925
2	1.000	0.867	0.983	1.000	0.963
3	1.000	1.000	0.950	1.000	0.988
4	0.950	0.933	0.933	0.883	0.925
5	0.950	0.883	1.000	0.900	0.933
6	0.983	0.983	1.000	0.950	0.979
7	0.950	0.900	0.983	1.000	0.958
8	1.000	0.883	0.950	0.933	0.942
9	0.933	0.867	0.933	1.000	0.933
10	0.950	0.850	0.983	0.950	0.933
Average	0.967	0.907	0.962	0.957	0.948
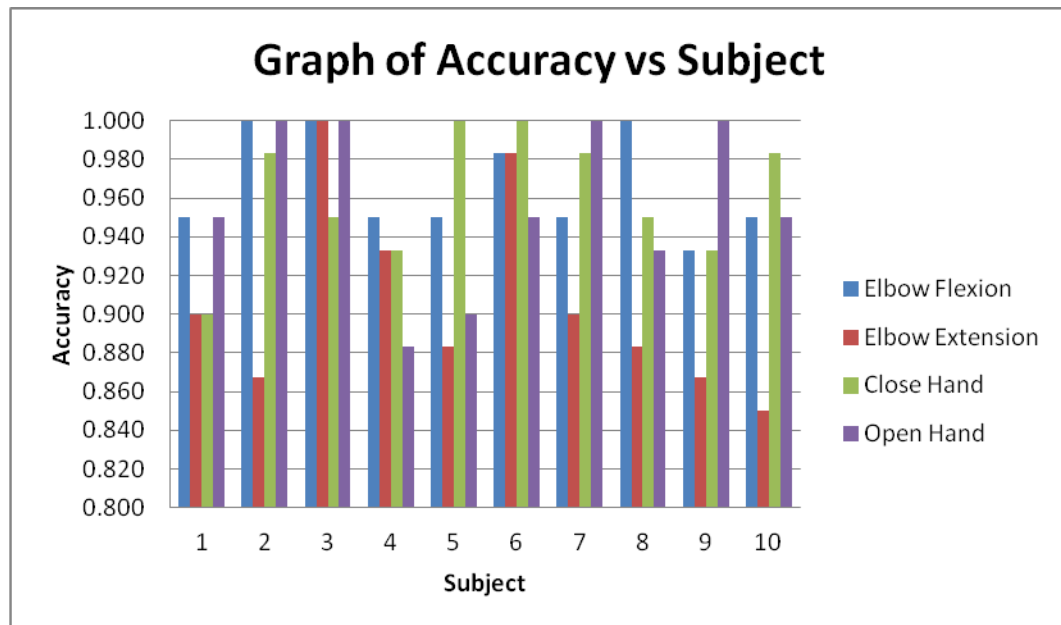
Figure 4.2: Graph of Accuracy vs Subject
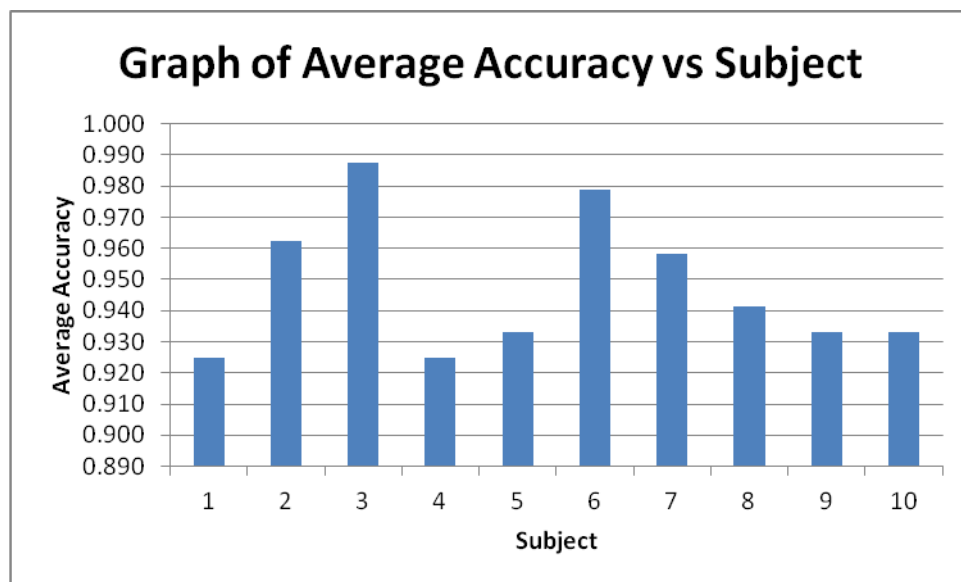
Figure 4.3: Graph of Average Accuracy vs Subject
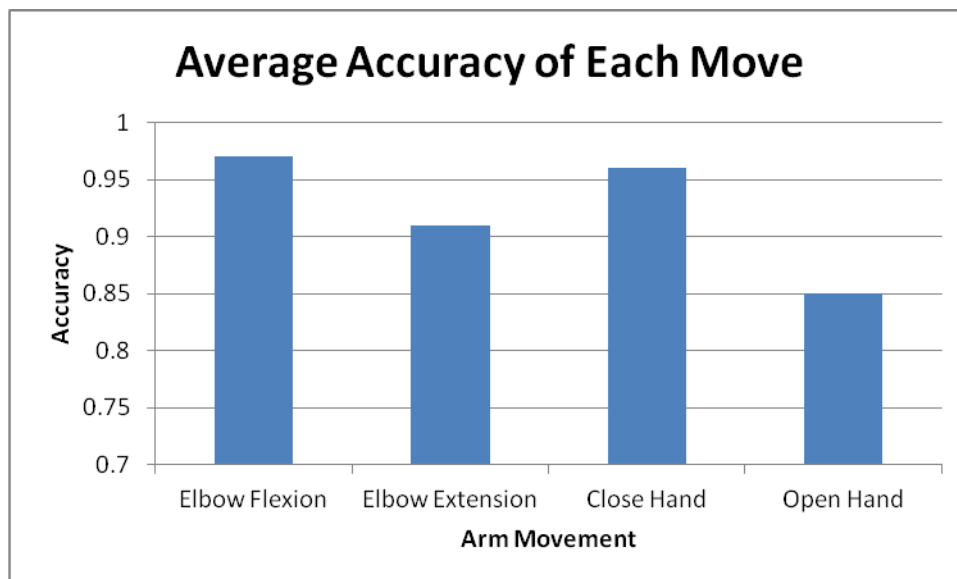
Figure 4.4: Graph of Average Accuracy of Each Move

Figure 4.2 shows that the minimum accuracy found among ten subjects is 0.85 which occurred for elbow extension of one subject (Subject 10) only while the rest accuracies are above 0.85. In addition, there are some possible factors that might affect the accuracy especially the emotion of the subject. Sometimes some subjects get nervous when they cannot get correct arm move and some subjects may feel irritated because each experiment consumes more than 30 minutes to finish. However, when we look at the average accuracy in Figure 4.3, we can observe that all average accuracies are above 92% and the overall accuracy ca;culated from ten subjects is 94.8%. By referring to the analyzed data, the performance of the BCI robotic arm is considered very good.

4.3 Determine the Minimum Number of Electrodes Required

In the previous experiment, ten subjects were tested by using an EPOC headset that has thirteen working electrodes. After the experimental result is found satisfying, this project is then proceeded to determine the minimum number of electrodes that were

required by this system. To determine it, I removed one electrode from the EPOC and observed the performance of the system. After the observation is done, assemble back the removed electrode and remove another electrode then observe the performance again. Repeat this step until all electrodes are tested and observed. The observations on all electrodes are show in Table 4.17 to 4.19. The whole progress is done on one subject (myself) only.

Table 4.16: Result when F3 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	29/30	1/30	0.9	0.9670	0.933
Elbow Extension	7/10	3/10	30/30	0/30	0.7	1.0000	0.850
Close Hand	10/10	0/10	29/30	1/30	1.0	0.9670	0.983
Open Hand	8/10	2/10	27/30	3/30	0.8	0.9000	0.850

Table 4.17: Result when FC5 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.0000	1.000
Elbow Extension	7/10	3/10	30/30	0/30	0.7	1.0000	0.850
Close Hand	10/10	0/10	28/30	2/30	1.0	0.9330	0.967
Open Hand	10/10	0/10	30/30	0/30	1.0	1.0000	1.000

Table 4.18: Result when F4 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.0000	1.000
Elbow Extension	8/10	2/10	30/30	0/30	0.8	1.0000	0.900
Close Hand	9/10	1/10	27/30	3/30	0.9	0.9000	0.900
Open Hand	10/10	0/10	29/30	1/30	1.0	0.9670	0.983

Table 4.19: Result when FC6 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.0000	1.000
Elbow Extension	8/10	2/10	30/30	0/30	0.8	1.0000	0.900
Close Hand	9/10	1/10	27/30	3/30	0.9	0.9000	0.900
Open Hand	10/10	0/10	29/30	1/30	1.0	0.9670	0.983

Table 4.20: Result when O2 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	30/30	0/30	0.9	1.0000	0.950
Elbow Extension	7/10	3/10	30/30	0/30	0.7	1.0000	0.850
Close Hand	9/10	1/10	26/30	4/30	0.9	0.8670	0.883
Open Hand	10/10	0/10	29/30	1/30	1.0	0.9670	0.983

Table 4.21: Result when O1 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.0000	1.000
Elbow Extension	8/10	2/10	30/30	0/30	0.8	1.0000	0.900
Close Hand	10/10	0/10	27/30	3/30	1.0	0.9000	0.950
Open Hand	9/10	1/10	30/30	0/30	0.9	1.0000	0.950

Table 4.22: Result when P7 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.0000	1.000
Elbow Extension	9/10	1/10	30/30	0/30	0.9	1.0000	0.950
Close Hand	1/10	9/10	29/30	1/30	0.1	0.9670	**0.533**
Open Hand	0/10	10/10	30/30	0/30	0.0	1.0000	**0.500**

Table 4.23: Result when P8 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.0000	1.000
Elbow Extension	8/10	2/10	30/30	0/30	0.8	1.0000	0.900
Close Hand	4/10	6/10	29/30	1/30	0.4	0.9670	**0.683**
Open Hand	2/10	8/10	30/30	0/30	0.2	1.0000	**0.600**

Table 4.24: Result when T8 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	3/10	7/10	28/30	2/30	0.3	0.9330	**0.617**
Elbow Extension	4/10	6/10	28/30	2/30	0.4	0.9330	**0.667**
Close Hand	8/10	2/10	28/30	2/30	0.8	0.9330	0.867
Open Hand	7/10	3/10	23/30	7/30	0.7	0.7670	**0.733**

Table 4.25: Result when F7 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	8/10	2/10	30/30	0/30	0.8	1.0000	0.900
Elbow Extension	0/10	10/10	30/30	0/30	0.0	1.0000	**0.500**
Close Hand	0/10	10/10	30/30	0/30	0.0	1.0000	**0.500**
Open Hand	0/10	10/10	28/30	2/30	0.0	0.9330	**0.467**

Table 4.26: Result when F8 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	8/10	2/10	29/30	1/30	0.8	0.9670	0.883
Elbow Extension	8/10	2/10	29/30	1/30	0.8	0.9670	0.883
Close Hand	10/10	0/10	29/30	1/30	1.0	0.9670	0.983
Open Hand	0/10	10/10	30/30	0/30	0.0	1.0000	**0.500**

Table 4.27: Result when T7 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.0000	1.000
Elbow Extension	5/10	5/10	30/30	0/30	0.5	1.0000	**0.750**
Close Hand	8/10	2/10	28/30	2/30	0.8	0.9330	0.867
Open Hand	0/10	10/10	30/30	0/30	0.0	1.0000	**0.500**

Table 4.28: Result when AF4 removed

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	0/10	10/10	30/30	0/30	0.0	1.0000	**0.500**
Elbow Extension	7/10	3/10	30/30	0/30	0.7	1.0000	0.850
Close Hand	9/10	1/10	27/30	3/30	0.9	0.9000	0.900
Open Hand	9/10	1/10	26/30	4/30	0.9	0.8670	0.883
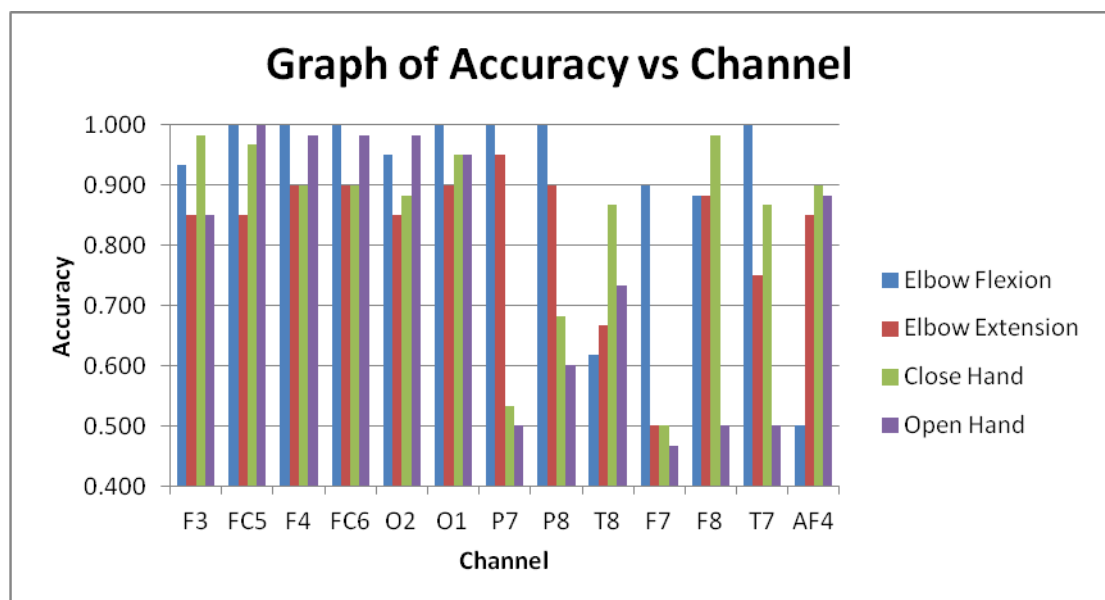
Figure 4.5: Graph of Accuracy vs Channel

By referring to the minimum accuracy achieved by previous experiment, any electrode that has achieved accuracy below 0.85 when it is removed is considered as important electrode. While the electrodes that still have high accuracy of performance are considered as removable electrodes. In the end, there are six removable electrodes and the minimum number of electrodes that are required by this project is seven. The Figure 4.6 visualizes the status of each electrode.
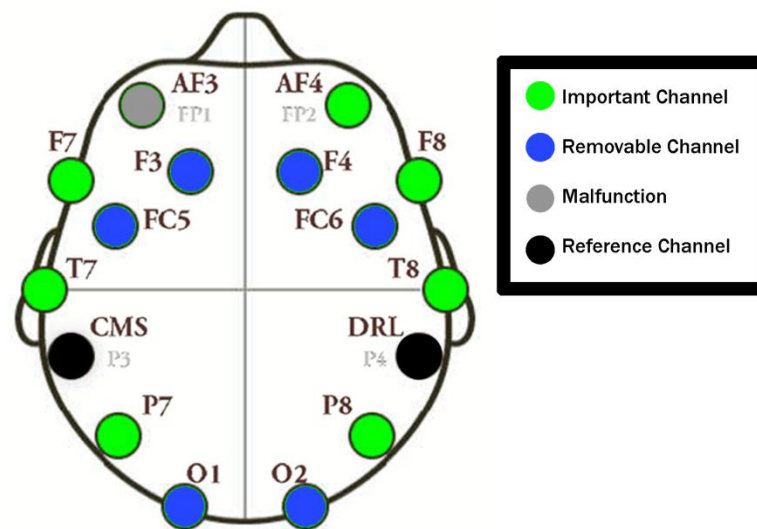
Figure 4.6: Status of each electrode or channel

4.4 Result of Experiment 2 (With seven Electrodes)

When the minimum number of electrodes are determined, the performance of the BCI robotic arm using seven electrodes (See Figure 4.7) is tested on same ten subjects. Same procedure as previous experiment except the EPOC headset has seven working electrodes only. The accuracies from all subjects are listed in following Table 4.30 to 4.39 and summarized in Table 4.40.
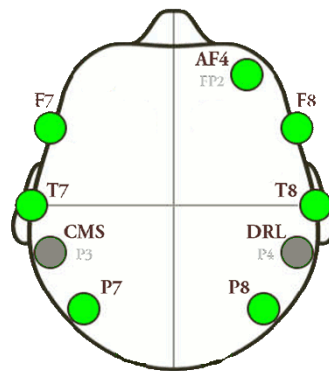
Figure 4.7: Mapping of 7 electrodes

Table 4.29: Result of Subject 1

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1	1.000	1.000
Elbow Extension	7/10	3/10	30/30	0/30	0.7	1.000	0.950
Close Hand	10/10	0/10	28/30	2/30	1	0.933	0.967
Open Hand	10/10	0/10	30/30	0/30	1	1.000	1.000

Table 4.30: Result of Subject 2

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	8/10	2/10	30/30	0/30	0.8	1.000	0.900
Elbow Extension	9/10	1/10	30/30	0/30	0.9	1.000	0.950
Close Hand	7/10	3/10	29/30	3/30	0.7	0.967	0.833
Open Hand	10/10	0/10	26/30	4/30	1	0.867	0.933

Table 4.31: Result of Subject 3

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	30/30	0/30	0.9	1.000	0.950
Elbow Extension	7/10	3/10	30/30	0/30	0.7	1.000	0.850
Close Hand	10/10	0/10	26/30	4/30	1	0.867	0.933
Open Hand	10/10	0/10	29/30	1/30	1	0.967	0.983

Table 4.32: Result of Subject 4

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	8/10	2/10	30/30	0/30	0.8	1.000	0.900
Elbow Extension	9/10	1/10	29/30	1/30	0.9	0.967	0.933
Close Hand	10/10	0/10	27/30	3/30	1	0.900	0.950
Open Hand	10/10	0/10	30/30	0/30	1	1.000	1.000

Table 4.33: Result of Subject 5

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1.0	1.0000	1.000
Elbow Extension	8/10	2/10	30/30	0/30	0.8	1.0000	0.900
Close Hand	10/10	0/10	27/30	3/30	1.0	0.9000	0.950
Open Hand	9/10	1/10	30/30	0/30	0.9	1.0000	0.950

Table 4.34: Result of Subject 6

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	30/30	0/30	0.9	1.000	0.950
Elbow Extension	8/10	2/10	30/30	0/30	0.8	1.000	0.900
Close Hand	10/10	0/10	29/30	1/30	1	0.967	0.983
Open Hand	10/10	0/10	30/30	0/30	1	1.000	1.000

Table 4.35: Result of Subject 7

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	30/30	0/30	1	1.000	1.000
Elbow Extension	7/10	3/10	29/30	1/30	0.7	0.967	0.933
Close Hand	9/10	1/10	28/30	2/30	0.9	0.933	0.917
Open Hand	10/10	0/10	30/30	0/30	1	1.000	1.000

Table 4.36: Result of Subject 8

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	8/10	2/10	30/30	0/30	0.8	1.000	0.900
Elbow Extension	8/10	2/10	30/30	0/30	0.8	1.000	0.900
Close Hand	9/10	1/10	30/30	0/30	0.9	1.000	0.950
Open Hand	9/10	1/10	30/30	0/30	0.9	1.000	0.950

Table 4.37: Result of Subject 9

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	9/10	1/10	30/30	0/30	0.9	1.000	0.950
Elbow Extension	9/10	1/10	28/30	2/30	0.9	0.933	0.917
Close Hand	10/10	0/10	27/30	3/30	1	0.900	0.950
Open Hand	10/10	0/10	30/30	0/30	1	1.000	1.000

Table 4.38: Result of Subject 10

Action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Elbow Flexion	10/10	0/10	29/30	1/30	1	0.967	0.983
Elbow Extension	8/10	2/10	27/30	3/30	0.8	0.900	0.850
Close Hand	9/10	1/10	29/30	1/30	0.9	0.967	0.933
Open Hand	10/10	0/10	30/30	0/30	1	1.000	1.000

Table 4.39: Accuracies of all subjects

Subject	Accuracy				
Number	Elbow Flexion	Elbow Extension	Close Hand	Open Hand	Average
1	0.950	0.900	0.983	1.000	0.958
2	0.900	0.950	0.833	0.933	0.904
3	0.950	0.850	0.933	0.983	0.929
4	0.900	0.933	0.950	1.000	0.946
5	1.000	0.900	0.950	0.950	0.950
6	1.000	0.950	0.967	1.000	0.979
7	1.000	0.933	0.917	1.000	0.963
8	0.900	0.900	0.950	0.950	0.925
9	0.950	0.917	0.950	1.000	0.954
10	0.983	0.850	0.933	1.000	0.942
Average	0.953	0.908	0.937	0.982	0.945
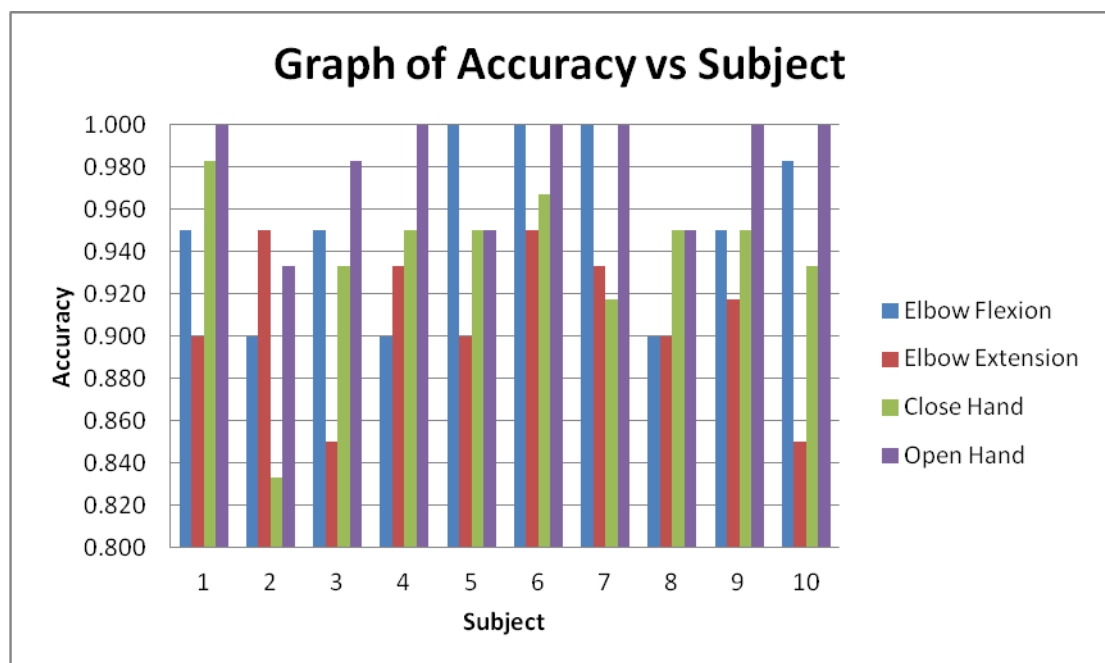
Figure 4.8: Graph of Accuracy vs Subject
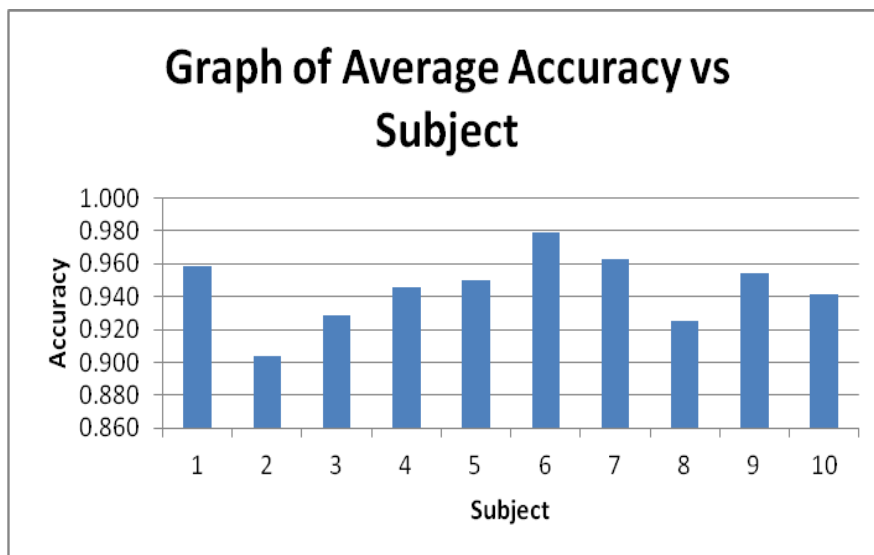
Figure 4.9: Graph of Average Accuracy vs Subject
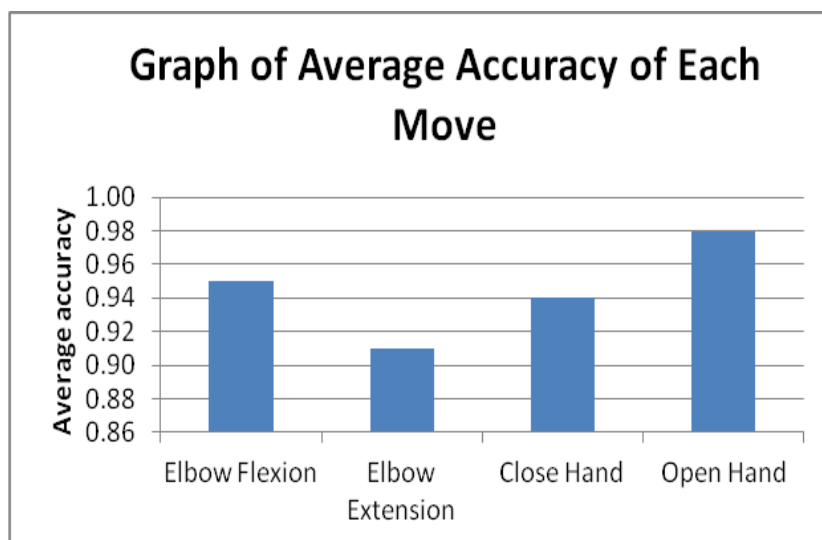
Figure 4.10: Graph of Average Accuracy of Each Move

Table 4.40: Percentage difference between both results

Subject	Average Accuracy		Percentage
Number	Experiment 1	Experiment 2	Difference (%)
1	0.925	0.958	-1.75
2	0.963	0.904	6.32
3	0.988	0.929	6.16
4	0.925	0.946	-2.24
5	0.933	0.950	-1.81
6	0.979	0.979	0.00
7	0.958	0.963	-0.52
8	0.942	0.925	1.82
9	0.933	0.954	-2.23
10	0.933	0.942	-0.96
Average	0.948	0.945	0.48

From Table 4.40, we can observe that the lowest accuracy achieved is 0.833 which is slightly lower but it happened once among all subjects. The average accuracies are above 90% while overall average accuracy is 94.5%. By comparing the results of Experiment 1 and Experiment 2, there are two subjects have percentage difference that exceeded 6% while the others have very low difference. So the performance of the system using seven electrodes only is considered very good.

4.5   Problems Encountered

4.5.1   Malfunction of EPOC Headset

An EPOC headset has sixteen electrodes, two are used as reference points while the rest fourteen are used to receive EEG signals. Unfortunately, one of the fourteen electrodes of EPOC used in this project is broken which is AF3. Without the EEG signal from AF3, it limited the functionality of the system. The malfunction headset having difficulty to detect some signals like eye blinking, left winking and some signal recognition. In short, the malfunction of channel AF3 does affect the EEG signal recognition.

4.5.2   Problems from Subjects

During data acquisition, there were some difficulties when I tried to get the result from Experiment 1 and Experiment 2. The first problem encountered in the experiment is to try to position the electrodes on subject head. Because every subject head shape is different, it is difficult to try to get all electrodes on right position. Some subjects have to use their hand to hold some electrodes on right position for whole experiment. Moreover, trying to get electrodes on right position is very time consuming, it took at least 15 minutes to make all electrodes to achieve green condition. Furthermore, we took at least 20 minutes from training phase to the end of the experiment. The whole process is very tedious. In addition, the subjects start feeling uncomfortable and ache when the EPOC clamped their head too long. All of these situations could affect the emotion of the subject and generate some EEG noise signal as well. In short, the performance of the BCI system is fully depending on the subject's mind situation.

4.6   Alternate Method to Apply EEG on BCI System

4.6.1   Control BCI by Thought

Instead of using facial expression to control the BCI system, there is one more ideal way to control the system which is using human thought. To realize this method, I tried to use the Cognitiv Suite provided by Emotiv Control Panel. Again, the system required user to train and record four signals to control the BCI robotic arm. The signals and its' outputs are listed in Table 4.43.

Table 4.41: Response of robotic arm

Cognitiv action	Movement
Push	Make a fist
Pull	Release fist
Left	Flexion of elbow
Right	Extension of elbow

This method was tested on two subjects with two moves only but the result did not go well. In addition, the difficulty of controlling will increase if the number of moves ares higher. So, this method is abandoned since the result is bad as shown in Table 4.44 and Table 4.45. The reason of the result is bad is probably due to the malfunction of one electrode channel which was mentioned before. Furthermore, there is a possibility that the subject having problem to maintain same thought as the EEG signal recorded during training phase and need a longer time to do training.

Table 4.42: Result from subject 1

Cognitiv action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Push	2/10	8/10	6/10	4/10	0.2	0.6	0.40
Pull	1/10	9/10	8/10	2/10	0.1	0.8	0.45

Table 4.43: Result from subject 2

Cognitiv action	TP	FN	TN	FP	Sensitivity	Specificity	Accuracy
Push	4/10	6/10	8/10	4/10	0.4	0.8	0.60
Pull	1/10	9/10	3/10	2/10	0.1	0.3	0.20
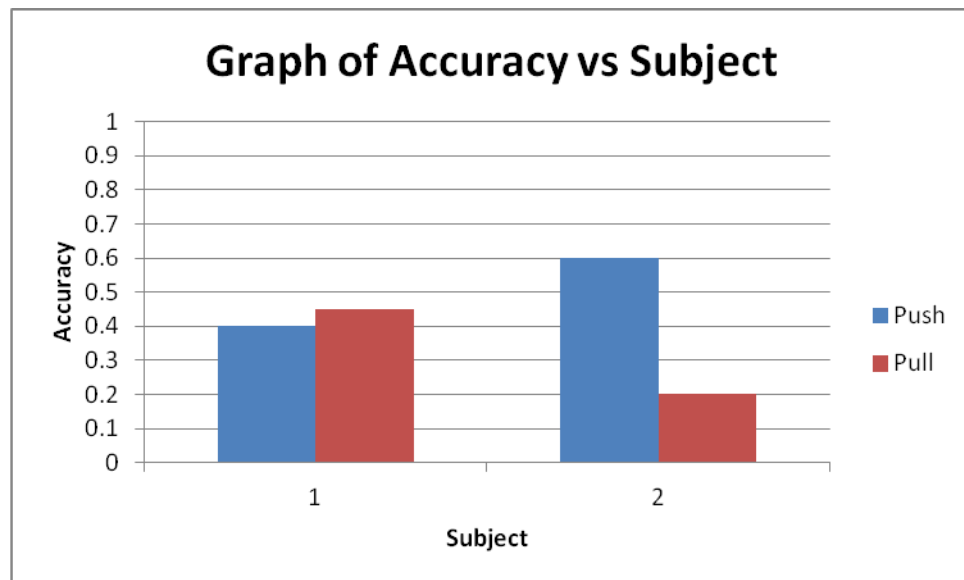
Figure 4.11: Graph of Accuracy vs Subject

4.6.2 Malfunction of EPOC Headset

Besides using Emotiv software, I studied the application of P300 which is another method to apply EEG signal on BCI device. To study the application of P300, a software called OpenVibe is used. The application of P300 requires assistance from P300 Speller which is provided by OpenVibe. The P300 Speller shows a matrix that consists of text and symbol, it can detect the text or symbol that the EPOC headset user is focusing on.

This method is tested on two subjects three times but the accuracy is 0. This might be due to the wrong setting I did on OpenVibe. However, there are some reasons that P300 is not encouraged to apply on some BCI system like prosthetic limbs. In current days, most of the application of P300 is relying on P300 speller, the

user has to focus on a letter or symbol on a screen for a period to detect what is in the user mind. This leads to response time problem. Furthermore, the P300 speller required a screen to display it which is not very convenient and not suitable for BCI prosthetic limbs.
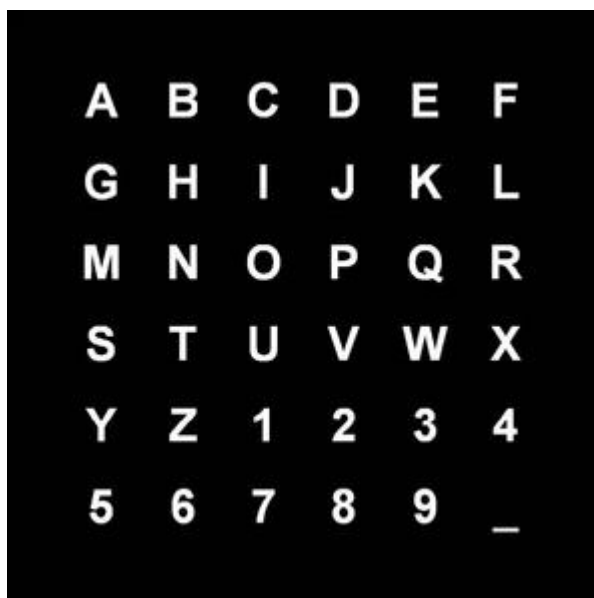
Figure 4.12: P300 Speller

Moreover, the electrode channels provided by EPOC headset are limited. Some central electrodes are important for P300 which are not provided by EPOC, this would lead to bad performance (Duvinage, 2013). In conclusion, P300 is avoided for this project.

4.7 Limitation of the System

The EEG signal is a very complicated signal, every single action, emotion and emotion will affect the signal. The performance of the BCI system is fully relied on the user mental state. Any strong emotion or unnecessary move would lower down the performance of BCI system. In short, the performance of the BCI system is depending on the mind of the user, user must keep their mind calm in order to achieve best performance.

In this project, the created BCI robotic arm is controlled by facial expression and this formed a limitation for the system. If the user made some unnecessary expression, it would give wrong signal to the robotic arm like when the user smile, the system might detects it as right smirk or left smirk. Thus, the arm will move even the user do not have the intention.

Last but not least, the designed robotic arm is not dexterous if compare to human arm. The robotic arm is able to make four moves (open hand, close hand, elbow flexion and extension) but the hand is not able make different pose or twist and the elbow is able to move to either position $0\,^\circ$ or $150\,^\circ$ only. If we want to enhance the mobility of the arm, the difficulty to control the arm will be higher and the cost will increase as well.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1   Conclusion

In this project, a BCI robotic arm that can be controlled by EEG signal is designed and developed successfully. An Emotiv EPOC headset was used to detect and collect the EEG signal. To ensure the performance of the BCI robotic arm is good, we decided to use EEG signal of facial expression to control the robotic arm instead of using cognitive action. The proposed robotic arm is able to make four moves (make a fist, release fist, extension and flexion of elbow), so four distinct EEG signals are required for doing each move. The four EEG signals (left smirk, right smirk, raise brow, and look left/ right) are sampled or trained by using Expressiv Suite that provided by Emotiv software.

The robotic arm for this project consists of three parts; hand, forearm and elbow. The hand part has many joints, it was printed by using 3D printer based on the hand design from Inmoov project. In order to reduce the cost of this project, the forearm and elbow part were built by using wooden board. Six servo motors were attached on forearm part to make the robotic arm move. While the power supply and Arduino board were attached on the elbow part.

After the robotic arm is created, it was tested on ten subjects to determine its' performance. From the experimental result, the overall accuracy of the system is 94.8%. The result was found satisfying, so we proceeded to investigate and determine the minimum number of electrodes required by this system. By the end of

the research, the number of electrodes were reduced to seven. The improved system was tested on same ten subjects to determine the performance. The overall accuracy of the system with reduced electrode is 94.5% which is almost the same as previous result. Hence, the system is able to function well by using seven electrodes only.

5.2 Recommendations

The robotic arm created in this project is controlled by facial expression which is a not very ideal method. The ideal way to control the artificial limbs is using thought or imagination without making any physical movement. To enhance this system into an ideal system, a deeper research on cognitive neuroscience is necessary especially for the motor imagery (Szachewicz, 2013). For the ability of the developed robotic arm, the movement is limited. To increase the mobility of the arm, more complicated arm design and more distinct EEG signal for each movement are needed.

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APPENDICES

APPENDIX A: Result of Experiment 1 (10 subjects)

The raw results collected in Experiment 1 are show in following pages (Table A.1 to A10).

Table A.1: Result of Subject 1

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O		O	
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right				O
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right		O		
17	Look left/ right		O		O
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk				O
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table A.2: Result of Subject 2

No.	Expression	Input	Output		
		Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O	O	
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right		O	O	
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	O
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table A.3: Result of Subject 3

No.	Expression	Input	Output		
		Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk				
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table A.4: Result of Subject 4

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow				
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O	O	
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk				O
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk		O		O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				
39	Right Smirk				O
40	Right Smirk				O

Table A.5: Result of Subject 5

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O	O		
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right				
16	Look left/ right				
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				
39	Right Smirk				O
40	Right Smirk				O

Table A.6: Result of Subject 6

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O	O		
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right	O			
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				

Table A.7: Result of Subject 7

No.	Expression	Input Elbow Extension	Output Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O	O		
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right			O	
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table A.8: Result of Subject 8

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right				
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right				
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	O
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk		O		O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table A.9: Result of Subject 9

No.	Expression	Input Elbow Extension	Output Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O	O		
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right	O	O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right		O		
17	Look left/ right			O	
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk		O	O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table A.10: Result of Subject 10

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O	O		
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right			O	
16	Look left/ right				
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk		O		O
40	Right Smirk				O

APPENDIX B: Result of Experiment 2 (10 subjects)

The raw results collected in Experiment 2 are show in following pages (Table B.1 to B.10).

Table B.1: Result of Subject 1

No.	Expression	Input	Output		
		Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right				
14	Look left/ right		O		
15	Look left/ right			O	
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O	O	
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table B.2: Result of Subject 2

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			O
7	Raise Brow	O			O
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right			O	
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk				
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	O
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	O
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table B.3: Result of Subject 3

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O		O	
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right			O	
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right			O	O
17	Look left/ right		O	O	
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table B.4: Result of Subject 4

No.	Input Expression	Output Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow		O	O	
8	Raise Brow	O		O	
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right		O	O	
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table B.5: Result of Subject 5

No.	Input Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
	Input	Output			
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right			O	
16	Look left/ right		O		
17	Look left/ right			O	
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk			O	
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table B.6: Result of Subject 6

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow				
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O	O	
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right				
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table B.7: Result of Subject 7

No.	Expression	Input	Output		
		Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right			O	
13	Look left/ right				
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O	O	
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk		O	O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table B.8: Result of Subject 8

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow				
6	Raise Brow	O			
7	Raise Brow				
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right				
15	Look left/ right		O		
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right				
21	Left Smirk				
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

Table B.9: Result of Subject 9

	Input	Output			
No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O	O		
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right		O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right		O		
16	Look left/ right			O	
17	Look left/ right		O	O	
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk			O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

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Table B.10: Result of Subject 10

No.	Expression	Elbow Extension	Elbow Extension	Close Hand	Open Hand
1	Raise Brow	O			
2	Raise Brow	O			
3	Raise Brow	O			
4	Raise Brow	O			
5	Raise Brow	O			
6	Raise Brow	O			
7	Raise Brow	O			
8	Raise Brow	O			
9	Raise Brow	O			
10	Raise Brow	O			
11	Look left/ right	O	O		
12	Look left/ right		O		
13	Look left/ right		O		
14	Look left/ right		O		
15	Look left/ right		O	O	
16	Look left/ right		O		
17	Look left/ right		O		
18	Look left/ right		O		
19	Look left/ right		O		
20	Look left/ right		O		
21	Left Smirk			O	
22	Left Smirk			O	
23	Left Smirk			O	
24	Left Smirk			O	
25	Left Smirk			O	
26	Left Smirk			O	
27	Left Smirk			O	
28	Left Smirk		O	O	
29	Left Smirk			O	
30	Left Smirk			O	
31	Right Smirk				O
32	Right Smirk				O
33	Right Smirk				O
34	Right Smirk				O
35	Right Smirk				O
36	Right Smirk				O
37	Right Smirk				O
38	Right Smirk				O
39	Right Smirk				O
40	Right Smirk				O

APPENDIX C:: Programming Code for Interactive Program

```matlab
1    function varargout = RoboticArmControl(varargin)
2
3    gui_Singleton = 1;
4    gui_State = struct('gui_Name',       mfilename, ...
5                       'gui_Singleton',  gui_Singleton, ...
6                       'gui_OpeningFcn', @RoboticArmControl_OpeningFcn, ...
7                       'gui_OutputFcn',  @RoboticArmControl_OutputFcn, ...
8                       'gui_LayoutFcn',  [] , ...
9                       'gui_Callback',   []);
10   if nargin && ischar(varargin{1})
11       gui_State.gui_Callback = str2func(varargin{1});
12   end
13
14   if nargout
15       [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
16   else
17       gui_mainfcn(gui_State, varargin{:});
18   end
19
20
21
22   % --- Executes just before RoboticArmControl is made visible.
23   function RoboticArmControl_OpeningFcn(hObject, eventdata, handles, varargin)
24
25
26   handles.output = hObject;
27
28   % Update handles structure
29
30   set(handles.figure1,'KeyPressFcn',@myFunction);
31
32   guidata(hObject, handles);
33   delete(instrfind({'Port'},{'COM15'}));
```

```
34 -     clear;
35 -     global a;
36 -     a=arduino('COM15');
37 -     servoAttach(a,6);
38 -     servoAttach(a,7);
39
40
41
42       % --- Outputs from this function are returned to the command line.
43     function varargout = RoboticArmControl_OutputFcn(hObject, eventdata, handles)
44
45 -     varargout{1} = handles.output;
46
47     function myFunction(src,evnt)
48
49 -     handles=guidata(src);
50 -     hObject=handles.output;
51 -     switch evnt.Key
52 -         case '1'
53 -             closehand_Callback(hObject,0,handles);
54 -         case '2'
55 -             openhand_Callback(hObject,0,handles);
56 -         case '3'
57 -             extension_Callback(hObject,0,handles);
58 -         case '4'
59 -             flexion_Callback(hObject,0,handles);
60 -         case '5'
61 -             relax_Callback(hObject,0,handles);
62
63
64 -     end
65       % --- Executes on button press in openhand.
66     function openhand_Callback(hObject, eventdata, handles)
67 -     global a;
68 -     servoWrite(a,6,0);
69
70
71
72       % --- Executes on button press in closehand.
73     function closehand_Callback(hObject, eventdata, handles)
74 -     global a;
75 -     servoWrite(a,6,175);
```

```matlab
76
77
78
79      % --- Executes on button press in extension.
80    ┌ function extension_Callback(hObject, eventdata, handles)
81 -   │   global a;
82 -   └   servoWrite(a,7,0);
83
84
85      % --- Executes on button press in relax.
86    ┌ function relax_Callback(hObject, eventdata, handles)
87 -   │   global a;
88 -   │   servoWrite(a,6,0);
89 -   └   servoWrite(a,7,0);
90
91
92
93      % --- Executes on button press in flexion.
94    ┌ function flexion_Callback(hObject, eventdata, handles)
95 -   │   global a;
96 -   └   servoWrite(a,7,150);
```