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CONTROL OF ROBOT BY MEANS OF HUMAN THOUGHT

Examiners: Associate Professor Huapeng Wu
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ABSTRACT

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Brain computer interface (BCI) is a kind of human machine interface, which provides a new interaction method between human and computer or other equipment. The most significant characteristic of BCI system is that its control input is brain electrical activities acquired from the brain instead of traditional input such as hands or eyes. BCI technique has rapidly developed during last two decades and it has mainly worked as an auxiliary technique to help the disable people improve their life qualities. With the appearance of low cost novel electrical devices such as EMOTIV, BCI technique has been applied to the general public through many useful applications including video gaming, virtual reality and virtual keyboard. The purpose of this research is to be familiar with EMOTIV EPOC system and make use of it to build an EEG based BCI system for controlling an industrial manipulator by means of human thought. To build a BCI system, an acquisition program based on EMOTIV EPOC system is designed and a MFC based dialog that works as an operation panel is presented. Furthermore, the inverse kinematics of RV-3SB industrial robot was solved. In the last part of this research, the designed BCI system with human thought input is examined and the results indicate that the system is running smoothly and displays clearly the motion type and the incremental displacement of the motion.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Unit	Meaning
HMI		Human machine interface
BMI		Brain machine interface
BCI		Brain computer interface
EEG		Electroencephalography
MEG		Magnetoencephalography
fMRI		Functional magnetic resonance imaging
ERP		Event related potential
VEP		Visual evoked potential
TVEP		Transient visual evoked potential
SSVEP		steady-state visual evoked potential
SCP		Slow cortical potential
CLIS		Complete Locked-In State
LIS		Locked-In State
FES		functional electrical stimulation
IFR		international federation of robotics
SCARA		selective compliance assembly robot arm
DOF		degree of freedom
ANT		Advanced Neuro Technology
SDK		Software development kit
API		Application Program Interface
ANSI		American National Standards Institute
MFC		Microsoft Foundation Classes

1 INTRODUCTION

Since the first machine was designed by human, human always try to build convenient connection with machines. Human-machine interface (HMI) is a bridge between human and machines that allow them to exchange information. Typical inputs of HMI are provided by mouse, keyboard, joystick and touchscreen. Recently, human thought has become a novel input for HMI because of the improvement of Brain computer interface (BCI) during last twenty years. With BCI system, controlling a machine by means of human thought is not a concept that appears in movies or novels, but can be achieved in real life now.

BCI is a system that offers human a new communication and control channel with computer or other machines. BCI research was studied for military uses in 1970s and appeared in Vidal's paper for the first time [1] [2]. After underwent a fast development over last decade, BCI technique has been far and wide studied in various fields. Its main applications are applied to help those with several motor disabilities. In 2005, Tanaka *et al.* designed a thought-controlled wheelchair [3]. In 2011, Sam F. and his group built a BCI for rehabilitation and restoration of hand control [4]. Furthermore, many groups designed various kinds of spellers for typing instead of conventional devices [5] [6] [7] [8] [9]. BCI system is also used for environmental control [10]. The control system, such as illumination of light and fan speed of air conditioner can be controlled by the physiological change of the users. Recently, the application of BCI has been used to non-disabled people for entertainment due to the improvements of its performance and the appearance of several novel neuroheadset [11] [12] [13] [14].

Although the BCI system has been widely studied in research labs, few groups worked on the BCI system in the field of industrial robot. This research is focusing on utilizing a new low-cost device with satisfying performance to control an industrial robot using human thought. It is a breakthrough project that human thought directly communicates with a robotic manipulator. The objective of this research consists of familiarizing the novel non-invasive electronic device and utilizing it to acquire and process brain electrical activities, building a BCI system that is applied to control industrial robot by means of human

thought. The topic of research covers literature survey, choosing a suitable electronic device for brain electrical activities acquisition and process, and building an operation panel to display the robot motion. This thesis work laid the foundation for the future work of controlling industrial robot with BCI system.

The organization of the study is presented below. In chapter 1, briefly introduce HMI, present the objective and scope of this study, and then introduce background knowledge of BCI and EEG signal. In chapter 2, a literature review of previous EEG based BCI research is given. In chapter 3, choose an appropriate electronic device for EEG signal and introduce the components. In chapter 4, briefly introduce industrial robot and kinematic. In chapter 5, develop a BCI system to present the motion of industrial robot by user EEG signal. In chapter 6, design experiments to examine the interface. In chapter 7, analyze the results and discuss the limitation of the study. In chapter 8, make a conclusion of study and future work.

1.1 Electroencephalography

1.1.1 Neuron

EEG is a graph that measures and records the brain electrical activities that are occurred from the neurons in cerebral cortex. Brain electrical signals are first recorded by Richard Caton in 1875 and the EEG signals in human brain was discovered by Hans Berger in 1920(Figure 1) [15] [16]. Firstly, a brief introduction to neurons is presented in this section.

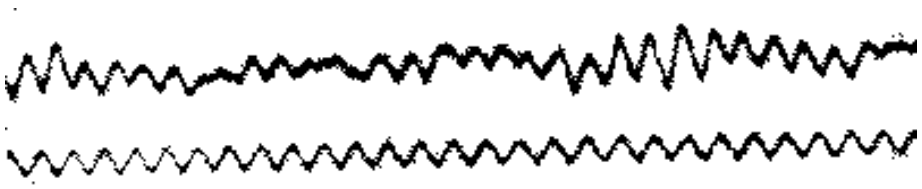


Figure 1.First EEG signal recorded by Hans Berger [16]

Neuron or nerve cell is the structural and functional unit of central nervous system. The essential of nervous system function is information transfer that not only transmits from one part of a cell to another but also between cells [17]. If there is a stimuli works on a neuron, dendrites will give respond and transmit nerve impulse to cell body. Then nerve impulse will be transmitted to other neuron. The structure of a neuron is shown in Figure 2.

Each neuron has a cell body which is the metabolism center and the nutrition center of nerve cell.

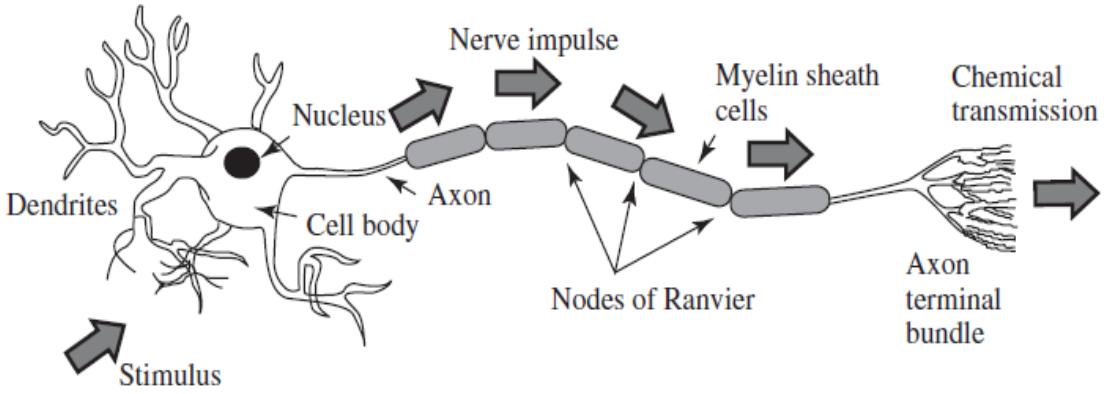


Figure 2. The structure of a neuron [18]

In a neuron, three elements make neuron different from other cells. These elements are axon, dendrite and synapse. The axon is a thin cylinder that transmits electrical signals or nerve impulse along its body from cell body to its terminal bundle. The length of axon ranges from micrometer to meters and the diameter of axon is almost unchanged all through its length [17]. Dendrites are branched from cell body and connected to axons or the dendrites of other cells. It is thicker and shorter than axon. Different from the function of axon, dendrites usually receive information from other neuron or somewhere else in the body. Sometimes, dendrites can also transmit electrical impulse like axon, even work for both information input and output [17]. Synapses are the junctions of axons and dendrites, or the junctions of dendrites and dendrites of other cells, which function is transmitting information from one part of nervous system to other parts. The transmitted information is called as action potential that is a temporary change of membrane potential [18]. Membrane potential is a potential recorded from the membrane, which usually changes with the synaptic activities.

After the neuron is introduced briefly, the concept of brain electrical activity can be defined. It is a summation of postsynaptic potential occurred in a large number of pyramidal neurons and apical dendrites. EEG signals are not recorded from one specific neuron, but are formed by the strong currents during synaptic excitations of large number of neurons in the cerebral cortex through electrodes [19].

1.1.2 Brain Rhythms

EEG is a direct way to show the brain activities. It is a good way to describe brain rhythms with EEG signals in clinical field [19]. Depending on different frequency ranges, EEG waves can be classified into five major bands that are listed in Table 1 [19]. Gamma represents the waves of above 30Hz and other bands range from 1-30Hz.

Table 1. EEG wave bands

Band	***Frequency (Hz)***
Delta (δ)	*1-4*
Theta (θ)	*4-7*
Alpha (α)	*7-13*
Beta (β)	*13-30*
Gamma (γ)	*30+*

These typical rhythms are shown in Figure 3. They are not only different in frequency ranges, but also are different in terms of state of human. Alpha wave is the basic rhythm of a normal adult brain. It occurs when a conscious human is closing eyes and disappears when human is opening eyes or thinking [20]. Beta wave is associated with active thinking and accepting information outside. Delta wave appears normally in babies and a human that sleeps deeply. Theta wave is usually recorded in young children or a human in early sleep or meditation [21].

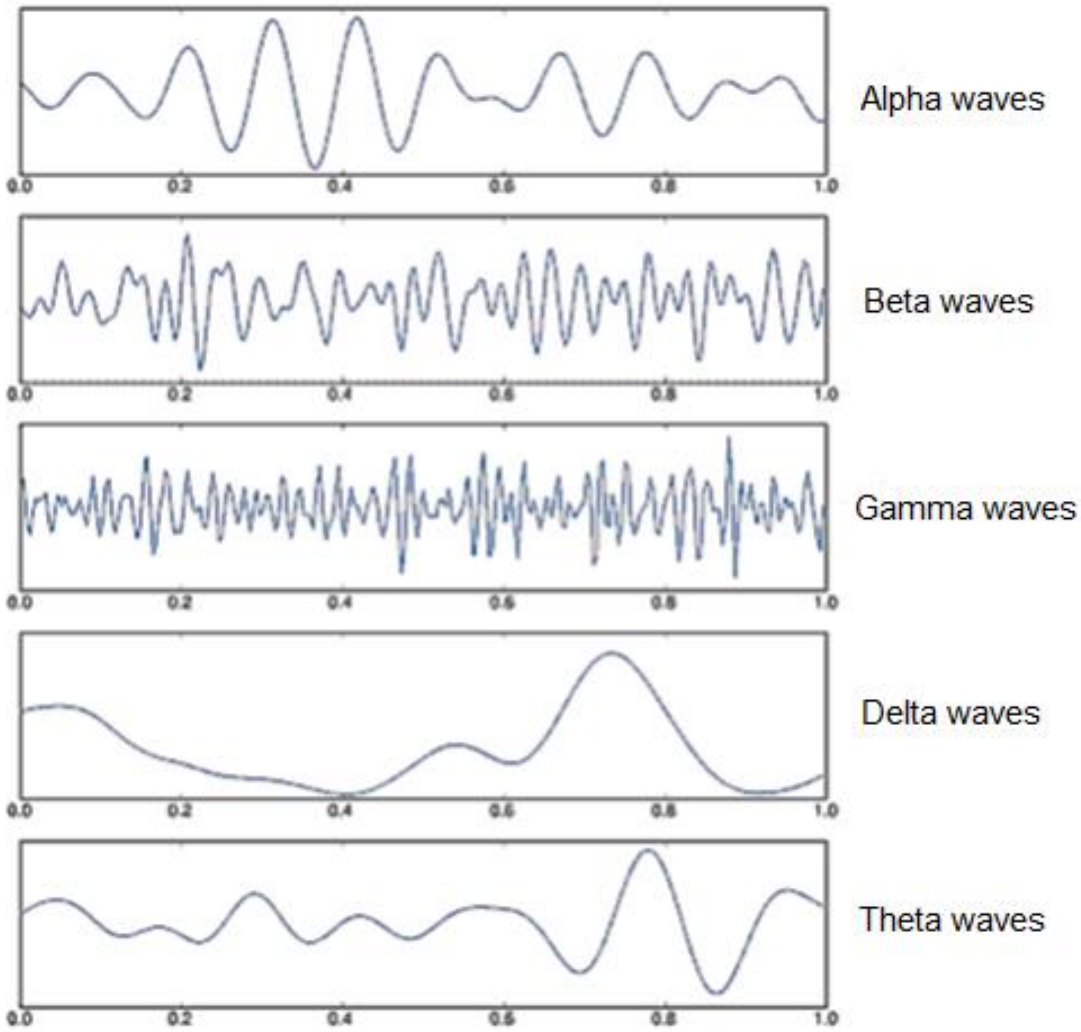


Figure 3. Typical EEG rhythms [16]

1.1.3 EEG Recording and Measurement

The change of potentials, which are recorded by the electrodes on scalp, reflects the functional activities in corresponding area of brain. The number and the position of electrodes placed on scalp are not random. There is a standard setting method named "10-20 International System of Electrode Placement"[15]. As shown in Figure 4, there are four anatomical landmarks work as essential position in this method. They are nasion, inion, and left/right pre-auricular points. Firstly, an equator is constructed from nasion to inion and goes through left and right pre-auricular points. Secondly, there is a longitude center line located between nasion and inion, which is divided into ten parts by points. Thirdly, there is a number of latitude lines that are coaxial with equator go through these points. Most of electrodes are placed on 10% or 20% position of latitude lines.

Electrodes are named using the rules below. The name of an electrode consists of number for identifying the hemisphere location and letter for identifying the lobe. The electrodes located on the left hemisphere are represented by odd number while the electrodes located on the right side are represented by even number. The number becomes smaller when the electrode is gradually close to mid line. The English letter is short for the name of the area that electrodes are placed on. The letters F, T, P, O and Fp refer to frontal lobe, temporal lobe, parietal lobe, occipital lobe and frontal polar respectively. Letter C means central position and Z represents the electrode to be found on the center line.

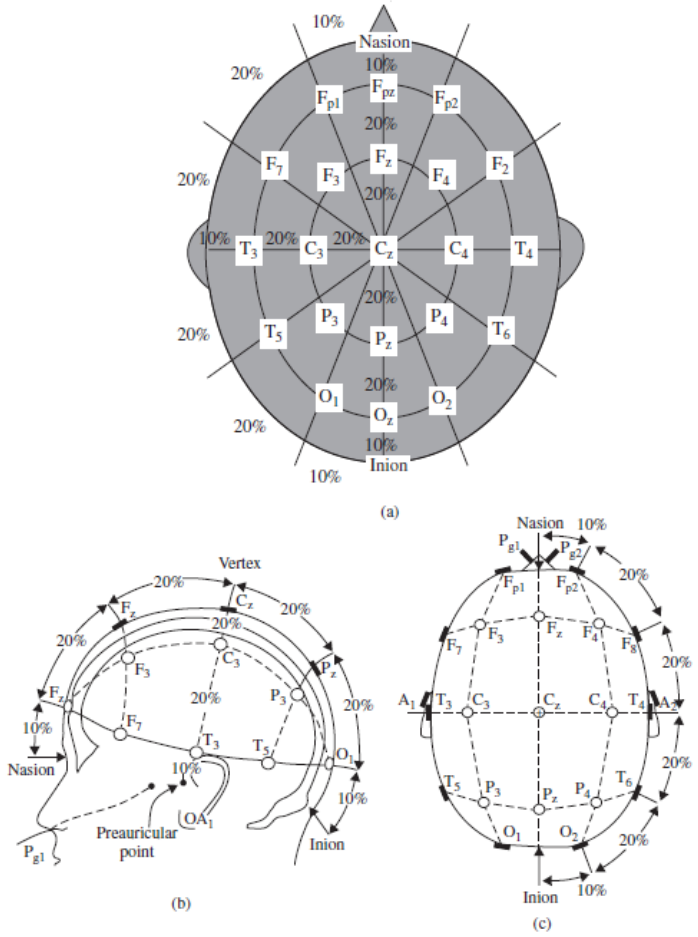


Figure 4. (a) electrode settings for the placement of 21 electrodes, (b) and (c) represents the placement in three-dimensional [15].

1.2 Brain Computer Interface

BCI is a technique that makes an interface between human and other devices by using the control signals produced from brain electrical activities completely without body movement or speaking [22]. Furthermore, brain electrical activities are acquired directly from the neurons by electrical device without peripheral nervous system and muscle [23].

In order to establish a BCI, an appropriate input signal should be selected at first. One condition is that a signal can reflect different states. The other one is that signal can be acquired promptly and identified efficiently. Nowadays, several methods and tools are suitable for observing brain signal in BCI, such as electroencephalography (EEG), magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI) [24]. In this thesis, EEG is chosen as input signal due to its easy collection and low cost. EEG signals will appear and have meaningful changes if human is stimulated by external force or controlled by consciousness. Furthermore, EEG can reflect various human activities such as visual stimuli, gaze angle and cognitive states [25] However, EEG signals are easy affected by the interference outside since they are acquired from scalp.

1.2.1 The Structure of BCI

Generally, a BCI system includes three functional modules: signal acquisition (acquiring, amplifier, filter, A/D converter), signal processing (feature extraction, feature translator), external application. The basic principle of a BCI system is presented in figure 5. The signal acquisition is the input part, which obtains and records brain electrical signals. Subsequently the signals are digitized and sent to the signal processing. In this module, the feature of brain signals is extracted and translated into useful device commands through different algorithms. And then commands are sent to the external devices of different level, such as computer, wheelchair, robotic arm and prosthetic limb. At last, external devices give users feedback for adjusting system inputs. The details of different parts are described in Table 2.

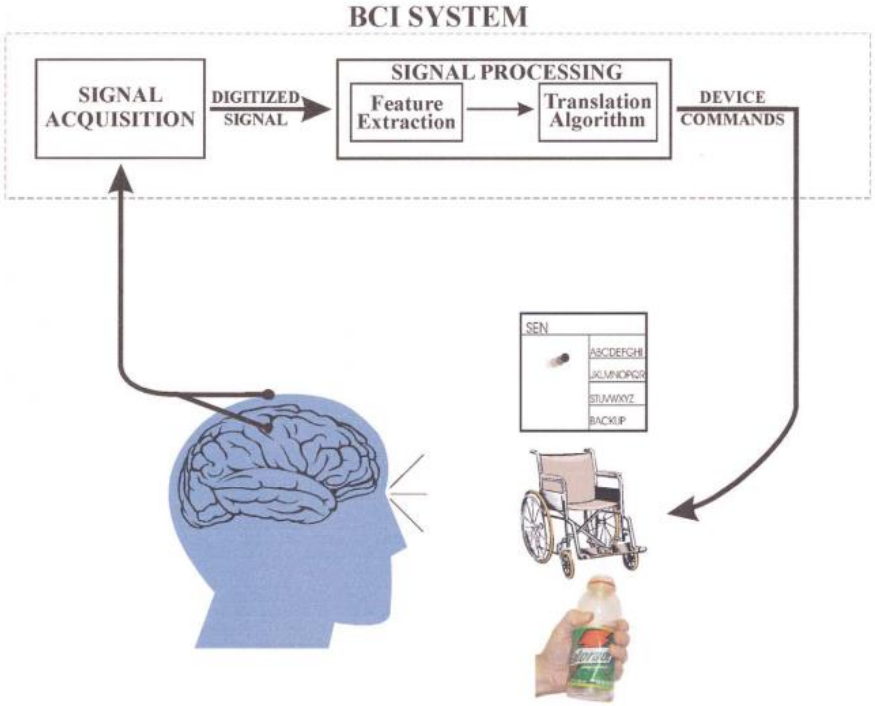


Figure 5. The basic principles of any BCI [26]

Table 2. The components and functions of BCI system [26]

Components	*Function*
controller	*Controller gives the orders and then brain electrical activities appear.*
electrode	*They are placed on different positions of brain. They detect and acquire the brain electrical activities in the form of digital signal.*
amplifier	*Because the EEG signals are weak and easily disturbed by noise, amplifier and band filter can make them stronger and clearer.*
Feature extraction	*Analyze the signal and transform into a reduced set of feature, which is easy to read and process by computer*
Feature translator	*Based on the feature signals, it outputs commands to communicate with external machine or human. Feature extraction and translator are the important parts of BCI system. Keep improving analysis and translation algorithm is an efficient way to increase veracity and optimize the BCI system*
External application	*Convert signal to the action in real, such as cursor movement, keyboard input and robotic arm moving*
Feedback	*Feedback shows results in a direct way, and help controller adjust*

	brain signal immediately. For example, design a bar to show the value of power.

Depending on the electrode position, there are mainly two ways of capturing brain waves: invasive, non-invasive techniques. In invasive BCI devices, electrodes are implanted directly into the brain and acquire signals from the grey matter. With this method, the position of electrode is stable and the highest quality signals are acquired comparing with other two methods [24]. However, the scar-tissue is formed and body may react to a foreign matter in brain. They may cause the signals to become weaker and even disappear at last. This method will attract more attention as the developing of biological materials and micromachining techniques [25]. In non-invasive BCI, electrodes are positioned on the scalp of the brain. In despite of producing poorer signals than other techniques, this method developed widely in human subjects since it is the most user-friendly technique by far. Nowadays, EEG has received great concerns in the research field of non-invasive technique [26].

1.2.2 Types

As introduced previously, brain signal such as EEG is a complicated object to study. Some phenomena of EEG are still studied and their origins are still in exploration. However, some phenomena have been decoded and controlled by human. Based on these decoded phenomena, several research approaches including P300 evoked potentials, visual evoked potentials, slow cortical potentials and sensorimotor rhythms (mu and beta rhythms), are mainly used in EEG based BCI system to solve communication or control tasks. They will be discussed below separately.

Event Related Potential (ERP) is a special kind of brain evoked potential. It is produced when brain is processing information related to certain event. P300 is kind of ERP, which appears 300ms after some infrequent stimuli. It is proven that the more infrequent the event, the more significant the P300 potential [25]. A typical application of P300 based BCI is to find a specific word, number or other symbol from a matrix. The most significant advantage of P300 based BCI is the short training period for user.

Visual evoked potential (VEP) is another kind of brain evoked potential. It responses to the visual stimuli produced during the processing of visual information. According to the frequency, VEP can be divided into transient VEP (TVEP) and steady-state VEP (SSVEP). TVEP occurs when the frequency is below 6 Hz and SSVEP occurs when the stimuli changes at a higher frequency [27]. The principle of SSVEP based BCI is presented below. Firstly, several virtual buttons are arranged and the brightness of each button is modulated at different frequencies for the visual stimulation for experimenter. Secondly, experimenter visually selects a button. Then the amplitude of SSVEP on this button increases and it can be identified. The requirement of the SSVEP based BCI is that user should be enabled to stare at the target.

Slow cortical potential (SCP) are the slow voltage shifts in the cortex that last 1s to 10 seconds [28]. It belongs to the EEG signals below 1Hz and it is related to motion and cortical activity. It is proven that people can regular SCP by themselves [29]. Patients learned to shift amplitude of SCP to produce positive deviation or negative deviation by feedback training. There are many factors affect the performance of this method such as the patient's mental and physical condition, motivation, external environment, or the relationship with people around [29].

When human is awake and relax, 8-12 Hz EEG activity that can be detected in the main sensorimotor cortex is called Mu rhythm. Mu rhythm is usually related to beta rhythm. The increase and decrease of these rhythms are affected by real or imagined motor movement [30]. Increases in these rhythms are called event related synchronization while decreases in these rhythms are called event related desynchronization.

Among the several research methods above, both P300 and SSVEP are brain evoked potentials. P300 based BCI extracts time domain feature and SSVEP based BCI extracts frequency-domain characteristics. Both of these methods have features of little time training, easy extraction and high accuracy. Both of SCP and sensorimotor rhythm are easily affected by subjective factors such as mood, fatigue and attention. Furthermore, they need a long time training to produce brain signal in specific mode.

2 PREVIOUS EEG BASED BCI RESEARCH

The development of BCI technology is not smooth. BCI was too strange to be taken seriously in scientific research. This is because that the reliability and resolution of detected brain signal is not in a high level. Furthermore, there was no suitable equipment to record real-time high variable brain signals [31].

However, the situation of BCI research has changed radically during last two decades. BCI research changed from an unpopular subject to a hot topic that was studied all over the world. There are several reasons for such change. Firstly, BCI research is a fresh multidisciplinary subject concerning the cultural areas of neuroscience, physiology, engineering, computer science and other technical. Hence the development of BCI research was benefited from the fast development of all these technical especially the computer science. For example, advanced computer hardware and software can perform complicated analysis and processing of brain signals accurately and efficiently [22]. Secondly, the disabled people have attached more and more attention in society, BCI as an auxiliary technology also gained more support and demand. Last but not least, some original and user-friendly applications appear in the view of public which can be used in the normal daily life, such as entertainment. These applications broadened the scope of BCI research. An overview of various BCI applications will be presented below.

BCI is a suitable assistant technology to help the people with severe motor disabilities and neurological disorders. According to the level of damage, the potential target populations of BCI applications are Locked-In State (LIS) patients and the people with partially paralyzed organs or disabled parts. LIS patients are the people who are almost paralyzed except the eyes. There are various applications to help these two kinds of people in different fields, such as communication, motor restoration and locomotion. Furthermore, BCI are also gradually used to help healthy people for entertainment.

2.1 Communication

Communication is one of the primary demands for patients even the LIS patients. Many BCI applications are designed for the communication which is based on eyes movement. This is because that the movement of eyes is a basic function of people even the LIS

people. One of most popular applications for communication is speller. The general principle of speller is that several letters are displayed on screen and then a letter is selected by user through BCI. Hinterberger, T. et al. reported that a SCP based BCI system can be used for speller [32]. In their research, the selection of a letter from an alphabet had to be divided into a number of binary selections because the number of brain response classes is two. After two letters were chosen, corresponding words were available for patients to choose.

To use eye blinks is another type of control signal to design a speller. Chambayil, B. et al. [8] designed a virtual keyboard based on eye blinks. The virtual keyboard included 26 English letters and space to separate words. Its principle was that users selected one target from three options by producing different times of eye blinks. Firstly, 27 symbols were divided into three blocks. Each block was a 3x3 matrix with nine letters and then user selected one block by producing single, two or three blinks. Secondly, the chosen block was separated into three set of three letters and then user selected again by eye blinks. At last, user repeated the procedure and selected one letter from three remaining letters. There is another kind of speller that also used this method of selection. Corley, J. et al. [33] designed a BCI based virtual keyboard with EMOTIV EPOC headset. The input of this virtual keyboard was not only based on eye blinks but more variable. It allowed customers to choose most suitable facial feature for themselves as input signal, such as left or right wink and smile. In order to design an application towards all users, the input signal also included custom neural states. At last a short-term training was necessary for customers to familiarize themselves with producing the corresponding neural states to control the virtual keyboard.

There are many other methods to design a speller, such as a letter speller based on standard Graz-BCI designed by Obermaier *et al.* [9] and a famous P300 based spellers designed by Farwell and Donchin [34]. P300 based speller is very popular because it does not require a long time training and it is still continually improved by many researchers [35][36][37][38].

2.2 Motor Restoration

Stroke, spinal cord injury or other nervous system injuries are the main reasons that cause paralysis and disability. These diseases dramatically limit the patients' activity space. They

have need of long-term therapy and require intensive home care services [39]. With the help of BCI applications, motor therapies become more effective and reduce the intensity of patient-practitioner interaction.

EEG based BCI could combine with functional electrical stimulation (FES) technology to help to restore movement [22]. Tavella *et al.* demonstrated that this way can be used to restore whole hand grasping [40]. FES delivered impulses which cause muscle contraction and BCI was used to turn on/off by opening and closing hand. However, FES requires the patients have residual movements at least, so it is not suitable for severely injured patients. Pfurtscheller *et al.* [41] has already developed a method to control hand orthosis for this kind of patients. In this study, they demonstrated that a patient can control an implanted neuroprosthesis based on BCI system after a short training. It proposed a possible approach for clinical purposes.

Furthermore, stroke damages the primary motor cortex where produces the signals of traditional BCI devices, hence Fok, S. et al. [4] designed a novel approach for hemiparetic patients to control hand by means of ipsilateral Cortical Physiology, namely using unaffected cortex ipsilateral to the affected limb. The theoretical basis of this new method is that distinct electrophysiological features from motor cortex related to ipsilateral hand movements [42]. Another highlight of this method was the usage of new device which saves the cost and training time.

2.3 Locomotion

BCI applications also give lots of help to disable people and old people in the field of locomotion. Intelligent wheelchair is one of most popular applications in this field. Borgolte stated that more than 2,000,000 people could get benefit from individually configurable intelligent wheelchair [43]. Generally intelligent wheelchair has two basic functions. One function is automatic navigation, such as avoiding obstacles and self-positioning. The other function is human-machine interaction, such as BCI.

To design an efficient wheelchair, there are several requirements for BCI system. Firstly, the number of the types after classifying brain signals should reach to the number of wheelchair motions such as going forward, turning left, turning right and stop. Secondly,

due to the target customer is human, the BCI should be non-invasive and has a training period as short as possible. Thirdly, the information transfer rate and accuracy should keep in a high level. EEG based BCI is the main study object in field of wheelchair due to it is non-invasive. In 2005, Tanaka *et al.* presented a study on EEG based control of an electric wheelchair. It was remarkable that controlling the wheelchair direction was achieved only by EEG signals [3]. After this, some more advanced researches have been presented over the past few years. Rebsaman et al. presented a P300 based brain controlled wheelchair that could work in a specific place, such as hospital environment [44]. In this research, they purposed a motion guidance strategy to ensure a high level information transfer rate. The detail was stated as follow. There was a path of wheelchair movement made by user at first. After that, guidance path was stored by system and there are several user-defined points on the path, so user only needs to decide where to stop with BCI control. An improved research was done by the same groups in 2007 [45]. Other BCI paradigms such as SSVEP and alpha rhythm are also applied to intelligent wheelchair [46][47].

2.4 Entertainment

In recent years, entertainment has become a popular BCI application for non-disabled people. It allows a novel communication channel which is more challenging than common channels such as keyboard, mouse and joystick. Millan (2003) designed a BCI for a classical Pacman game [48]. In this research, Millan made two mental missons to represent two motions of Pacman. The same group made a research about controlling the motion of a Khepera robot to avoid obstacle and turn smoothly [49]. Furthermore, Roman made a Berlin BCI for several classical games [11]. As the development of EMOTIV, there are many new video games, such as Spirit Mountain Demo Game and Cortex Arcade, which specifically match these novel headsets. It provides a new developing direction of game industry.

3 INDUSTRIAL ROBOTS

3.1 Brief Introduction to Robot

Robots often appear in the science fiction, movies and cartoon. The term *robot* first appeared in a drama that written by Karel Capek [50]. Karel Capek coined a robot slave named “Robota” which has human’s appearance, characters and functions. In this drama, Robota is described as a machine that worked for human like a salve.

In real world, robot is an electronic mechanical device which combines human-like specialty and the features of machine. Usually it has an anthropomorphic shape and a rapid response to the sensory inputs. It also can communicate with other machines and has the abilities of analyzing and making decisions. Furthermore, it has the advantages of machine. It can be substituted for humans in hazardous or uncomfortable work environments. It also can work long hours with high accuracy and repeatability that cannot be attained from human.

Unlike other technological term has a clear concept, the definition of robot is changed as the science and technology goes on. This is because that robotics is still developing. New models are continuously designed and new functions keep upgrading. In 1984, International Standardization Organization made a definition for robot according to the Robot Institute of America [51]. Robot is *a reprogrammable and multifunctional manipulator, devised for the transport of materials, parts, tools or specialized systems, with varied and programmed movements, with the aim of carrying out varied tasks.* Therefore, robotics is an advanced subject concerning the cultural areas of computer, controlling, mechanics, information technology, sensor technology and electronics.

3.2 Definition of Industrial Robots

Industrial robot is a kind of robot and has reached the level of a mature technology. As defined by ISO 8373, industrial robot is *an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications* [52]. The key element of

this definition is reprogrammable. When the current task is finished, an industrial robot can be reprogrammed and equipped with the necessary tools to work on another different task. Industrial robots have already been widely used in many industries for different purposes. According to the international federation of robotics (IFR) report, robot sales increased to 178,132 units in 2013, which is the highest level recorded for one year [53]. The worldwide annual supply of industrial robots by industries is shown in Figure 6. The most important customer of industrial robots was the automotive industry. The share of the total supply was about 39%. The automotive industry has continuously increased the number of robot installations since 2011 from 60,000 units to 69,400 units in 2013. Furthermore, the typical applications of industrial robots included handling, welding, assembly, dispensing, processing and others.

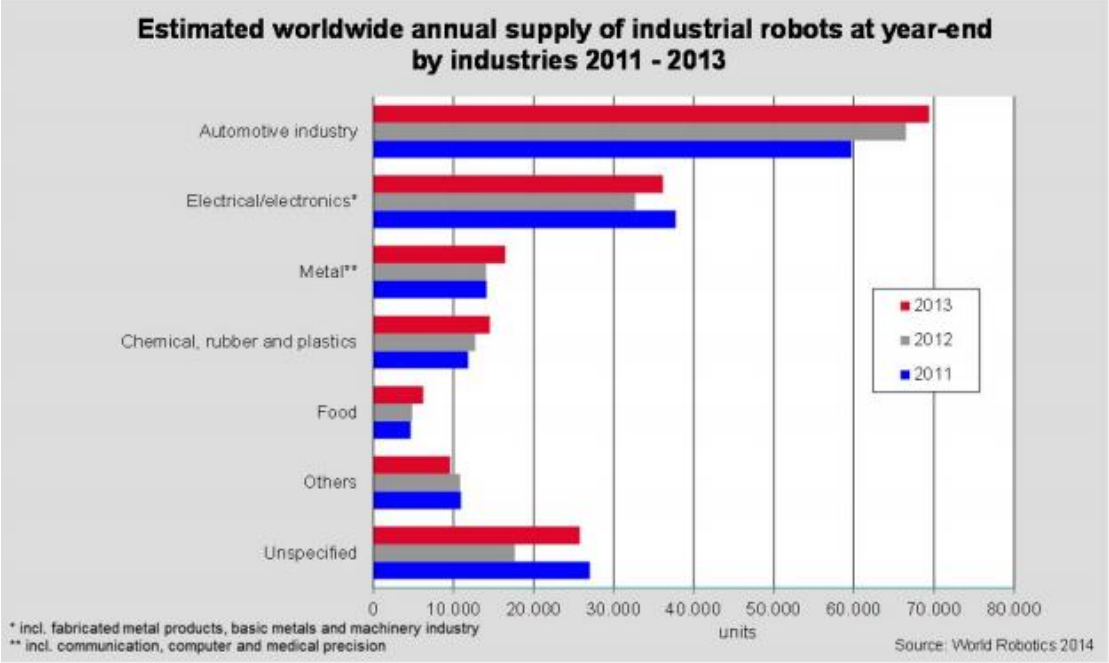


Figure 6. The worldwide annual supply of industrial robots by industries [53]

3.3 Classification

There are many way to classify industrial robots. According to mechanical structures, industrial robots can be classified as serial robot and parallel robot. Serial robot includes articulated robot, cylindrical robot, linear robot and selective compliance assembly robot arm (SCARA) robot. They will be introduced separately below.

Articulated robot is a robot with rotary joints, which works just like human's arm. It can have one or two rotary joints, and more joints can be used if necessary. As it is shown in

Figure 7, rotary joints are arranged in a chain and one joint supports another further in the chain, so articulated robots allow a large range of motion and high flexibility. Hence articulated robots commonly are used on manufacturing line.

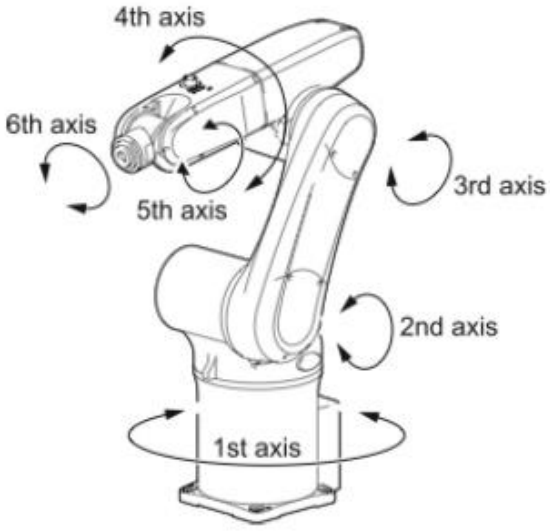


Figure 7. 6-axis articulated robot

Cylindrical robot is a robot arm that moves around a cylinder shaped pole (Figure 8). It has two linear axes and one rotary axis. Normally it has a tight structure and it can be combined with tool such as pneumatic clamps. For this reason, cylindrical robot is able to perform handling and assembly. Nowadays, the cylindrical robot is not popular due to the articulated robot that has more versatility and more degrees of freedom.

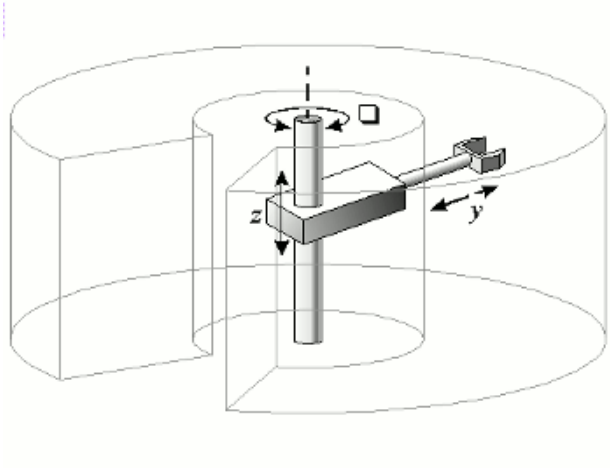


Figure 8. The cylindrical robot

The linear robot includes Cartesian robot and Gantry robot (Figure 9). Cartesian robot is a common type of industrial robots that has three linear axes which are perpendicularly

oriented at each other. Because all three axes are linear rather than rotational, this type of robots has a simple structure that can be used in bad environment for a long time and easy to maintain. Its most common application is computer numerical control machine. Following the written commands, the robot can move very fast and precisely and thus are suitable for different processing functions such as milling and drawing. Comparing to Cartesian robot, a gantry robot usually encloses its work envelope from outside. As it shown in Figure 9, this big robot stands on four strong beams. It can lift objects with heavy weight and large dimensions. As a result, gantry robots can be used for handling and assembly.

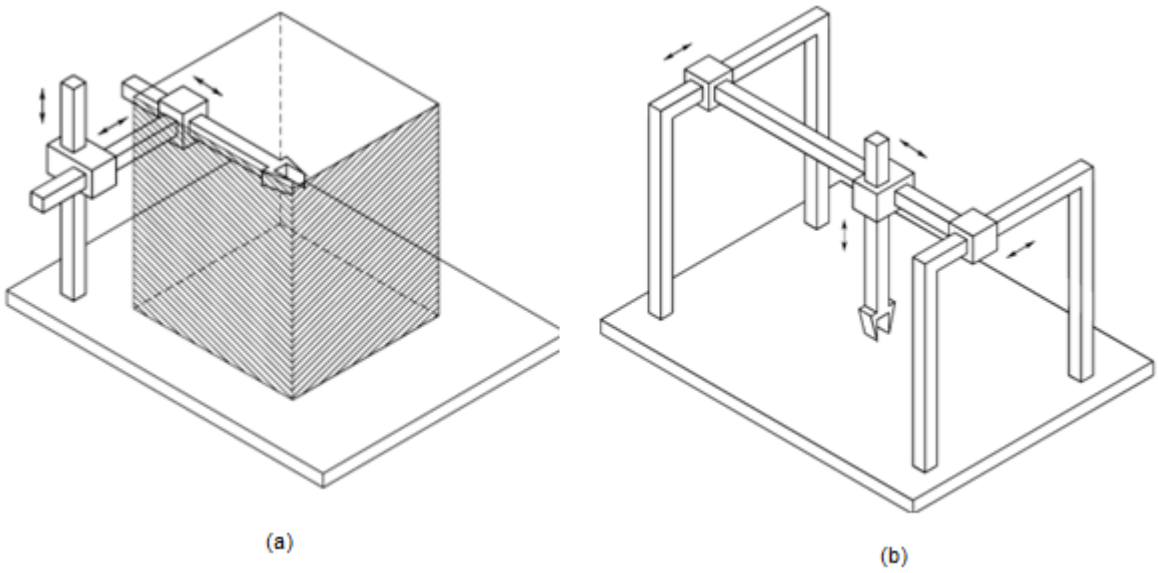


Figure 9. (a) Cartesian robot (b) Gantry robot

A SCARA robot is one of the most popular types of robots on an assembly line (Figure 10). It is designed by imitating human's shoulder, elbow and wrist. As it shown in figure, SCARA robot has two rotary joints in parallel which make robot move in horizontal, and a linear joint makes robot move in vertical. It is famous for high speed, efficiency and low cost. It also has large range of motion, and it is faster and more precise than Cartesian robot. However, it cannot carry heavy weight, so it works best when handling small objects such as small electronic items.

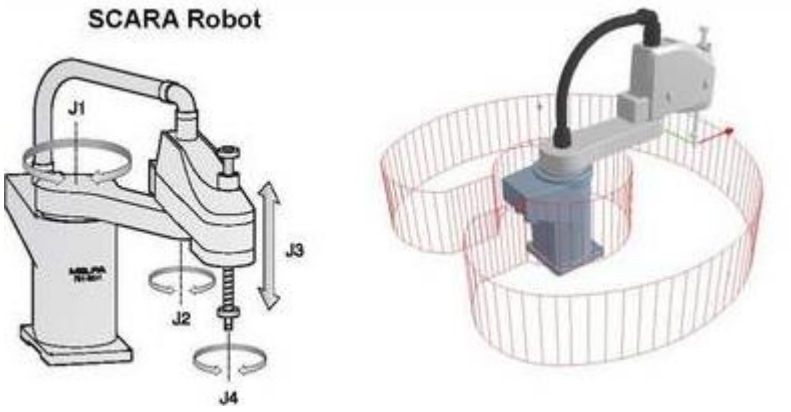


Figure 10. SCARA Robot and its workspace

As it is shown in Figure 11, it is IRB 360 FlexPicker, a parallel robot made by ABB Group. In a parallel robot, the work platform or the end-effector is connected to the basis by several kinematic chains forming a closed loop. Parallel robots are stiffer, faster, and more accurate than serial robots. However, they have a limited workspace due to the legs may collide. They have been used in several applications such as flight simulator, parallel machine tool. They also have a good performance on assembly line.

Figure 11. ABB IRB 360 FlexPicker

3.4 Robot Components

An industrial robot, as a system, consists of machinery, end-effector, actuation, sensors, controller, and processor. Machinery consists of two sections: One is body-and –arm which

is used for positioning the objects in the robot's workspace. The other is wrist assembly which has two or three degree of freedom (DOF) such as roll, yaw and patch. End-effector is attached to wrist assembly. It directly connects to the objects, tools or other machines to finish the required tasks. Generally end-effectors are not made by robot manufacturers but specifically designed by customers for a purpose. Actuation is the device which provides the power for robot. Common types of actuation are servomotors, pneumatic or hydraulic cylinders and electric motors. Sensors are used to collect information of internal state of robot and outside environment. They enhance the motility and adaptability of robot. Sometimes sensors are more effective than human's sense organ. The sensor feedback information can support controller to control and adjust the motion of actuation. The controller receives the data from the computer and controls the motion of actuation to move the arm according to the purposes. The processor is the central part of robot system. It calculates the motions of joins and processes other data of robot system. It generally requires an operation system, programs and peripheral equipment such as information panel and alarm.

3.5 Robot Kinematics

Kinematics studies the relationship between robot joints variables, position and orientation as a function of time without consideration of the force and moment that cause motion [54]. It consists of forward kinematics and inverse kinematics. The relationship between forward kinematics and inverse kinematics is illustrated in Figure 12. Forward kinematics studies the position and orientation of end-effector when joints variables and links parameters are known. Inverse kinematics studies the joints variables when links parameters are known and the position and orientation of end-effector are given. It is a much more complex problem than forward kinematics. It will be mentioned later.

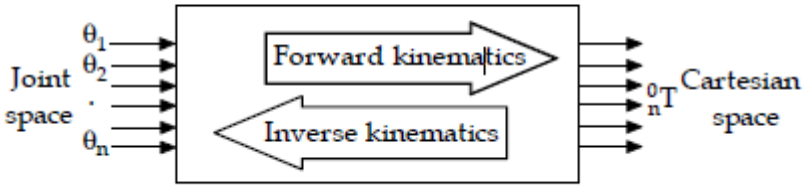


Figure 12. Relationship between forward kinematics and inverse kinematics[54]

3.5.1 Forward Kinematics

The main body of robot consists of joints and links. Joints provide relative motion, and their types are linear and rotary. The rigid members between joints are links. Each couple of joint and link provides a DOF. The links are serial and each link connects with other two links at most.

Formulating a suitable kinematics model is very important for analyzing the manipulator of robot. One of common coordinate systems used in kinematics modeling is Cartesian coordinate system. There is a Cartesian coordinate system in every joint. In coordinate system, i is the joint number and A_i is the axis of joint. Generally the first link A_0 is attached on the base and there is a reference coordinate system. The transformation between two coordinate systems consists of a rotation and a translation. Each rotation or translation can be expressed by a matrix and then the transformation can be represented by the cross product of matrices known as homogenous matrix.

Denavit and Hartenberg (1955) mentioned that using homogenous matrix was a useful way to represent the rotation and the translation [55]. Homogenous matrix is a 4x4 orthonormal matrix which requires four link parameters: a_i, α_i, d_i, and θ_i, which refer to the link length, link twist, link offset and joint angle separately. These parameters are known as Denavit-Hartenberg (DH) method parameters, which have become the typical factors for describing robot kinematics. In order to determine DH parameters, a Cartesian coordinate frame is attached to the D-H method. Z_i axis of the coordinates is pointing along the rotary or sliding direction of the joints. There is a coordinate frame of a general manipulator in figure 13, where origin o_i is located on the point of intersection of a_i and A_i, z_i axis coincides with A_i. a_i is the length between z_{i-1} and z_i pointing along x_{i-1} axis. α_i is the angle that z_{i-1} rotates to z around x_{i-1}. d_i is the distance between x_{i-1} and x_i along with z_i. θ_i is the angle that x_{i-1} rotates to x_i around z_i. a_i should equal or greater than 0, while α_i, d_i, and θ_i could be positive or negative.

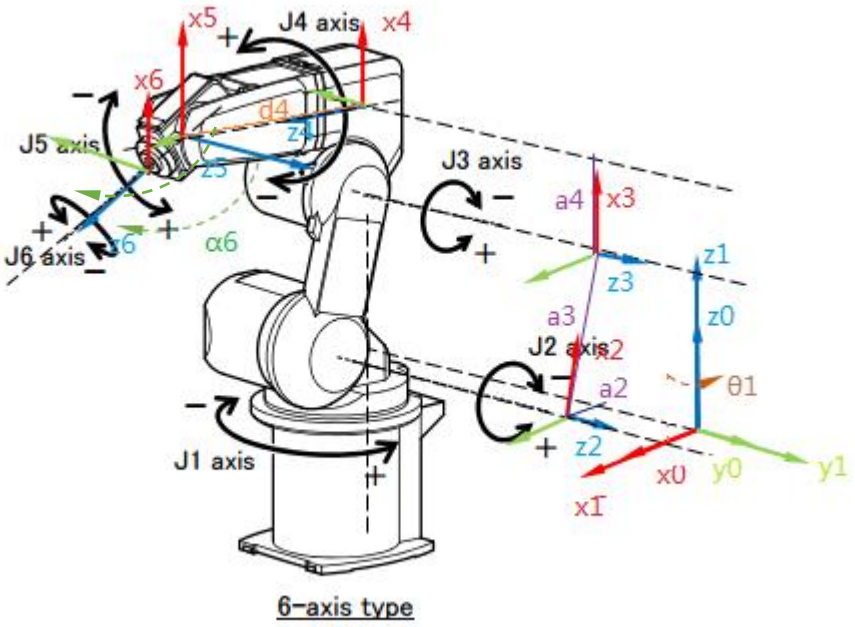


Figure 13. A Cartesian coordinate system attached to the DH method

The general transformation matrix ${}^{i-1}T_i$ for the process that coordinate system i-1 is transferred into coordinate system i can be obtained as follows. Firstly, system i-1 translates along z_i axis by a distance d_i. Secondly, it rotates around the z_i axis by an angle θ_i. Thirdly, it translates along the x_{i-1} axis by a distance a_i. Al last it rotate around the x_{i-1} axis by an angle α_i. DH in mathematical order from right to left:

$${}^{i-1}T_i = R(x_{i-1}, \alpha_i)Trans(x_{i-1}, a_i)R(z_i, \theta_i)Trans(z_i, d_i)$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha_i & -\sin\alpha_i & 0 \\ 0 & \sin\alpha_i & \cos\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_i \\ \sin\theta_i\cos\alpha_i & \cos\theta_i\cos\alpha_i & -\sin\alpha_i & -\sin\alpha_i\, d_i \\ \sin\theta_i\sin\alpha_i & \cos\theta_i\sin\alpha_i & \cos\alpha_i & \cos\alpha_i\, d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The solution of forward kinematics:

$${}^{0}T_i = {}^{0}T_1\, {}^{1}T_2 \cdots {}^{i-1}T_i$$

$${}^{0}T_i = {}^{0}T_1(q_1)\, {}^{1}T_2(q_2) \cdots {}^{i-1}T_i(q_i),$$

where $q_i=(\theta_i, d_i, a_i, \alpha_i)$ is the joint variable

3.5.2 Inverse Kinematics

Inverse kinematics solves the problem of where to place the joints to get the end-effector in the right place. In a problem of inverse kinematics, numerical and closed- form methods exist. A system, which has rotary and linear joints, should have numerical solution when its DOF is less than six. However, this method takes a long time to calculate. In reality, there are a few special conditions. For instance, a number of axes of joints intersect; several axes are parallel or vertical. In such conditions, a 6 DOF robot has an analytical solution. Therefore, industrial robot are tried to design simply in order to satisfy the special conditions. In this thesis, analytical or closed-form methods are concentrated.

Generally, the inverse kinematics problem has multiple solutions. Moreover, singularities and nonlinearities make the problem more difficult to solve. There are a number of methods to eliminate unnecessary solutions. 1) Choosing a suitable solution according to the limits of workspace and joint angle. 2) Choosing a suitable solution by avoiding the possible obstructions in workspace. 3) Choosing a suitable solution which has smallest movement amount of all joints.

In 1981, Paul mentions a method to computes the inverse kinematics problem. Firstly, we suppose that the transformation matrix of end-effector relating to the base frame ${}^{0}T_{\mathrm{i}}$ can be written as

$$ {}^{0}T_{\mathrm{i}} = \begin{bmatrix} n_x & s_x & a_x & p_x \\ n_y & s_y & a_y & p_y \\ n_z & s_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

where n, s, a is the unit vector and matrix $[n\ s\ a]$ represents the rotational elements of transformation matrix. p_x, p_y and p_z denotes the elements of the position vector.

Secondly, to solve the inverse kinematics of the first joint, the first translation matrix ${}^{0}T_{1}$ is pre-multiplied on both ends of the forward kinematics equation. After that, making the corresponding elements of both sides equal and unknown q_1 can be shown through an expression with known elements n, s, a, p_x, p_y p_z and fixed link parameters.

$({}^{0}T_{1})^{-1}\,{}^{0}T_{\mathrm{i}} = {}^{1}T_{2}\,{}^{2}T_{3}\cdots{}^{\mathrm{i-1}}T_{\mathrm{I}}$

Thirdly, pre-multiplying next matrix and another unknown q_2 can be shown through a new expression.

$$({}^{1}T_{2})^{-1}\,({}^{0}T_{1})^{-1}\,{}^{0}T_{i} = {}^{2}T_{3}\,{}^{3}T_{4}\cdots{}^{i-1}T_{I}$$

$$\vdots \qquad\qquad \vdots$$

$$({}^{i-1}T_{i})^{-1}\cdots({}^{1}T_{2})^{-1}\,({}^{0}T_{1})^{-1}\,{}^{0}T_{i} = E$$

Repeat the above processes till all the expression are obtained.

The suitable solution should be selected by human. Usually arctg2(y,x) function are used to select suitable θ. It can place arctg(y/x) in the right sub-frame

$$\theta = \tan^{-1} 2(y,x) = \begin{Bmatrix} 0^{\circ} \le \theta \le 90^{\circ}, for + x\ and + y \\ 90^{\circ} \le \theta \le 180^{\circ}, for - x\ and + y \\ -180^{\circ} \le \theta \le -90^{\circ}, for - x\ and - y \\ -90^{\circ} \le \theta \le 0^{\circ}, for + x\ and - y \end{Bmatrix}$$

4 THE EMOTIV SYSTEM

To acquire and process the EEG data from human brain, many non-invasive electrical devices came into the view of public. Neurosky Mindwave is a neuroheadset that can response to user brainwaves and monitors user attention levels. It has provided a set of software tools for third party developers to develop applications [56]. However, lack of channels is the main limitation of this device. In this research, multiple-electrode headsets are considered, such as the Advanced Neuro Technology (ANT) acquisition system and EMOTIV EPOC system. ANT has a standard medical headcap which has 128 electrodes covering all the major brain cortical area and offers several software tools. EMOTIV system applies a commercial data acquisition device which has 16 electrodes and a set of software. For the research edition, the total cost is 699$ [56]. Finally the EMOTIV EPOC is chosen in this research for a number of reasons: 1). It is a low cost system which is much cheaper than ANT. 2). Matthieu Duvinage etc. have researched the performance of the EPOC for P300-based applications [57]. The results show that EPOC is able to record EEG data and could be used for communication systems. Lievesley, R. etc. have done a research of the performance of EPOC. They found that EPOC could build a channel between brain and computer [58]. 3). EPOC has a powerful software development kit for consumers. Many research teams have acquired signals with this system [59].

4.1 EMOTIV EPOC

The EMOTIV EPOC is revolutionary new personal BCI interface which is made by a bioinformatics company in San Francisco, USA. It gives human a possibility to control the world with mind. EMOTIV EPOC consists of a headset kit for acquiring EEG signals and a software sort for processing and analyzing the data [60].

The appearance of headset is shown in Figure 14. It looks like a normal headphone and several arms branch from the position of each ear. In the end of each arm there is a slot for inserting sensor. For instance, two rubber sensors are inserted in the slots behind each ear lobe to correct the position of headset. More details of the headset are listed in table 3. 16 sensor units are placed in corresponding slots according to “10-20 International System of Electrode Placement”. Among of them, two sensors located in P3 and P4 form a feedback

loop as reference for measurement of other sensors. Before these sensor units are inserted in slots, they should be properly wetted with saline solution first to get outstanding performance of electrode/skin interface. Moreover, the headset has a bandwidth of 0.2-45 Hz and has a build-in filter to process the EEG signals. At last but not the least, the headset is connected with computer wirelessly by USB transceiver dongle, which facilitates customer.

Figure 14.Tthe EPOC headset

Table 3. The parameters of EMOTIV neroheadset [60]

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 (2048 Hz internal)*
Bandwidth	*0.2 - 45Hz, digital notch flters at 50Hz and 60Hz*
Filtering	*Built in digital 5th order Sinc flter*

Dynamic range (input referred)	*8400μV (pp)*
Connectivity	*Proprietary wireless, 2.4GHz band*
Power	*LiPoly*
Battery life (typical)	*12 hours*
Impedance Measurement	*Real-time contact quality using patented system*

4.2 Software Development Kit (SDK)

After the hardware of EPOC is introduced, the software development kit will be presented below. Two Glossaries are introduced firstly. One is Emostate which is data structure holding information about the current status of all activated EMOTIV detections. The other is EmoEngine which decodes and processes the data acquired by headset. EmoEngine provides a few built-in brainwave processing suites including Expressiv, Affectiv and Cogntiv. It also monitors the headset battery level, contact quality and the raw EEG data [62].

4.2.1 EMOTIV Control Panel

The EPOC Control Panel is a convenient operation panel for customer to connect with the EPOC headset. All these mentioned functionality can be used through the EPOC Control Panel supplied by EMOTIV Company. After it is opened, the EmoEngine will start automatically. The Control Panel preprocesses and classifies the acquired brain signals. Moreover, it gives feedback of battery and contact quality to the user. It also helps the user to explore the EMOTIV detection suites. The main panes of Control Panel are introduced below.

As shown in Figure 15, the EmoEngine Status Pane provides the current state of EmoEngine, such as system up time, wireless signal quality and battery power. On the right side of the pane, it is the sensor locations. Each circle refers to one sensor and its approximate position on user's head. Different sensor colors indicate different contact qualities. The colors and corresponding qualities are listed in Table 4. Ideally, all the sensors should be green which represents the best contact quality. It is acceptable that most sensors are green and some are yellow. The user name and the number of headset are also shown on this pane. The default number is zero.

Figure 15. The EmoEngine Status Pane

Table 4. The senor color and corresponding quality

The Color of sensors	*Contact quality*
Black	*No signal*
Red	*Very poor signal*
Orange	*Poor signal*
Yellow	*Fair signal*
Green	*Good signal*

Under the EmoEngine Pane, the Control Panel has a tab for each processing suites mentioned above. The Expressiv suite is designed to measure the facial expressions by reading EMG signals. In Figure 16, a robot face is on the left side. When user wears the headset, the facial expressions that are performed by user are displayed on the face of the robot. There is a series of graphs in the middle of the panel, which indicate the feature of various signals that are related to expressions. The expressions which are displayed include normal eyes blink, right/left wink, eye movements to the left and right, raise brow, furrow brow, smile, clench, right/left smirk and laugh. The sensitivity adjustments for these expressions are offered on the right side of the Expressiv suite.

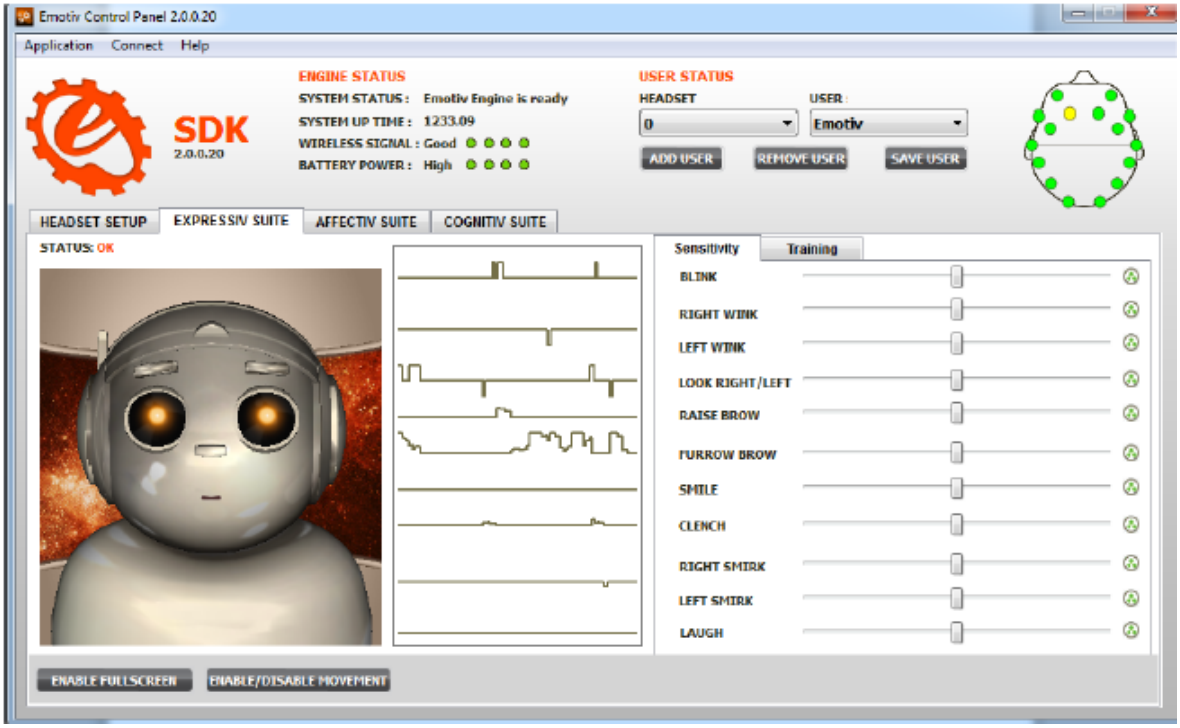


Figure 16. The Expressiv suite panel

The Affectiv suite is developed to measure and display the user's emotional responses. It is usually used in video games. Currently it can display many affective types shown in Figure 17. Levels of these emotion detections are translated into graphical measurement on the panel.

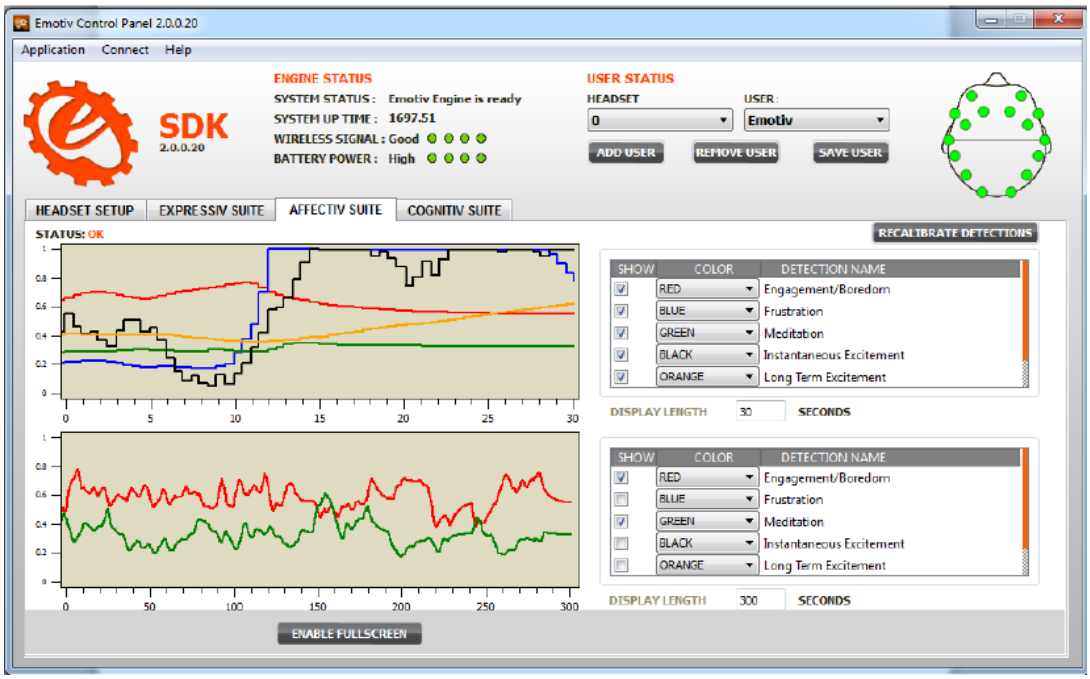


Figure 17. The Affectiv suite Panel

The Cognitiv suite is the key suite in this research. It is designed to classify a user's raw EEG signals to distinguish the user's conscious thought in real time. As it is shown in Figure 18, there is a virtual 3D cube on the suite. It could do a number of physical actions under the control of user's thought. The action power is shown in the left of the 3D display. Currently, Cognitiv suite can measure 13 active thought: push, pull, movement to left/right, lift, drop, rotate left/right, rotate clockwise/counterclockwise, rotate forward/ backward and disappear. However, four separate thought can be distinguished at most. This is because that adding more thought can significantly increase the difficulty of distinguishing the thought. Each active thought has a built-in "prototype thought". For example, based on hundreds of test cases which thinking "push", the data for prototype thought of "push" is formed and then serves as a standard base for classifying the input signals from the electrodes.

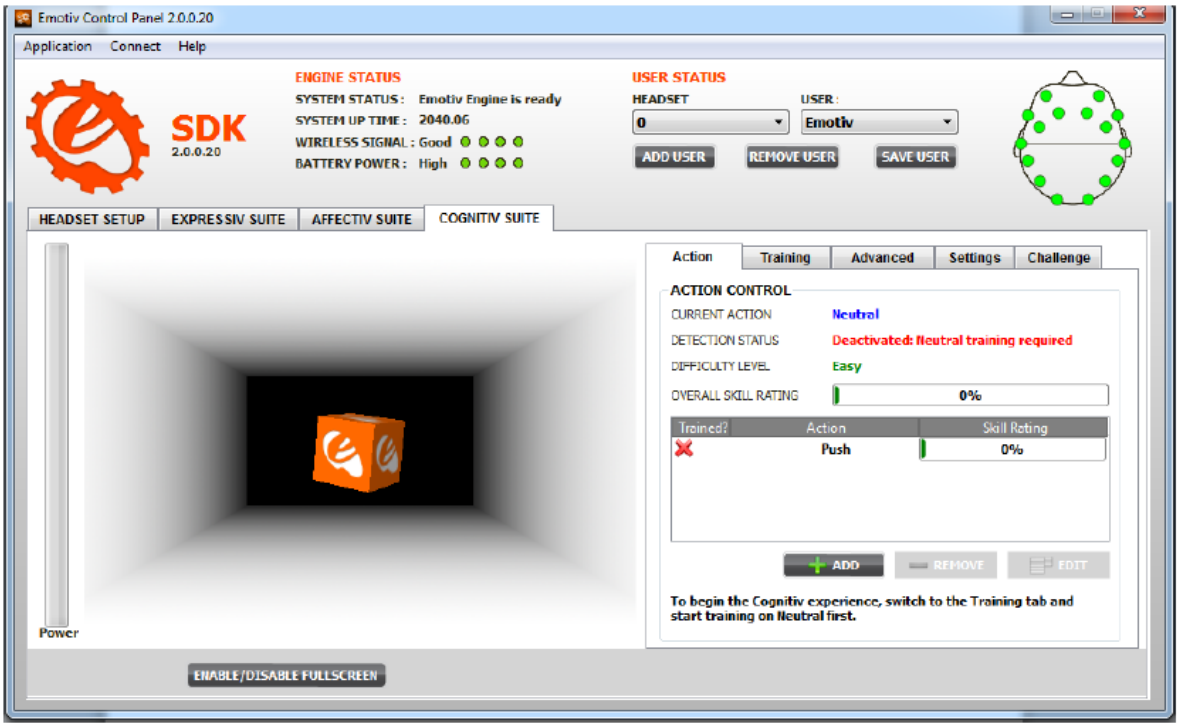


Figure 18. The Cognitiv suite

Unlike other mentioned suites, the training process of Cognitiv suite must be done first otherwise Cognitiv suite cannot automatically detect user thought. The training process enables the EmoEngine to analyze user's brainwaves from the electrodes through a neural network and then attempt to classify the signals as one of the 13 built-in prototype thought. Before starting to train the mentioned active thought, the Neutral action which is user's passive mental state should be trained first. Typically it means the state that user is reading

or relaxing. It works as a reference for other active thought. Providing more Neural action training is a good way to get better Cognitiv performance. During the training process, user should think deliberately.

There are mainly two main potential problems for user during training period. One is to find what the prototype thought is. The more thought matches up to the prototype thought defined by EMOTIV the higher the skill rating is. The other is to think consistently for the full training period.

The Cognitiv suite moreover supplies a function that user can customize and control imported 3D objects. Firstly a user-defined model is imported and placed in desired position. Secondly custom scenery is created and then this 3D object can be used through Cognitiv suite. It is possible to make a simple simulation of robotic arm in future research.

4.2.2 EmoComposer

EmoComposer is designed to stimulate the behavior of EmoEngine and headset and then send user-defined orders to Control Panel and other applications. It is a convenient tool for EMOTIV SDK developers. It help user understand the working principle of different suites early in the development process. It also offers user help in the way of testing the program in the development cycle. Interactive mode is one useful mode of EmoComposer. It allows user to define and send mock signals to other EMOTIV application. The operation interface is shown in Figure 19. On the top of the panel, the player number and wireless quality can be chosen. The length of EmoState interval can be defined and the interval can be sent repeatedly. In contact quality tab, overall contact quality can be chosen. If it is chosen as “custom”, the contact quality for each sensor can be chosen separately. Only two reference sensors always report a CQ value of good. In detection tab, EmoState detection values and training results values can be defined. All previously mentioned suite could be defined in this mode. Firstly the active thought of Cognitiv suite can be chosen and its power can be defined. Secondly the user emotion could be chosen. At last the facial expressions could be defined. In a ward, the EmoComposer is an emulator to facilitate the development of EMOTIV related software.

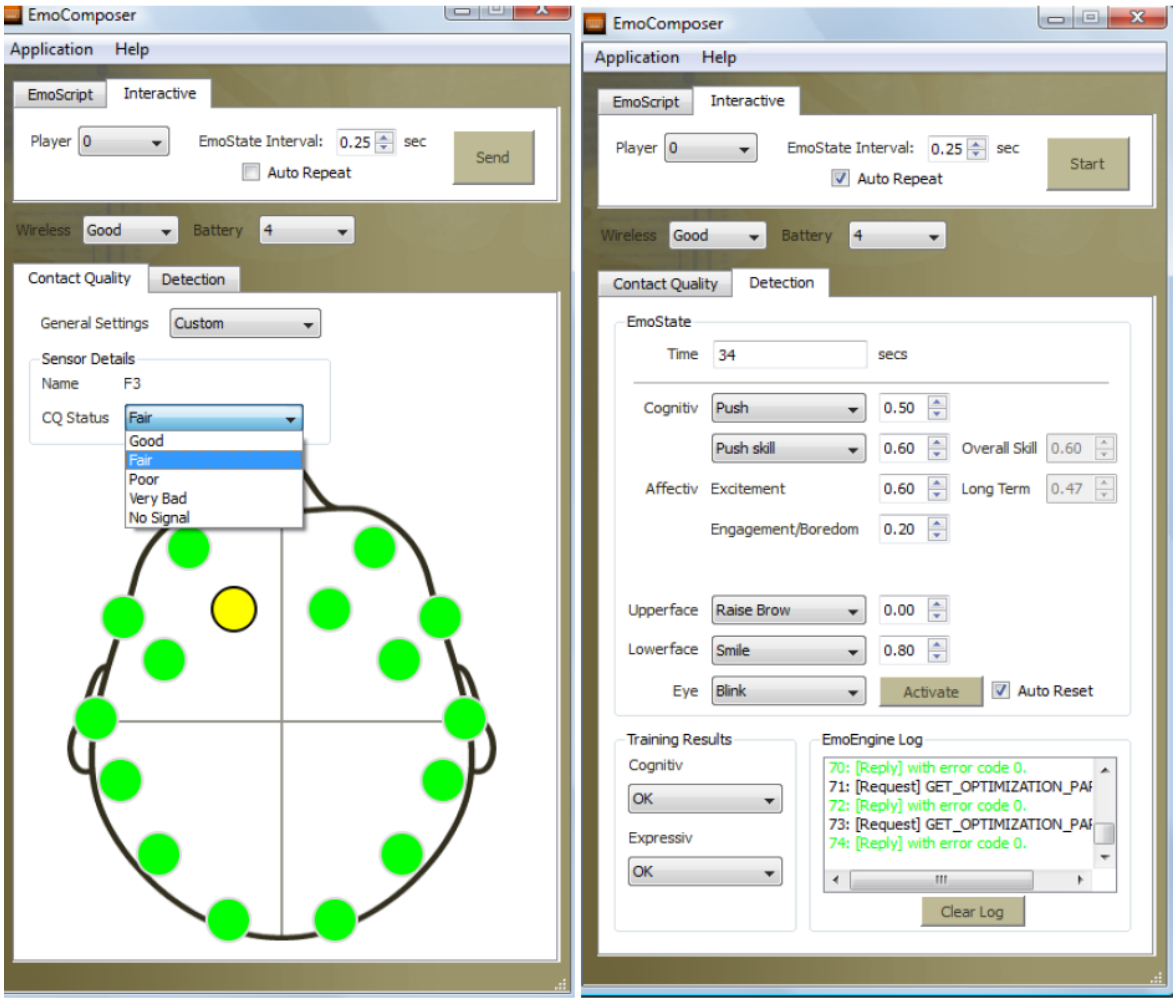


Figure 19. The EmoComposer

5 EXPERIMENT SETUP

5.1 The Scope and Setup

In previous chapters, BCI system has been presented and a novel electronic device has been introduced in detail. In this chapter, the objective of this research, which designs an EEG based BCI as a bridge of human thought and industrial robot, will be implemented with previous information. As previously mentioned, in the Cognitiv Suite of EMOTIV Control Panel, there is a virtual 3D cube that can be used for training to control several actions (*pull, push, right, left, lift and drop*) by means of user thought. In this research, these actions are used to represent the translation of the end-effector of an industrial robot. As it is shown in Figure 20, we assume that motion *pull* represents the +X axis and *push* motion represents the -X axis. Likewise, *right* represents the +Y axis and *left* represents the -Y axis. *Lift* represents the +Z axis and *drop* represents the -Z axis. Furthermore, the action power which can be measured through an acquisition program written by user is used to represent the incremental motion of end-effector in each direction. It is concluded that we use cubic motion for training our thought and then we used action power for controlling the robot. After that, the inverse kinematic of an industrial robot is used to determine the angles of joints through the position of end-effector. An operation panel is designed to display the desired values for user.

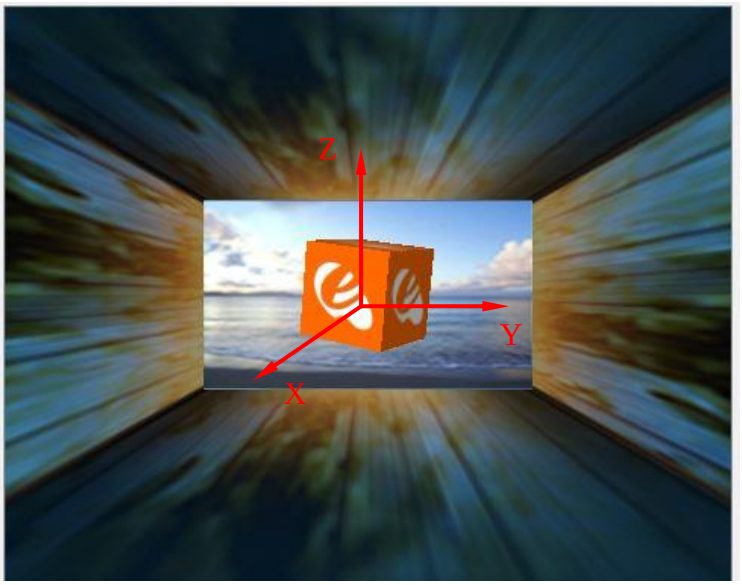


Figure 20 coordinate system of cube

The current BCI structure of this research is illustrated in figure 21. In this research, the BCI system in red frame is planned. As previously mentioned, there are three modules to build a BCI system: signal acquisition, signal processing and external application. Therefore, there are three stages to complement modules in this research. In the first stage, an acquisition program is designed to acquire and process the EEG signals with EMOTIV EPOC system. Program displays the action power and action type as command output when action is done by user thought. In the second stage, the inverse kinematic of an industrial robot is solved. It is a technique preparation for the next stage. In the last stage, a simple operation panel is designed as the external application to display all the wanted values for user such as action type, action power, the coordinate of the end-effector, and the rotation angles of joints. Besides the current BCI system, there is a more complex BCI system in future planning. In that BCI system, a robot control panel will receive the numbers from the operation panel and uses them to control industrial robot. The control panel of industrial robot is a very complicated system to design, so it will be finished in future work.

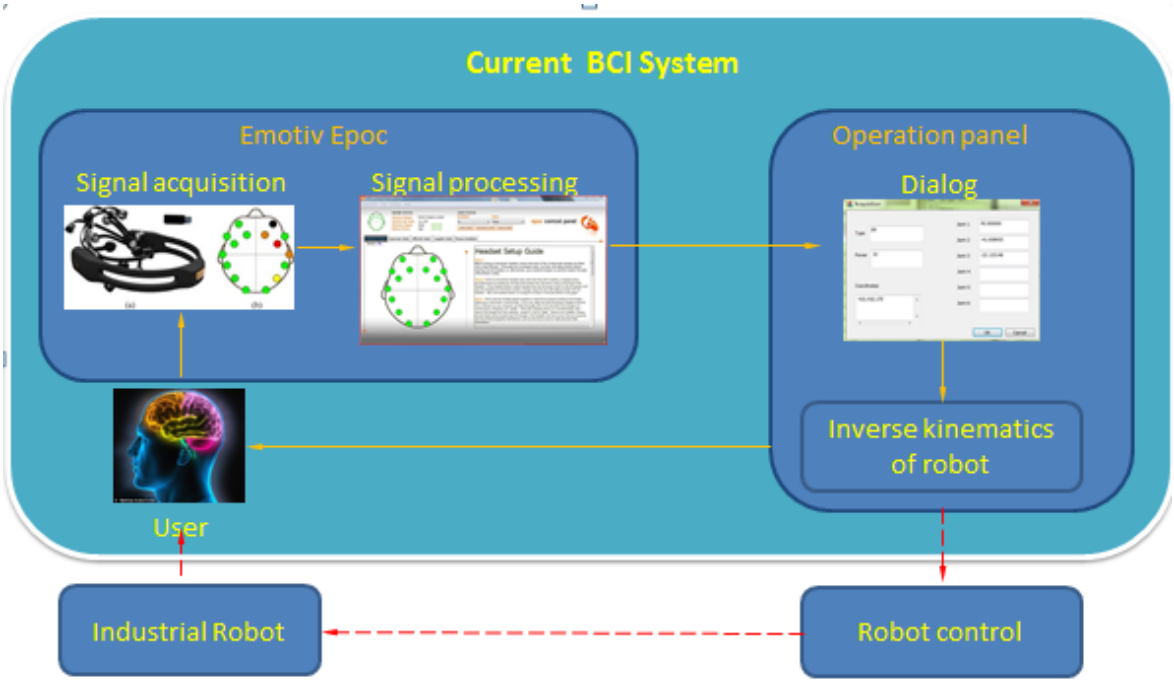


Figure 21.The BCI structure in this research

5.2 Equipment

There are two major components that were considered in this research: 1) EMOTIV EPOC Neuroheadset, a device for the EEG data acquisition 2) industrial robot. The EMOTIV EPOC Neuroheadset in this research is premium version which includes the raw EEG data and software Testbench. The industrial robot is the Mitsubishi RV-3SB Robot Manipulator. The detail of this robot will be described in later section. There is a laptop as the third component which is used to process the signal and edit the control program. For the future signal processing platform, more processors may be used.

5.3 EMOTIV Application Program Interface

Application Program Interface (API) plays an important role of computer programming. It is in close relationship with EmoEngine and Emostate previously mentioned. The correlation between different components of process in this research is shown in Figure 22. The EmoEngine receives the control command from user edited program through EMOTIV API and then connect to EPOC Neuroheadset. Then EmoEngine processes the EEG signal acquired from headset and translates detection results into EmoState which reflects user's facial and cognitive state. The handling of EmoState data also depends on fitting EMOTIV API functions.

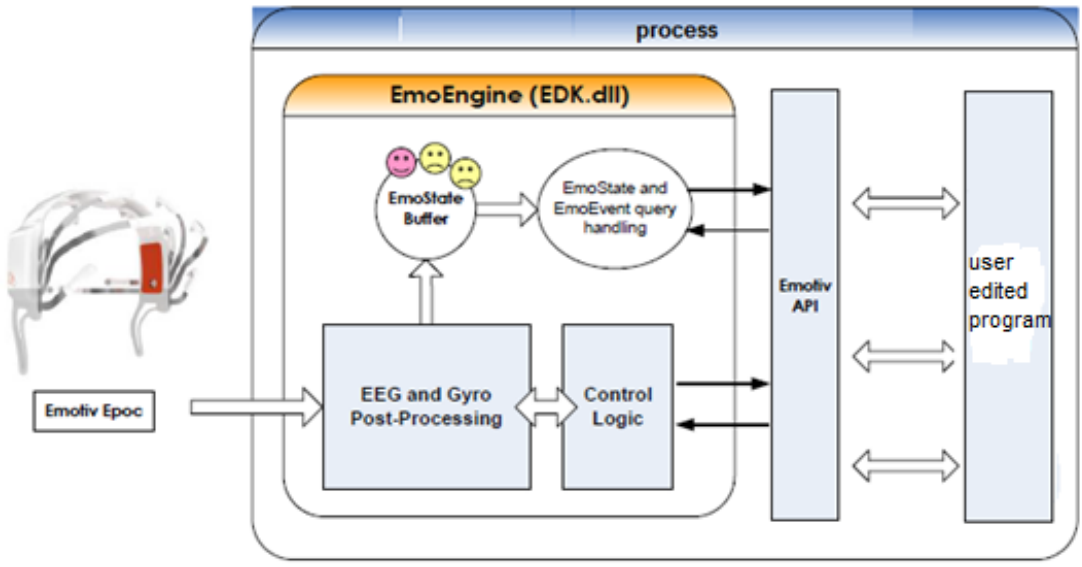


Figure 22. The components and theirs relationship

The utilization of EMOTIV API is illustrated in Figure 23. It helps user to understand the functions of EMOTIV API which includes connecting to EmoEngine, detecting and handling new EmoStates, and querying for new EmoState.

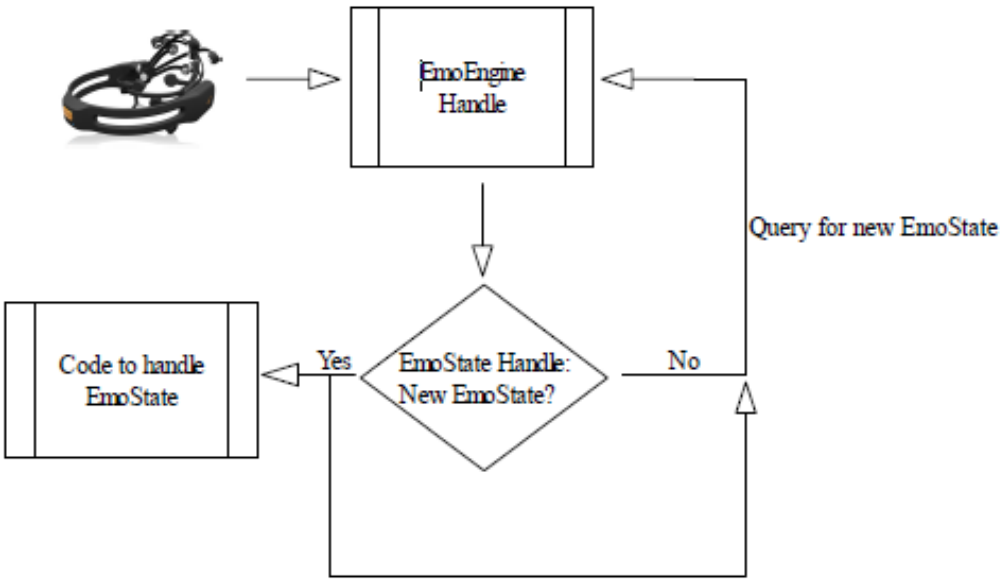


Figure 23. The utilization of EMOTIV API

5.4 Acquiring Program

The program for this research was written in Microsoft Visual C++. This is because that C++ is easy to call the American National Standards Institute (ANSI) C libraries exposed in the EMOTIV API. The code implementing the acquiring program is separated into three stages: connecting to the EMOTIV headset via EMOTIV API, real-time reading and decoding EMOTIV events and showing corresponding results on the screen, and closing the connections when user is done. The complete code is listed in Appendix 1.

5.4.1 EMOTIV connection

Generally, there are two methods to build the connection with headset: using the EE_EngineConnect or using EE_EngineRemoteConnect. In this research, EE_EngineRemoteConnect was selected because program application is desired to connect to EMOTIV Control Panel which queries connection status and provides Cognitiv Suite to control the virtual cube. Thus the function for connecting headset is:

EE_EngineRemoteConnect (“127.0.0.1”, 3008)

5.4.2 Real-time decoding and handling EmoStates

There are three basic steps to read and decode the information acquired form the EPOC headset: creating EmoEngine and EmoState Handle, querying the most recent EmoEngine event and identifying the event type, and decoding the EmoState if it is new. EmoEngnine Handle is a structure that store a handle that is generated by EE_EmoEngineEventCreate() and EmoState Handle is allocated by EE_EmoStateCreate():

```
EmoEngineEventHandle eEvent        = EE_EmoEngineEventCreate ( );
EmoStateHandle eState              = EE_EmoStateCreate ( );
```

Before the last two steps, there is a problem to solve firstly. This problem is how to achieve the real-time acquisition. Therefore, the problem of real-time acquisition can be solved by calling:

```
While (true);
{
⋮      ⋮
Sleep (5);
};
```

By using While (true), the program will give a response immediately if there is a EmoEngine event. To detect every event, most applications should poll at least 10-15 times per second or one time per 0.05s. sleep (5) can give system a break in order to avoid the problem of system crash, where 5 represents the break time is 0.005s which is much short than 0.05s.

The second step is retrieving the EmoEngine event by calling EE_EngineGetNextEvent() and identifying it. There are three main types of EmoEngine events: Hardware-related events, new EmoState events and Suite-specific events. Hard ware-related events are the events that connect or disconnect headset with computer, which include EE_UserAdded and EE_UserRemoted. New EmoState events are the events that are related to user's facial and cognitive state. The most common event of this type is EE_EmoStateUpdated. Suite-specific events are the events for training and configuring Cogntiv or Expressiv Suites, such as EE_CognitivEvent. In order to identify the type of EmoEngine event, EE_EmoEngineEventGetType () can be used:

```
int state = EE_EngineGetNextEvent(eEvent);
```

```
if (state == EDK_OK) {
    EE_Event_t eventType = EE_EmoEngineEventGetType(eEvent);
}
```

The last step is to decode the EmoState event. In this research, the Cognitiv Suites is the main unit to concentrate, so only Cognitiv action is detected and decoded. Action type represents the direction and action power represents the value of motion. They can be obtained by follow codes:

```
EE_CognitivAction_t actionType = ES_CognitivGetCurrentAction(eState);
        float actionPower = ES_CognitivGetCurrentActionPower(eState);
        type=static_cast<int>(actionType);
       power=static_cast<int>(actionPower*100.0f);
```

EE_CognitivAction_t is a Cognitiv action type enumerator. Comparing to the defined enumerator values in Table 5, the integer value of the actionType can be gained.

Table 5. Action motions and their defined enumerator values

Action	*Value*	*Action*	*Value*
Neutral	*0x0001*	*Rotate Left*	*0x0080*
Push	*0x0002*	*Rotate Right*	*0x0100*
Pull	*0x0004*	*Rotate Clockwise*	*0x0200*
Lift	*0x0008*	*Rotate Counterclockwise*	*0x0400*
Drop	*0x0010*	*Rotate Forward*	*0x0800*
Left	*0x0020*	*Rotate Backward*	*0x1000*
Right	*0x0040*		

As previously mentioned, there are six possible actions in this case: pull/push, left/right, and lift/drop. The action should be trained before experiment starts, so only these six types can be detected after training and other actions are ignored automatically. The action power of thought is initially used as the moving distance of robot end-effector. However, it is difficult to obtain a specific required power of thought. Hence the direction of robotic action is what we focus on, no matter the thought-power. At last, presenting the results on screen by follow codes:

```
std::cout<<"actiontype:" <<static_cast<int>(actionType) << "," <<
"actionpower:"<<static_cast<int>(actionPower*100.0f)<<std::endl;
```

5.4.3 EMOTIV disconnection

In the last stage, disconnection is finished and the internal memory is released by calling:

```
EE_EngineDisconnect ();
EE_EmoStateFree (eState);
EE_EmoEngineEventFree (eEvent);
```

5.5 Inverse Kinematic of RV-3SB Robot Manipulator

The industrial robot used in this research is Mitsubishi RV-3SB Robot Manipulator with high speed and high precision. It is a 6-axis type with brakes for all axes. The first three joints are used to determine the position of end-effector, while the rest three joints are used to decide the orientation of end-effector. In this research, we only consider the translation of the end-effector in this thesis work, so the angles of first three joints are demanded and displayed. The physical representation of this robot arm is shown in Figure 24. It consists of several parts: Base, Waist, Shoulder, Upper arm, Elbow, Elbow block, Fore arm, Wrist and mechanical interface. The optional dimensions are illustrated in Figure 25.

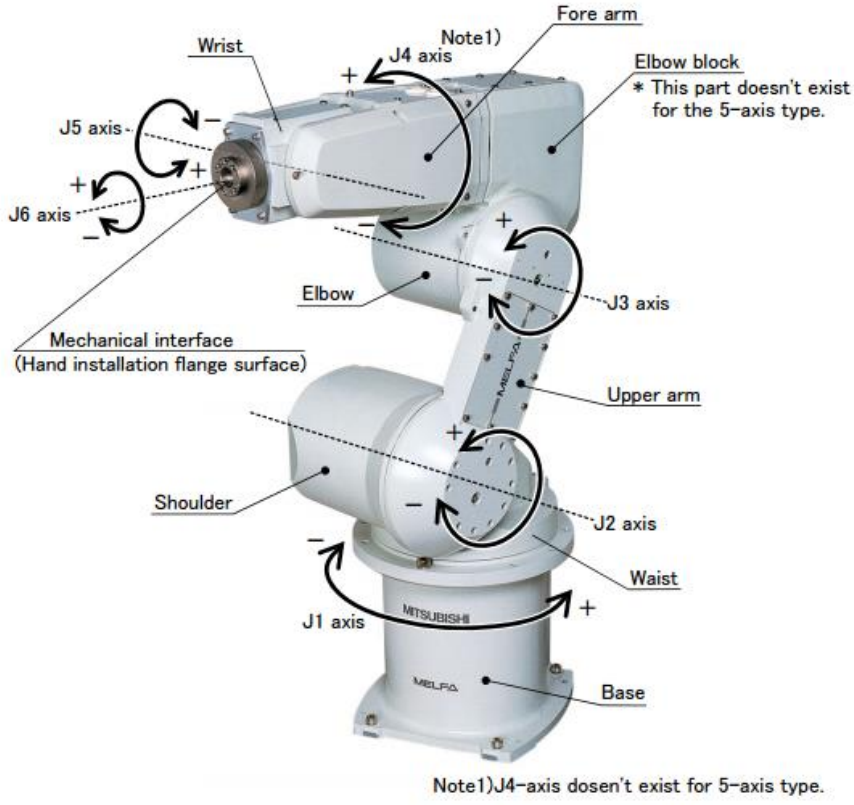


Figure 24. The physical representation of manipulator

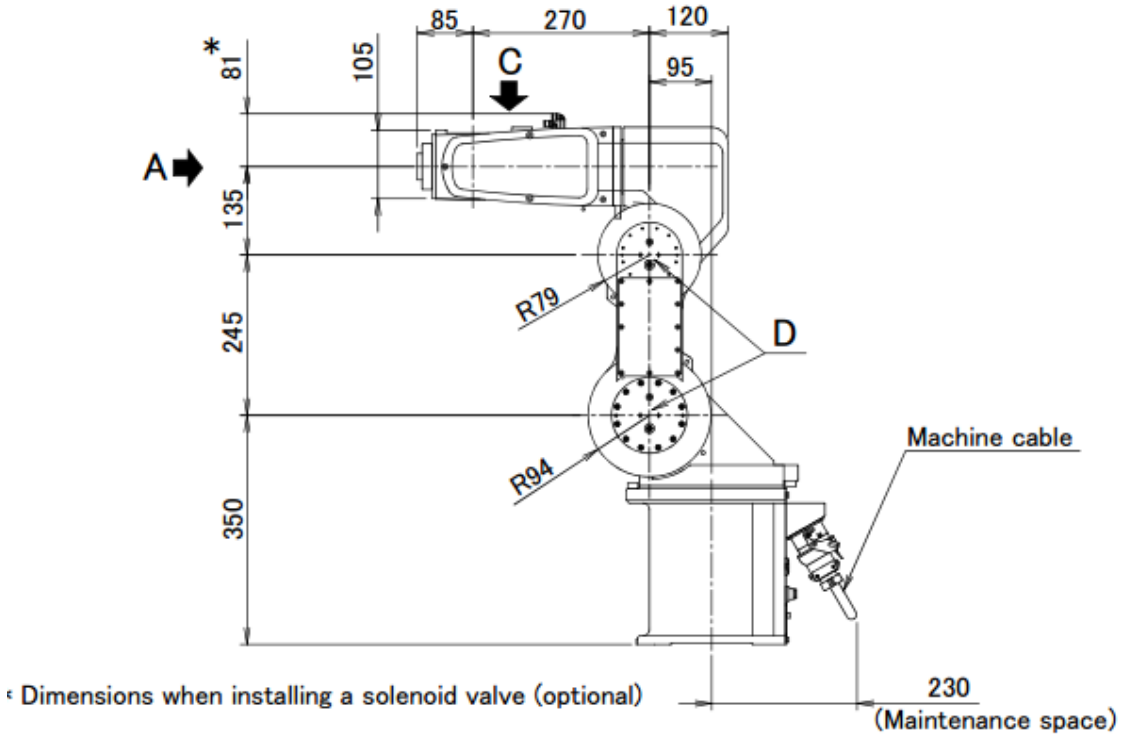


Figure 25. Optional dimensions of manipulator

To solve the inverse kinematic of this manipulator, the first step is analyzing the forward kinematic of robot manipulator by DH method. The robot manipulator coordinate system attached to the DH method is established according to its structure. It is shown in Figure 26.

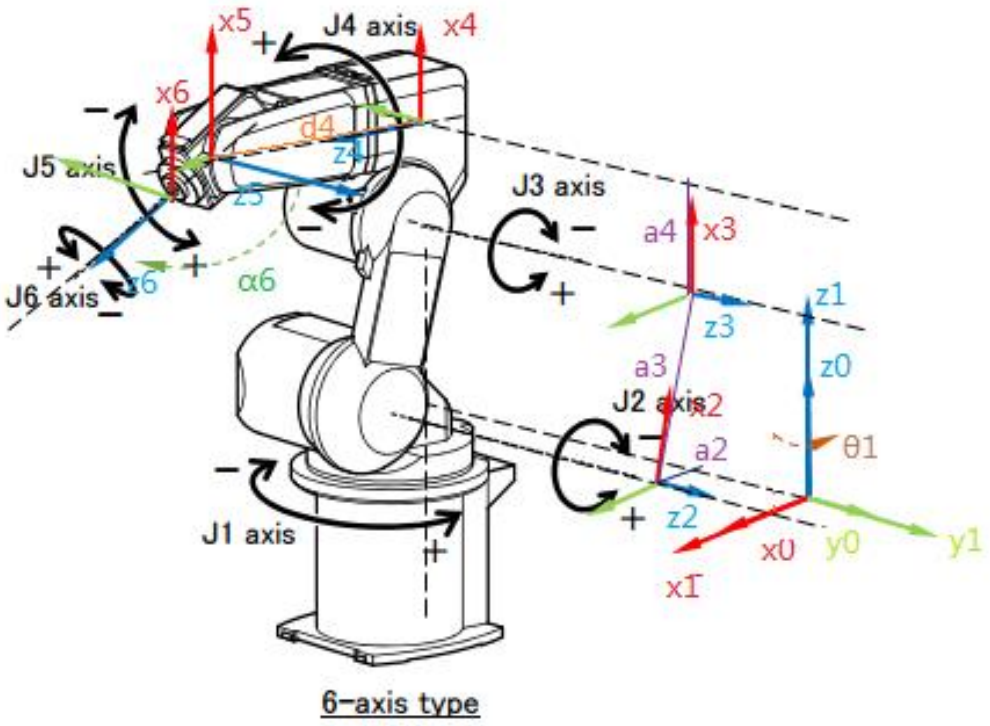


Figure 26. Coordinate system attached to D-H method

The four DH parameters of every joint are defined and listed in Table 6, where a1= 95mm, a2=245mm, a3=135mm and d4=270mm. The Then transformation matrix ${}^{i-1}T_i$ can be calculated.

Table 6. Four DH parameters of every joint

Joint i	d_i	θ_i	a_i	α_i
1	*0*	θ_1	*0*	0^o
2	*0*	θ_2	*95*	-90^o
3	*0*	θ_3	*245*	0^o
4	*270*	θ_4	*135*	-90^o
5	*0*	θ_5	*0*	90^o
6	*0*	θ_6	*0*	-90^o

$$
{}^{0}T_{1}=\begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & a_1 \\ \sin\theta_1\cos\alpha_1 & \cos\theta_1\cos\alpha_1 & -\sin\alpha_1 & -\sin\alpha_1 d_1 \\ \sin\theta_1\sin\alpha_1 & \cos\theta_1\sin\alpha_1 & \cos\alpha_1 & \cos\alpha_1 d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
=\begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{1}T_{2}=\begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & a_2 \\ \sin\theta_2\cos\alpha_2 & \cos\theta_2\cos\alpha_2 & -\sin\alpha_2 & -\sin\alpha_2 d_2 \\ \sin\theta_2\sin\alpha_2 & \cos\theta_2\sin\alpha_2 & \cos\alpha_2 & \cos\alpha_2 d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
=\begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & a_2 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_2 & -\cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{2}T_{3}=\begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & a_3 \\ \sin\theta_3\cos\alpha_3 & \cos\theta_3\cos\alpha_3 & -\sin\alpha_3 & -\sin\alpha_3 d_3 \\ \sin\theta_3\sin\alpha_3 & \cos\theta_3\sin\alpha_3 & \cos\alpha_3 & \cos\alpha_3 d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
=\begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & a_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{3}T_{4}=\begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & a_4 \\ \sin\theta_4\cos\alpha_4 & \cos\theta_4\cos\alpha_4 & -\sin\alpha_4 & -\sin\alpha_4 d_4 \\ \sin\theta_4\sin\alpha_4 & \cos\theta_4\sin\alpha_4 & \cos\alpha_4 & \cos\alpha_4 d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
=\begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & a_4 \\ 0 & 0 & 1 & d_4 \\ -\sin\theta_4 & -\cos\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{4}T_{5}=\begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & a_5 \\ \sin\theta_5\cos\alpha_5 & \cos\theta_5\cos\alpha_5 & -\sin\alpha_5 & -\sin\alpha_5 d_5 \\ \sin\theta_5\sin\alpha_5 & \cos\theta_5\sin\alpha_5 & \cos\alpha_5 & \cos\alpha_5 d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
=\begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin\theta_5 & \cos\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{5}T_{6}=\begin{bmatrix} \cos\theta_6 & -\sin\theta_6 & 0 & a_6 \\ \sin\theta_6\cos\alpha_6 & \cos\theta_6\cos\alpha_6 & -\sin\alpha_6 & -\sin\alpha_6 d_6 \\ \sin\theta_6\sin\alpha_6 & \cos\theta_6\sin\alpha_6 & \cos\alpha_6 & \cos\alpha_6 d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$= \begin{bmatrix} \cos\theta_6 & -\sin\theta_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_6 & -\cos\theta_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

After transformation matrix of each joint is calculated, the general transformation matrix equation is:

$${}^0T_6 = {}^0T_1\,{}^1T_2\,{}^2T_3\,{}^3T_4\,{}^4T_5\,{}^5T_6 \qquad (1)$$

In this research, we assume that the general transformation matrix is:

$${}^0T_6 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where r_{kj} represent the rotational elements (k and j=1, 2 and 3). p_x, p_y and p_z denote the elements of position vector. The equations of position elements are listed below:

$p_x = \cos\theta_1[a_4\cos(\theta_2 + \theta_3) - d_4\sin(\theta_2 + \theta_3) + a_3\cos\theta_2 + a_2]$

$p_y = \sin\theta_1\,[a_4\cos(\theta_2 + \theta_3) - d_4\sin(\theta_2 + \theta_3) + a_3\cos\theta_2 + a_2]$

$p_z = -a_4\sin(\theta_2 + \theta_3) - d_4\cos(\theta_2 + \theta_3) - a_3\sin(\theta_2)$

After forward kinematics is solved, the inverse kinematic can be solved with previous mentioned method. To find the inverse kinematics solution for the first joint as a function of the known elements of ${}^0T_6$, the link transformation inverses are pre-multiplied as follow:

$$({}^0T_1)^{-1}\,{}^0T_6 = {}^1T_2\,{}^2T_3 \cdots {}^5T_6$$

$$= \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} =$$

$$\begin{bmatrix} r_{11}\cos\theta_1 + r_{21}\sin\theta_1 & r_{12}\cos\theta_1 + r_{22}\sin\theta_1 & r_{31}\cos\theta_1 + r_{32}\sin\theta_1 & p_x\cos\theta_1 + p_y\sin\theta_1 \\ -r_{11}\sin\theta_1 + r_{21}\cos\theta_1 & -r_{12}\sin\theta_1 + r_{22}\cos\theta_1 & -r_{31}\sin\theta_1 + r_{32}\cos\theta_1 & -p_x\sin\theta_1 + p_y\cos\theta_1 \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= {}^1T_2\,{}^2T_3 \cdots {}^5T_6$$

$$= \begin{bmatrix} \cdot & \cdot & \cdot & a_2 + a_4cos(\theta_2 + \theta_3) - d_4sin(\theta_2 + \theta_3) + a_3cos(\theta_2) \\ \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & -a_4\sin(\theta_2 + \theta_3) - d_4\cos(\theta_2 + \theta_3) - a_3\sin\theta_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} = A_1$$

The $A_1(2,4)$ in each side of equation should be equal:

$$-p_x \sin\theta_1 + p_y \cos\theta_1 = 0 \quad (2)$$

$$\theta_1 = \tan^{-1}(p_y/p_x)$$

$A_1(1,4)$ and $A_1(3,4)$ in each side of equation should be equal separately:

$$p_x \cos\theta_1 + p_y \sin\theta_1 = a_2 + a_4 cos(\theta_2 + \theta_3) - d_4 sin(\theta_2 + \theta_3) + a_3 cos(\theta_2) \quad (3)$$

$$p_z = -a_4 \sin(\theta_2 + \theta_3) - d_4 \cos(\theta_2 + \theta_3) - a_3 \sin\theta_2 \quad (4)$$

Squared equation (2), (3) and (4), and then add them together:

$$p_x{}^2 + p_y{}^2 + p_z{}^2 + a_2{}^2 - 2a_2 p_x \cos\theta_1 - 2a_2 p_y \sin\theta_1 = a_4{}^2 + d_4{}^2 + a_3{}^2 + 2a_3 a_4 \cos\theta_3 - 2a_3 d_4 \sin\theta_3 \quad (5)$$

We define that

$$a_4 \cos\theta_3 - d_4 \sin\theta_3 = K \quad (6)$$

Where $K = (p_x{}^2 + p_y{}^2 + p_z{}^2 + a_2{}^2 - 2a_2 p_x \cos\theta_1 - 2a_2 p_y \sin\theta_1 - a_4{}^2 - d_4{}^2 - a_3{}^2)/(2a_3)$ *(7)*

We assume that $a_4 = \rho \sin\gamma$, $d_4 = \rho \cos\gamma$, where $\rho = \sqrt{a_4{}^2 + d_4{}^2}$, $\gamma = \tan^{-1}(a_4/d_4)$

substitute into equation (6):

$$\rho \sin\gamma \cos\theta_3 - \rho \cos\gamma \sin\theta_3 = K$$

$$\sin(\gamma - \theta_3) = K/\rho, \cos(\gamma - \theta_3) = \pm\sqrt{1 - \left(\frac{K}{\rho}\right)^2}$$

$$\gamma - \theta_3 = \tan^{-1}\left(\pm K/\sqrt{\rho^2 - K^2}\right)$$

$$\theta_3 = \tan^{-1}(a_4/d_4) - \tan^{-1}\left(\pm K/\sqrt{\rho^2 - K^2}\right)$$

In order to calculateθ_2, $({}^0T_1\,{}^1T_2{}^2T_3)^{-1}$ is pre-multiplied to the both side of equation (1).

$$({}^0T_1\,{}^1T_2{}^2T_3)^{-1}{}^0T_6 = ({}^0T_1\,{}^1T_2{}^2T_3)^{-1}{}^0T_1\,{}^1T_2\,{}^2T_3\,{}^3T_4\,{}^4T_5\,{}^5T_6$$

$$\begin{bmatrix} \cdot & \cdot & \cdot & -p_z \sin(\theta_2+\theta_3) - a_2 \cos(\theta_2+\theta_3) - a_3 \cos\theta_3 + p_x \cos(\theta_2+\theta_3)\cos\theta_1 + p_y \cos(\theta_2+\theta_3)\sin\theta_1 \\ \cdot & \cdot & \cdot & -p_z \cos(\theta_2+\theta_3) + a_2 \sin(\theta_2+\theta_3) + a_3 \sin\theta_3 - p_x \sin(\theta_2+\theta_3)\cos\theta_1 - p_y \sin(\theta_2+\theta_3)\sin\theta_1 \\ \cdot & \cdot & \cdot & -p_x \sin\theta_1 + p_y \cos\theta_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \cdot & \cdot & \cdot & a_4 \\ \cdot & \cdot & \cdot & d_4 \\ \cdot & \cdot & \cdot & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = A_2$$

A_2 (1,4) and A_2(2,4) in both side of equation are equal, then

$$-p_z \sin(\theta_2+\theta_3) - a_2\cos(\theta_2+\theta_3) - a_3\cos\theta_3 + p_x\cos(\theta_2+\theta_3)\cos\theta_1 + p_y\cos(\theta_2+\theta_3)\sin\theta_1 = a_4 \quad (7)$$

$$-p_z\cos(\theta_2+\theta_3) + a_2\sin(\theta_2+\theta_3) + a_3\sin\theta_3 - p_x\sin(\theta_2+\theta_3)\cos\theta_1 - p_y\sin(\theta_2+\theta_3)\sin\theta_1 = d_4 \quad (8)$$

From equation (8) and (9), we can get:

$$\frac{-p_z \sin(\theta_2+\theta_3) - a_2\cos(\theta_2+\theta_3) - a_3\cos\theta_3 + p_x\cos(\theta_2+\theta_3)\cos\theta_1 + p_y\cos(\theta_2+\theta_3)\sin\theta_1}{-p_z\cos(\theta_2+\theta_3) + a_2\sin(\theta_2+\theta_3) + a_3\sin\theta_3 - p_x\sin(\theta_2+\theta_3)\cos\theta_1 - p_y\sin(\theta_2+\theta_3)\sin\theta_1} = \frac{a_4}{d_4}$$

$$\theta_2+\theta_3 = \tan^{-1}\left[\frac{-p_z(a_4+a_3\cos\theta_3) - (d_4 - a_3\sin\theta_3)\left(p_x\cos\theta_1 + p_y\sin\theta_1 - a_2\right)}{(a_4+a_3\cos\theta_3)\left(p_x\cos\theta_1 + p_y\sin\theta_1 - a_2\right) - p_z(d_4 - a_3\cos\theta_3)}\right]$$

$$\theta_2 = \theta_2+\theta_3-\theta_3$$

Now, we have got the expression of $\theta_1, \theta_2, \theta_3$ with DH parameters and position elements. According to standard specifications of robot, the ranges of θ_1, θ_2 *and* θ_3 are: -170 to +170, -180 to 45 and -110 to +81, respectively. The calculating process is done by Matlab and the codes are shown in Appendix 2.

5.6 Operation Panel

After inverse kinematic of industrial manipulator is solved, an operation panel is built up to display the real-time information for users. In this research, the panel in Windows system is based on Microsoft Foundation Classes (MFC). MFC is a library that wraps Windows API in C++ classes. It includes a default application framework to reduce the workload of developers. It also includes a lot of windows handle wrapper classes and classes for predefined windows controls.

Generally, there are two basic steps to build a MFC based operation panel. The first step is to design a simple and clear user panel. A typical panel has a number of common controls, such as Button, Check Box and Edit Control. The second step is to edit code in response to controls and then a MFC application is completed. The complete code is listed in Appendix 3.

5.6.1 Designing User Panel

Firstly building a MFC project follows the MFC Application Wizard. There are two basic application types: document and dialog. The type of the application in this research is dialog based which applies a simple interface, and project style is standard MFC. After a dialog box named “Acquisition” is created, various controls should be added on it. The common controls in this research are: Button, Static Text and Edit Control. The layouts of these controls are illustrated in Figure 27. There are nine Edit boxes corresponding to nine captions to show different text. The meanings of the captions are: Type refers to the type of the action done by human thought, power represents the action power or the incremental displacement of the end-effector done by human thought, coordinates is the position of end-effector in artificial coordinate system, and joint 1-6 mean the angle of each joint separately. The first three joints are calculated through inverse kinematic with known position of cube.

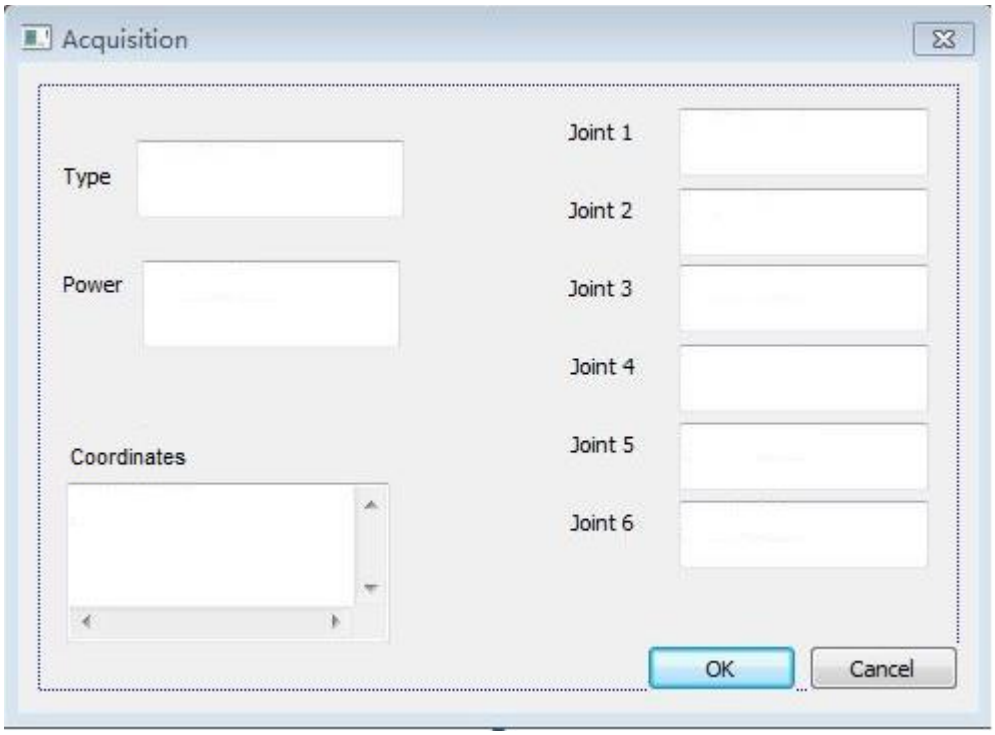


Figure 27. The MFC application for presenting

5.6.2 Editing Code for Controls

Now it is time to edit code for the controls. Firstly, each edit box is added with a variable. They are listed in Table 7. There are two main problems to solve in this step: 1) real-time detecting the signal 2) constantly refreshing edit boxes in real time to display the latest data.

Table 7. The control units and variables

Control name	*Caption*	*Variable name*
IDC_EDIT1	*Type*	*m_edit1*
IDC_EDIT2	*Power*	*m_edit2*
IDC_EDIT3	*Coordinates*	*m_edit3*
IDC_EDIT4	*Joint 1*	*m_edit4*
IDC_EDIT5	*Joint 2*	*m_edit5*
IDC_EDIT6	*Joint 3*	*m_edit6*
IDC_EDIT7	*Joint 4*	*m_edit7*
IDC_EDIT8	*Joint 5*	*m_edit8*
IDC_EDIT9	*Joint 6*	*m_edit9*

1) Real-time detecting the signal

In the codes of acquisition program, while (true) was used to solve the problem of acquiring in real-time. However, if this function is used directly for button “ok”, the system will be crashing. If “true” is replaced by a specific number, for example “while (number<2)”, the program will detect and decode event twice and close then. The problem is that function “while(true)” intensively uses computer resources all the time, which makes button”ok” cannot be responded, viz., that system will be halted. In this research, this problem is solved by using multithread programming. It is an easy and safe way to perform background calculation and maintenance. Firstly, creating a new class named “AcquisitionThread” that is based on class CWinThread through MFC class Wizard. A thread is easily created and operated by function AfxBeginThread ( ). Here is a brief introduction for it. The definition of this function in Microsoft Developer Network library is [63]:

```
CWinThread* AfxBeginThread (
  AFX_THREADPROC pfnThreadProc,
```

```
  LPVOID pParam,
  int nPriority = THREAD_PRIORITY_NORMAL,
  UINT nStackSize = 0,
  DWORD dwCreateFlags = 0,
  LPSECURITY_ATTRIBUTES lpSecurityAttrs = NULL
);
```

Where pfnThreadProc points a controlling function for worker thread and it must be declared as follow:

```
  unsigned int MyThreadFunction (LPVOID pParam);
```

Parameter pParam is to be passed to the controlling function; it can be a structure because of LPVOID;

nPriority means the desired priority of the thread. Normally it is 0 and it shares same priority with main thread;

nStackSize specifies the size bytes of the stack for new thread;

dwCreateFlags specifies an additional flag that controls the creation of the thread. It is 0 and then it runs automatically;

lpSecurityAttrs is structure that specifies the security attributes for the thread. If NULL, it shares same security attributes with main thread;

Return value is a Pointer to the newly created thread object, or NULL if a failure occurs.

Firstly, pfnThreadProc and other parameters are declared in "AcquisitionThread.h" below, and it is edited in "AcquisitionThread.cpp" which will be listed particularly in Appendix 3.

```
   static CWinThread * m_pAcquisitionThread;
   static unsigned int ThreadAcquisitionDataFunc(LPVOID pParam);
   static double * m_pParam4Data;
```

Secondly, AfxBeginThread ( ) is created in CAcquisitionApp::InitInstance ( ) below and it will run automatically if this MFC application starts.

```
If (AcquisitionThread::m_pAcquisitionThread == NULL)
                {
                  AcquisitionThread::m_pAcquisitionThread = AfxBeginThread
                  (AcquisitionThread::ThreadAcquisitionDataFunc,
                  (LPVOID)AcquisitionThread::m_pParam4Data);
```

};

At last, other parameters can be defined as default. Therefore, a new thread is built and the previous mentioned acquiring program should be written in this thread. After the action power and type are gained, we attach them to a Cartesian coordinate system to describe the coordinate of end-effector. The code for positioning the cube in coordinate system is shown below:

```
switch(Type){
case 0 :{
                    AcquisitionThread::Direction =_T("neural");
                    break;
            }
case 2 :{
             m_dX = m_dX-m_dPower;
             m_dY = m_dY;
             m_dZ = m_dZ;
             AcquisitionThread::Direction =_T("push");
            break;
            }
case 4 :{
                    m_dX = m_dX+m_dPower;
              m_dY = m_dY;
              m_dZ = m_dZ;
                    AcquisitionThread::Direction =_T("pull");
                    break;
            }
            case 8 :{
                    m_dX = m_dX;
              m_dY = m_dY;
              m_dZ = m_dZ+m_dPower;
                    AcquisitionThread::Direction =_T("lift");
                    break;
```

```
                }
  case 16 :{
                        m_dX = m_dX;
                m_dY = m_dY;
                m_dZ = m_dZ-m_dPower;
                        AcquisitionThread::Direction =_T("drop");
                        break;
                }
                case 32 :{
                        m_dX = m_dX;
                m_dY = m_dY-m_dPower;
                m_dZ = m_dZ;
                        AcquisitionThread::Direction =_T("left");
                        break;
  }
  case 64 :{
                        m_dX = m_dX;
                m_dY = m_dY+m_dPower;
                m_dZ = m_dZ;
                        AcquisitionThread::Direction =_T("right");
                        break;
  }
}
  m_dx=m_dX;
  m_dy=m_dY;
  m_dz=m_dZ;
```

Where m_dx, m_dy, m_dz refer to the position of the end-effector in X axis, Y axis, Z axis separately. m_dPower refers to the action power.

2) Constantly refreshing edit boxes in real-time to display the latest data

Function OnTimer ( ) is a suitable way to refresh the edit boxes in real time. It can be called by class CWnd and its derived class. Firstly, creating a timer in the program of button ”ok” as follow:

```
void CAcquisitionDlg::OnBnClickedOk()
{
        SetTimer(nIDEvent, nElapse, NULL);
}
```

Where nIDEvent is the ID of timer and nElapse represents interval time.

At last, edit the timer in function CAcquisitionDlg::OnTimer(UINT_PTR nIDEvent). This function includes the codes for the assigning the necessary variables to different controls. Button ”OK” is used to start the program and “Cancel” is used to quit.

6 EXPERIMENT FOR SYSTEM TESTING

Based on the designed BCI system above, a series of experiments including three stages are carried out for testing the feasibility and accuracy of this system. The first stage is a testing experiment for the acquisition program. The second stage is a testing experiment for the MFC application. As previous mentioned, EmoComposer connected to EMOTIV Control Panel and sent built-in data signals as system input to it. In this research, the program was allowed to use EmoComposer with the aim of making a quick and testable prototype before using user's thought. Another method to obtain the input for building BCI system is acquiring user's thought actually through EMOTIV headset. In the last stage, an experiment of the designed BCI system is done. Actual signals acquired from headset were used as inputs instead of stimulated signals from EmoComposer.

6.1 Testing of the Acquisition Program

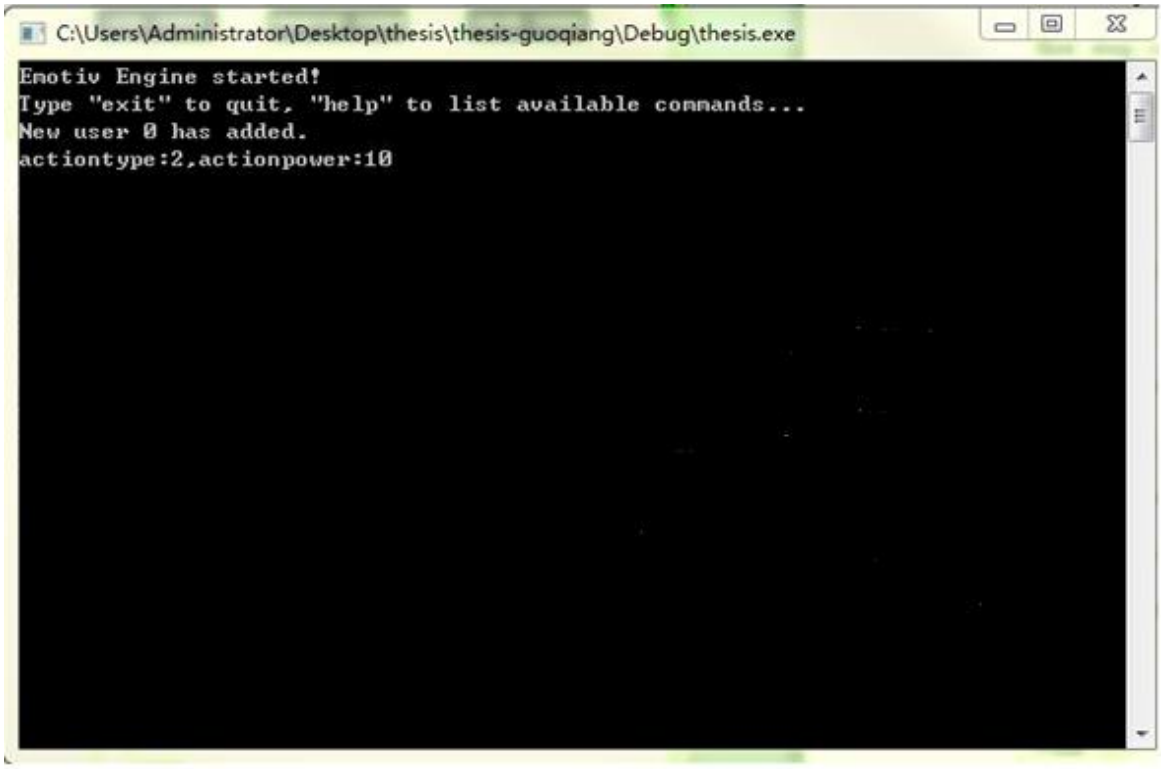
The aim of this test is to examine whether the acquisition program detects the type and the power of cube motion. The steps of this experiment are described below. At first, EMOTIV Control Panel and EmoComposer were started and then Acquisition program was run. After that, EMOTIV Control Panel was connected to EmoComposer. Then the option "Contact Quality" in EmoComposer was set as all good and we started to control the cube. In this test, there are six groups corresponding to six cube motions: push, pull, lift, drop, left and right. Based on the defined enumerator values, the integer value of the action type of these motions is 2, 4, 8, 16, 32 and 64. The motions are sorted by value from small to large and each motion is sent twice with different action power by EmoComposer. The motions and corresponding given value of power are listed in Table 8.

Table 8. Motion type and given power

Motion type (integer value)	*Power 1*	*Power 2*
Push (2)	*10*	*20*
Pull (4)	*30*	*40*
Lift (8)	*50*	*40*
Drop (16)	*60*	*50*

Left (32)	*60*	*50*
Right (64)	*80*	*60*

The result of this testing is stated as follow. When acquisition program was run, it is shown that "*EMOTIV Engine started! Type 'exit' to quit, 'help' to list available commands… New user 0 has used*." When we sent the first command following the plan through EmoComposer, the action type and power were shown on the screen instantly as shown in Figure 28 (a). After all the planned motions were done, the final result is shown in Figure 28 (b).



(a)

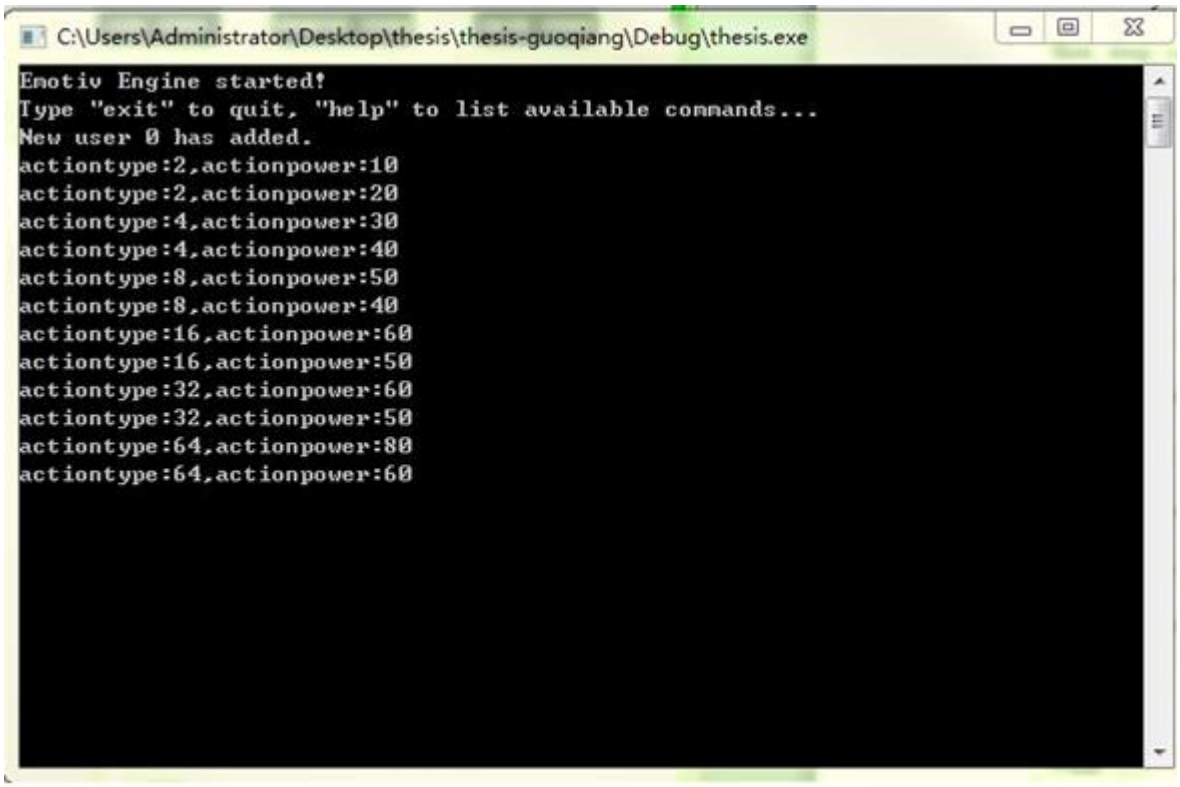


Figure 28. (a) The state after EMOTIV Engine started, (b) The testing results of acquisition program

6.2 Experiment of MFC Application

Comparing the results in Figure 28 and the given value, it is obvious that the acquisition program is efficient. Based on this precondition, the second stage is designed to examine the feasibility of the MFC application. The detailed scheme is stated as follow. At first, EMOTIV Control Panel and EmoComposer were started and then MFC application was run. After that, EMOTIV Control Panel was connected to EmoComposer. Then the option "Contact Quality" in EmoComposer was set as all good and then we started the testing. In this experiment, we assumed that the cognitive state was neural and the end-effector was located at the origin of coordinate system. Considering the workspace of manipulator, we planned to move end-effector from (300, 0, 0) to (400, 400, 150) to test six motions following the steps shown in Table 9. At last, the corresponding series of joints angles of each given position which are used for comparison are also listed in Table 9. The angles of different joints are calculated by Matlab based on the inverse kinematic analysis.

Table 9. The planned steps and optional angles of joints in each step

Step	*Coordinate*	*Joint 1*	*Joint 2*	*Joint 3*
1	*300,0,0*	*0*	*-83.7561*	*74.1052*
2	*350,0,0*	*0*	*-74.2459*	*62.1745*
3	*350,350,0*	*45.0000*	*-48.8836*	*23.1428*
4	*410,350,0*	*40.4860*	*-40.2399*	*8.4255*
5	*410,410,0*	*45.0000*	*-30.8478*	*-7.9948*
6	*410,410,100*	*45.0000*	*-39.7626*	*-12.8455*
7	*410,410,170*	*45.0000*	*-41.6590*	*-23.1331*
8	*400,410,170*	*45.7073*	*-44.1032*	*-19.2352*
9	*400,400,170*	*45.0000*	*-46.4155*	*-15.6018*
10	*400,400,150*	*45.0000*	*-46.0697*	*-12.3395*

When MFC application was run, there was a pop-up messagebox with message "EMOTIV Engine started" which means that application has connected with EMOTIV Engine successfully. Firstly, we need to place end-effector at point (300,0,0). When we sent the commands through EmoComposer, the action type, power and the angles were shown on the dialog instantly. The angles at the point (300,0,0) moreover are displayed on it. The result is shown in Figure 29. Then we started to move following the planned position. After all the planned motions were done, the result of point (400, 400, 150) is shown in Figure 30 and all the wanted values are listed in table 10. The results of other points are shown in Appendix 4.

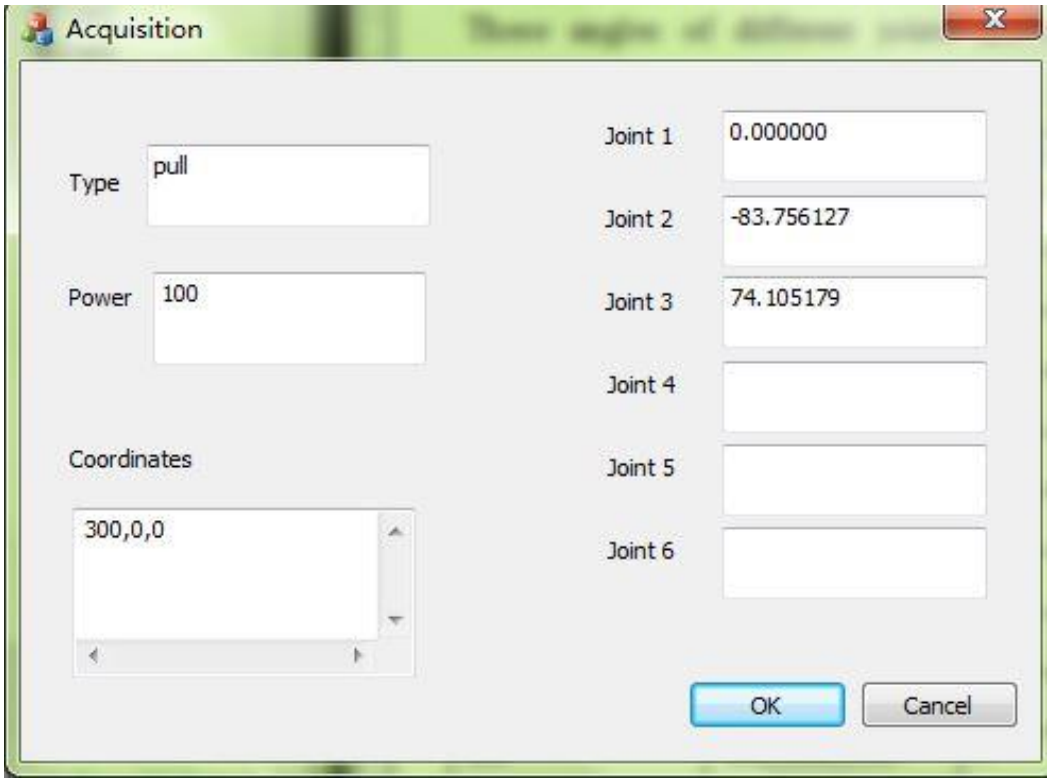


Figure 29. The wanted information at point (300,0,0)

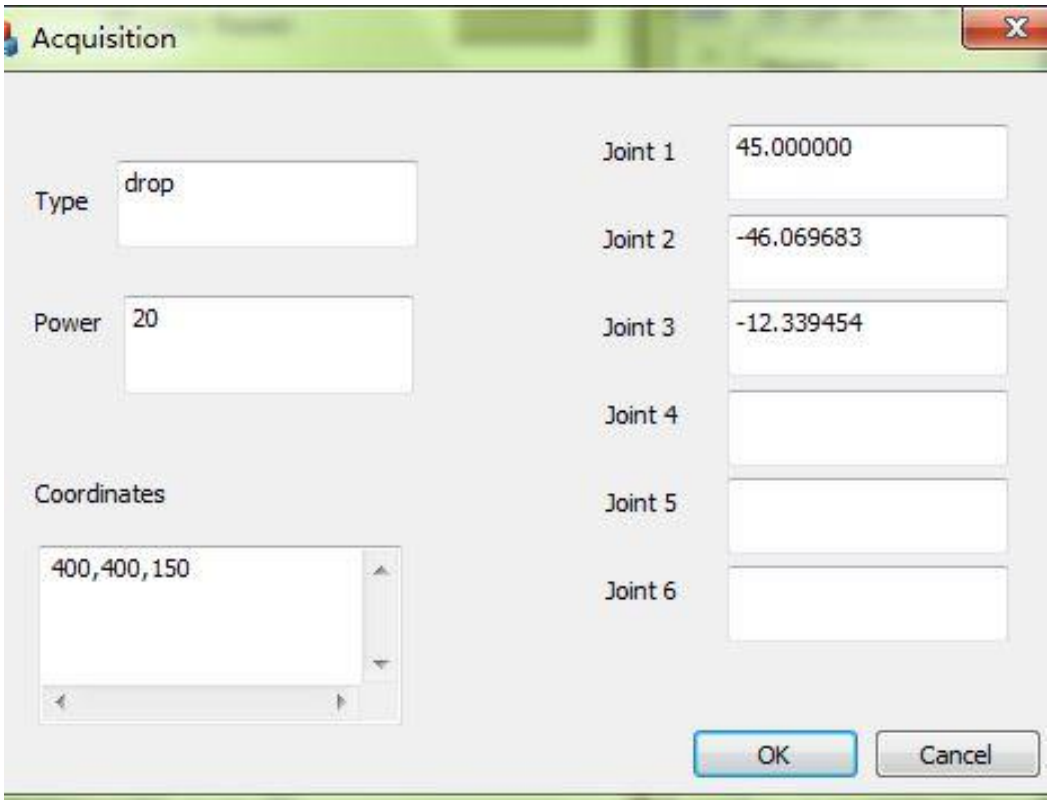


Figure 30. The wanted information at point (400,400,150)

Table 10. The results of the MFC test

step	Coordinate	Joint 1	Joint 2	Joint 3
1	300,0,0	0.000000	-83.756127	74.105179
2	350,0,0	0.000000	-74.245943	62.174465
3	350,350,0	45.000000	-48.883555	23.142761
4	410,350,0	40.486012	-40.239886	8.425479
5	410,410,0	45.000000	-30.847764	-7.994793
6	410,410,100	45.000000	-39.762559	-12.845492
7	410,410,170	45.000000	-41.658955	-23.133148
8	400,410,170	45.707319	-44.103210	-19.235226
9	400,400,170	45.000000	-46.415548	-15.601815
10	400,400,150	45.000000	-46.069683	-12.339454

6.3 The Experiment of BCI System with Human Thought Input

Before the last experiment, a training period is arranged for us to be familiar with the EMOTIV EPOC system. The virtual cube in the Cognitiv Suite previously mentioned was used to train user thought. First of all, the “neutral” state was trained for three times to make the cube stay in a static situation. Then action “push” was trained. This action was trained four times and the skill rating was 12%. After that action “pull” was added and trained four times. The skill rating was 9%. We trained two motions for much more times in two hour. The skill rating was 23% and 19% separately and then we made ten attempts and eight attempts were successful. Then we began the last experiment.

In the last experiment, we run the designed BCI system and utilize human thought as input instead of mock signals through EmoComposer. Because both action “push” and “pull” are trained, we plan to achieve action “pull” five times and each time lasts 3sec. After one action is detected, we will keep mind neutral for 5sec since we need time to record the result. First of all, headset was put on the head of the experimenter and the connect quality of all electrodes or most of them at least should be regulated to good. The current state of control panel was shown in Figure 31. There were three electrodes with fair performance while others were good. Then we run EMOTIV Control Panel and the MFC based dialog. After that we started to do action “pull” by experimenter thought. The coordinates, action power and angles were displayed on dialog. The information of the passed points is listed

in Table 11. The power of each action was 0 since we recorded the result when mind state is neural. The results are listed in Appendix 5.

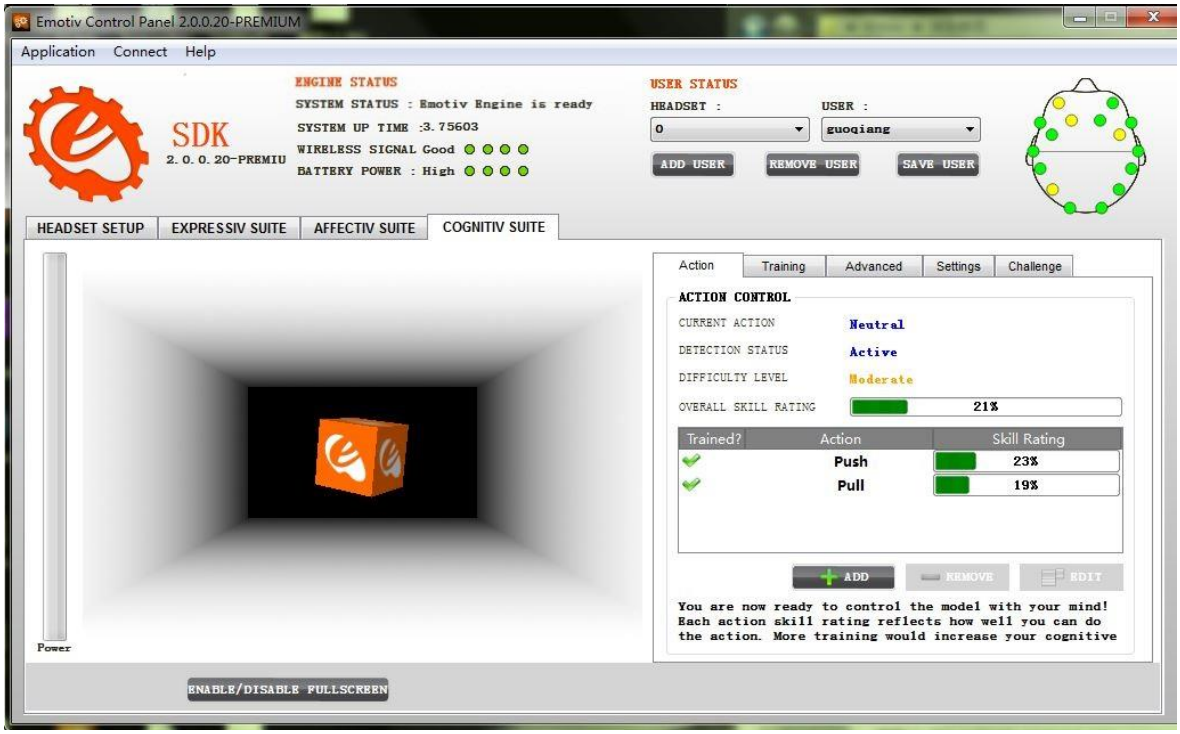


Figure 31. The state of Control Panel in the last experiment

Table 11.The information of the passed point

step	*Coordinate*	*type*	*Joint 1*	*Joint 2*	*Joint 3*
1	*179,0,0*	*Pull*	*0.000000*	*-125.743626*	*103.512084*
2	*443,0,0*	*Pull*	*0.000000*	*-58.141668*	*38.285042*
3	*520,0,0*	*Pull*	*0.000000*	*-44.109804*	*15.070857*
4	*255,0,0*	*push*	*0.000000*	*-94.022779*	*84.645699*
5	*328,0,0*	*pull*	*0.000000*	*-78.281153*	*67.472444*

7 DISCUSSION

According to the results from the first and second testing, it is proven that both the acquisition program and the MFC project meet the requirements that are detecting and processing the input signals accurately and instantly. They can be used in the future research of BCI studying due to its satisfactory performance.

According to the result of the last experiment, it is shown that the human thought, which are in the form of EEG signals, can be read and decoded truly and are used to achieve the action through designed BCI system after training our thought by controlling the virtual cube. These actions could represent the motion of industrial robot. Therefore designed BCI system provides a bridge between the motions of robot and the human thought.

However, there are unexpected results obtained in the last experiment. As shown in Table 11, the incremental displacement in every step was different and even the direction was wrong sometimes. In other words, the action power of human thought is hard to control with high level accuracy and even the action type detected by EMOTIV headset is incorrect sometimes. Besides the shortages of EEG signals and EMOTIV product previously mentioned, there are several possible reasons for unexpected results: 1).The contact quality of few electrodes is not good. That the electrodes were lack of saline may be the reason for bad contact quality. Another possible reason was that EMOTIV headset was not worn perfectly. 2).The training time was not long enough to achieve the desired result. This is the main reason for unexpected results. The intensity of thought is hard to control accurately by human himself although it can be expressed by EEG signals and measured by EMOTIV software. Therefore a longer training time is needed. Moreover, identifying two actions at the same time the made the test more difficult than detecting one action.

In response to the defects above, there are a number of ways to improve. 1). Handling the electrodes carefully and replacing old electrodes regularly due to the oxidation of the electrodes [64]. 2). Wearing the headset and placing every electrodes strictly in right

position following the instruction of EPOC User Manual. 3). Taking a longer training time and summing up experiences of training in order to increase the skill rating.

8 CONCLUSION AND FUTURE WORK

BCI system, as a new communication channel between brain and machine, has developed rapidly during the past few years. It is not only applied to improve the life quality of those disabled people but also it enters the field of controlling robot even industrial robot with the appearance of several new devices. Controlling industrial robot by using BCI is an innovative research task which has great expectation. With the help of BCI system, it is possible that industrial robot is controlled by human thought directly and this method is different from the traditional methods, such as manual control and numerical control. In this research, we built an EEG based BCI system for implementation of controlling an industrial manipulator by means of human thought.

In this thesis, we firstly introduced BCI and selected EEG signals as the input signals of BCI system due to its easy collection. Furthermore, we made a short review of previous research on EEG based BCI. We made a briefly introduction to industrial robot and studied robot kinematics. Meanwhile we chose EMOTIV EPOC as the research instrument due to its acceptable performance and low cost, and made a detailed introduction. With EMOTIV applications, we designed the BCI system in three steps: 1). we designed a C++ program that cooperated with EMOTIV EPOC for acquiring and processing the detected EEG signals. 2). we solved the inverse kinematics of MITSUBISHI RV-3SB industrial robot. 3). we designed a MFC based dialog as operation panel and solved the problem of real-time acquisition by using multithread programming and timer. In the last part of this research, we tested acquisition program and MFC application separately. In the tests, both of them had satisfactory performance. Finally, we designed an experiment to examine the designed BCI system with human thought. We found that the human thought was successfully detected and processed by the BCI system we built. Furthermore, we offered a few suggestions to improve the accuracy of designed BCI system.

In this research, we chose EMOTIV EPOC as research equipment due to its low cost and user-friendly. EMOTIV Neuroheadset was used to acquire EEG signals from user’s brain. Furthermore, other EMOTIV applications such as EMOTIV Control Panel and EmoComposer were used to process the signals and were applied to build BCI system.

These EMOTIV applications are designed on the basis of built-in prototype which is based on lots of data. However, the algorithm and data sample still have room for improvement. In the future study, we can obtain the raw EEG signals by EMOTIV TestBench and process raw signals by different filters. Based on lots of experimental data, we may also improve the algorithm.

In this research, we trained our thought by controlling the motion of a virtual cube to represent the movement of end-effector of industrial robot. In the future, we can build a 3D model of industrial robot and insert it into the Cogntiv Suite of EMOTIV Control Panel. Furthermore, as shown in Figure 20, we can also build a panel to control RV-3SB robot and make it as the external device of BCI system. In the end, this research is an attempt of BCI system used in the field of robot controlling and builds the foundation of future work.

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APPENDICES

APPENDIX 1.1

The complete C++ based code of acquiring program

```
#include<iostream>
#include<conio.h>
#include<sstream>
#include<cassert>
#include"EmoStateDLL.h"
#include"edk.h"
#include"edkErrorCode.h"
#pragma comment(lib, "Ws2_32.lib")
#pragma comment(lib, "edk.lib")
void Cognitiv(EmoStateHandle eState);
int type;
int power;
int main()
{

                EmoEngineEventHandle eEvent             = EE_EmoEngineEventCreate();
                EmoStateHandle eState                   = EE_EmoStateCreate();
                unsigned int userID                                 = 0;


 try{

                if (EE_EngineRemoteConnect("127.0.0.1", 3008) != EDK_OK) {
                                std::cout<<"EMOTIV Engine start up failed."<<std::endl;
                                }
  else {
    std::cout << "EMOTIV Engine started!" << std::endl;

   }
     std::cout << "Type \"exit\" to quit, \"help\" to list available commands..." <<
     std::endl;
  while (true){
                        int state = EE_EngineGetNextEvent(eEvent);
                        if (state == EDK_OK) {
          EE_Event_t eventType = EE_EmoEngineEventGetType(eEvent);
          EE_EmoEngineEventGetUserId(eEvent, &userID);
                                        switch (eventType) {
            // New headset connected, create a new socket to send the animation
           case EE_UserAdded:
            {
             std::cout << "New user "<<userID<< " has added." << std::endl;
             break;
```

APPENDIX 1.2

```
                                                                    }
                case EE_UserRemoved:
            {
              std::cout << std::endl << "User" << userID  << " has been removed." <<
                                  std::endl;
                                    break;
                                                                    }
                case EE_EmoStateUpdated:
            {
                                    EE_EmoEngineEventGetEmoState(eEvent, eState);
                    Cognitiv(eState);
                   break;
                                                                    }
                                          }
                     }
       }
   }
   catch (const std::exception& e) {
    std::cerr << e.what() << std::endl;
    std::cout << "Press any keys to exit..." << std::endl;
    getchar();
    }
  EE_EngineDisconnect();
  EE_EmoStateFree(eState);
  EE_EmoEngineEventFree(eEvent);
  return 0;
}
void Cognitiv(EmoStateHandle eState)
{
    EE_CognitivAction_t actionType = ES_CognitivGetCurrentAction(eState);
    float actionPower = ES_CognitivGetCurrentActionPower(eState);
    type=static_cast<int>(actionType);
                power=static_cast<int>(actionPower*100.0f);
     std::cout<<"actiontype:" <<type << ","
                << "actionpower:"<<power<<std::endl;
}
```

APPENDIX 2

The complete Matlab based code for solving inverse kinematics

```
syms c1  c2 c3 c4  c5  c6  r1 r2 r3 r4 r5 r6 a2 a3  a4 d4
syms r7 r8 r9 px py pz
pi=3.141592654;
a2=95;
a3=245;
a4=135;
d4=270;
% M1...M6 refers to the transformation matrix of each joint
M1=[cos(c1) -sin(c1) 0  0;sin(c1) cos(c1) 0  0;0 0 1 0; 0 0 0 1];
M2=[cos(c2) -sin(c2) 0 a2; 0 0 1 0;-sin(c2) -cos(c2) 0 0;0 0 0 1];
M3=[cos(c3) -sin(c3) 0 a3; sin(c3) cos(c3) 0 0 ; 0 0 1 0;0 0 0 1];
M4=[cos(c4) -sin(c4) 0 a4; 0 0 1 d4; -sin(c4) -cos(c4) 0 0;0 0 0 1];
M5=[cos(c5) -sin(c5) 0  0; 0 0 -1 0; sin(c5) cos(c5) 0 0;0 0 0 1];
M6=[cos(c6) -sin(c6) 0 0;0 0 1 0; -sin(c6) -cos(c6) 0 0; 0 0 0 1];

% the general transformation matrix
T=[r1 r2 r3 px; r4 r5 r6 py;r7 r8 r9 pz;0 0 0 1];
% solve C1, the angle of joint 1
c1=atan2(py,px);
angle1=c1*180/pi;
% solve c3,the angle of joint 3, due to A(1,4) and A(3,4) on both side of equation should
be
% equal then we have:
K=(px^2+py^2+pz^2+a2^2-2*a2*px*cos(c1)-2*a2*py*sin(c1)-a4^2-d4^2-a3^2)/(2*a3);
J=sqrt(d4^2+a4^2-K^2);
c3=atan2(a4,d4)-atan2(K,J);
angle3=c3*180/pi;

% solve c2, the angle of joint 2,  A2(1,4)and A2(2,4) on both side of equation should
be %equal then
simplify(inv(M1*M2*M3)*T);
A2=simplify(M4*M5*M6);

% we have:
K1=-pz*(a4+a3*cos(c3))-(d4-a3*sin(c3))*(px*cos(c1)+py*sin(c1)-a2);
K2=(a4+a3*cos(c3))*(px*cos(c1)+py*sin(c1)-a2)-pz*(d4-a3*sin(c3));
c23=atan2(K1,K2);
c2=c23-c3;
angle2=c2*180/pi;
str=[px,py,pz];
disp(str);

disp(angle1);
disp(angle2);
disp(angle3);
```

APPENDIX 3.1

The complete C++based code for MFC application

1). "AcquisitionThread.h"

```
#pragma once
// AcquisitionThread
class AcquisitionThread : public CWinThread
{
		DECLARE_DYNCREATE(AcquisitionThread)
protected:
		AcquisitionThread();   // protected constructor used by dynamic creation
		virtual ~AcquisitionThread();
public:
		virtual BOOL InitInstance();
		virtual int ExitInstance();
protected:
		DECLARE_MESSAGE_MAP()
public:
		static CWinThread * m_pAcquisitionThread;
public:
  static unsigned int ThreadAcquisitionDataFunc(LPVOID pParam);
		static int m_dType;
		static int m_dPower;
		static int m_dX;
  static int m_dY;
  static int m_dZ;
		static double m_dx;
		static double m_dy;
		static double m_dz;
		static double m_dangle1;
		static double m_dangle2;
		static double m_dangle3;
		static double m_dAngle1;
		static double m_dAngle2;
		static double m_dAngle3;
		static void Calculation();
		static CString Coordinates;
		static CString Direction;
		static CString Angle1;
		static CString Angle2;
		static CString Angle3;
		static double k;
public:
		static double * m_pParam4Data;
};
```

APPENDIX 3.2

2). “AcquisitonTheard.cpp”

```
// AcquisitionThread.cpp : implementation file
#include "stdafx.h"
#include "Acquisition.h"
#include "AcquisitionThread.h"
#include<iostream>
#include<conio.h>
#include<sstream>
#include<cassert>
#include <cmath>
#define PI 3.141592654
#include"EmoStateDLL.h"
#include"edk.h"
#include"edkErrorCode.h"

#pragma comment(lib, "Ws2_32.lib")
#pragma comment(lib, "edk.lib")
CWinThread * AcquisitionThread::m_pAcquisitionThread = NULL;
double * AcquisitionThread::m_pParam4Data = NULL;
int AcquisitionThread::m_dType = 0;
int AcquisitionThread::m_dPower = 0;
int AcquisitionThread::m_dX = 0;
int AcquisitionThread::m_dY = 0;
int AcquisitionThread::m_dZ = 0;
double AcquisitionThread::m_dx = 0;
double AcquisitionThread::m_dy = 0;
double AcquisitionThread::m_dz = 0;
double AcquisitionThread::m_dangle1 = 0;
double AcquisitionThread::m_dangle2 = 0;
double AcquisitionThread::m_dangle3 = 0;
double AcquisitionThread::m_dAngle1 = 0;
double AcquisitionThread::m_dAngle2 = 0;
double AcquisitionThread::m_dAngle3 = 0;
double AcquisitionThread::k = 0;
int Type = 0;
CString AcquisitionThread::Coordinates =_T(" ");
CString AcquisitionThread::Angle1 =_T(" ");
CString AcquisitionThread::Angle2 =_T(" ");
CString AcquisitionThread::Angle3 =_T(" ");
CString AcquisitionThread::Direction =_T("neural");
// AcquisitionThread

IMPLEMENT_DYNCREATE(AcquisitionThread, CWinThread)
```

APPENDIX 3.3

```
AcquisitionThread::AcquisitionThread()
{
}

AcquisitionThread::~AcquisitionThread()
{
}

BOOL AcquisitionThread::InitInstance()
{
		// TODO:  perform and per-thread initialization here
		return TRUE;
}

int AcquisitionThread::ExitInstance()
{
		// TODO:  perform any per-thread cleanup here
		return CWinThread::ExitInstance();
}

BEGIN_MESSAGE_MAP(AcquisitionThread, CWinThread)
END_MESSAGE_MAP()


// AcquisitionThread message handlers

unsigned int AcquisitionThread::ThreadAcquisitionDataFunc(LPVOID pParam)
{
		// my own code for the thread
		EmoEngineEventHandle eEvent		= EE_EmoEngineEventCreate();
		EmoStateHandle eState			= EE_EmoStateCreate();
		unsigned int userID                                    = 0;
  try{
	while(true){
		int state = EE_EngineGetNextEvent(eEvent);
		if (state == EDK_OK) {
		EE_Event_t eventType = EE_EmoEngineEventGetType(eEvent);
		EE_EmoEngineEventGetUserId(eEvent, &userID);
		    switch (eventType) {
			case EE_UserRemoved:
			    {
			     CString str2=_T("User has been removed!");
			      AfxMessageBox(str2);
			break;
			      }
```

APPENDIX 3.4

```
case EE_EmoStateUpdated:
                        {
                          EE_EmoEngineEventGetEmoState(eEvent, eState);
                    EE_CognitivAction_t actionType = ES_CognitivGetCurrentAction(eState);
                   float actionPower = ES_CognitivGetCurrentActionPower(eState);
                          m_dType=static_cast<int>(actionType);
                          Type=m_dType;
                         m_dPower=static_cast<int>(actionPower*100.0f);
                            Calculation();
                            break;
                              }
                      }
                  }
                 Sleep(5);
             }
         }
          catch (const std::exception& e) {
        std::cerr << e.what() << std::endl;
        getchar();
        }
       EE_EngineDisconnect();
       EE_EmoStateFree(eState);
       EE_EmoEngineEventFree(eEvent);
       return 0;
}
void AcquisitionThread::Calculation()
{
 switch(Type){
   case 0 :{
              AcquisitionThread::Direction =_T("neural");
                break;
            }
   case 2 :{
              m_dX = m_dX-m_dPower;
              m_dY = m_dY;
              m_dZ = m_dZ;
              AcquisitionThread::Direction =_T("push");
               break;
               }
   case 4 :{
               m_dX = m_dX+m_dPower;
              m_dY = m_dY;
              m_dZ = m_dZ;
               AcquisitionThread::Direction =_T("pull");
               break;
```

APPENDIX 3.5

```
}
   case 8 :{
                m_dX = m_dX;
                m_dY = m_dY;
                m_dZ = m_dZ+m_dPower;
                AcquisitionThread::Direction =_T("lift");
                break;
                }
   case 16 :{
                m_dX = m_dX;
                m_dY = m_dY;
                m_dZ = m_dZ-m_dPower;
                AcquisitionThread::Direction =_T("drop");
                break;
                }
   case 32 :{
                m_dX = m_dX;
               m_dY = m_dY-m_dPower;
                m_dZ = m_dZ;
                AcquisitionThread::Direction =_T("left");
                break;
              }
   case 64 :{
                m_dX = m_dX;
                m_dY = m_dY+m_dPower;
                m_dZ = m_dZ;
                AcquisitionThread::Direction =_T("right");
                break;
             }
  }
  m_dx=m_dX;
  m_dy=m_dY;
  m_dz=m_dZ;

  m_dangle1= atan2(m_dy,m_dx);
  m_dAngle1=(m_dangle1)*180.0/PI;

  k=(m_dx*m_dx+m_dy*m_dy+m_dz*m_dz+95.0*95.0-190.0*m_dx*cos(m_dangle1)-
 190.0*m_dy*sin(m_dangle1)-270.0*270.0-135.0*135.0-245.0*245.0)/(2.0*245.0);

  m_dangle3= atan2(135.0,270.0)-atan2(k,sqrt(135.0*135.0+270.0*270.0-k*k));
  m_dAngle3= (m_dangle3)*180.0/PI;

 m_dangle2=(atan2((-m_dz*(135.0+245.0*cos(m_dangle3))-(270.0-
 245.0*sin(m_dangle3))*(m_dx*cos(m_dangle1)+m_dy*sin(m_dangle1)-95.0))
```

APPENDIX 3.6

```
 ,(135.0+245.0*cos(m_dangle3))*(m_dx*cos(m_dangle1)+m_dy*sin(m_dangle1)-95.0)-
 m_dz*(270.0-245.0*sin(m_dangle3))))-m_dangle3;
 m_dAngle2=(m_dangle2)*180.0/PI;


 AcquisitionThread::Angle1.Format(_T("%lf"),m_dAngle1);
 AcquisitionThread::Angle2.Format(_T("%lf"),m_dAngle2);
 AcquisitionThread::Angle3.Format(_T("%lf"),m_dAngle3);
 AcquisitionThread::Coordinates;
 AcquisitionThread::Coordinates.Format(_T("%d,%d,%d"),m_dX,m_dY,m_dZ);

}
```

3). Acquisiton.cpp

```
// Acquisition.cpp : Defines the class behaviors for the application.
//
#include "stdafx.h"
#include "Acquisition.h"
#include "AcquisitionDlg.h"
#include "AcquisitionThread.h"
#include"EmoStateDLL.h"
#include"edk.h"
#include"edkErrorCode.h"
#ifdef _DEBUG
#define new DEBUG_NEW
#endif
// CAcquisitionApp
BEGIN_MESSAGE_MAP(CAcquisitionApp, CWinApp)
		ON_COMMAND(ID_HELP, &CWinApp::OnHelp)
END_MESSAGE_MAP()


// CAcquisitionApp construction

CAcquisitionApp::CAcquisitionApp()
{
		// support Restart Manager
		m_dwRestartManagerSupportFlags =
AFX_RESTART_MANAGER_SUPPORT_RESTART;

		// TODO: add construction code here,
		// Place all significant initialization in InitInstance
}


// The one and only CAcquisitionApp object
```

APPENDIX 3.7

```
CAcquisitionApp theApp;


// CAcquisitionApp initialization

BOOL CAcquisitionApp::InitInstance()
{
		// InitCommonControlsEx() is required on Windows XP if an application
		// manifest specifies use of ComCtl32.dll version 6 or later to enable
		// visual styles.  Otherwise, any window creation will fail.
		INITCOMMONCONTROLSEX InitCtrls;
		InitCtrls.dwSize = sizeof(InitCtrls);
		// Set this to include all the common control classes you want to use
		// in your application.
		InitCtrls.dwICC = ICC_WIN95_CLASSES;
		InitCommonControlsEx(&InitCtrls);

		CWinApp::InitInstance();


		AfxEnableControlContainer();

		// Create the shell manager, in case the dialog contains
		// any shell tree view or shell list view controls.
		CShellManager *pShellManager = new CShellManager;

		// Standard initialization
		// If you are not using these features and wish to reduce the size
		// of your final executable, you should remove from the following
		// the specific initialization routines you do not need
		// Change the registry key under which our settings are stored
		// TODO: You should modify this string to be something appropriate
		// such as the name of your company or organization
		SetRegistryKey(_T("Local AppWizard-Generated Applications"));
		if(AcquisitionThread::m_pAcquisitionThread == NULL)
		{
			if (EE_EngineRemoteConnect("127.0.0.1", 3008) != EDK_OK){
				CString str=_T("EMOTIV Engine start up failed.");
	AfxMessageBox(str);
			}
			else {
				CString str1=_T("EMOTIV Engine started.");
	AfxMessageBox(str1);
			}
			AcquisitionThread::m_pAcquisitionThread =
```

APPENDIX 3.8

```
AfxBeginThread(AcquisitionThread::ThreadAcquisitionDataFunc,(LPVOID)AcquisitionThre
ad::m_pParam4Data);

		}
		else
		{
		   CString str = _T("Data Acquistion Thread is NOT created!\n");
				AfxMessageBox(str);

		}
		CAcquisitionDlg dlg;
		m_pMainWnd = &dlg;
		INT_PTR nResponse = dlg.DoModal();
		if (nResponse == IDOK)
		{
				// TODO: Place code here to handle when the dialog is
				//  dismissed with OK
		}
		else if (nResponse == IDCANCEL)
		{
				// TODO: Place code here to handle when the dialog is
				//  dismissed with Cancel
		}
		// Delete the shell manager created above.
		if (pShellManager != NULL)
		{
				delete pShellManager;
		}

		// Since the dialog has been closed, return FALSE so that we exit the
		//  application, rather than start the application's message pump.
		return FALSE;
}
```

4). AcquisitonDlg.cpp

```
// AcquisitionDlg.cpp : implementation file
//
#include "stdafx.h"
#include "Acquisition.h"
#include "AcquisitionDlg.h"
#include "afxdialogex.h"
#include "AcquisitionThread.h"
#ifdef _DEBUG
#define new DEBUG_NEW
#endif
```

APPENDIX 3.9

```
// CAboutDlg dialog used for App About

class CAboutDlg : public CDialogEx
{
public:
		CAboutDlg();

// Dialog Data
		enum { IDD = IDD_ABOUTBOX };

		protected:
		virtual void DoDataExchange(CDataExchange* pDX);    // DDX/DDV support

// Implementation
protected:
		DECLARE_MESSAGE_MAP()
};

CAboutDlg::CAboutDlg() : CDialogEx(CAboutDlg::IDD)
{
}

void CAboutDlg::DoDataExchange(CDataExchange* pDX)
{
		CDialogEx::DoDataExchange(pDX);
}

BEGIN_MESSAGE_MAP(CAboutDlg, CDialogEx)
END_MESSAGE_MAP()


// CAcquisitionDlg dialog
CAcquisitionDlg::CAcquisitionDlg(CWnd* pParent /*=NULL*/)
		: CDialogEx(CAcquisitionDlg::IDD, pParent)
		, m_edit3(_T(""))
		, m_edit1(_T(""))
		, m_edit4(_T(""))
		, m_edit5(_T(""))
		, m_edit6(_T(""))
		, m_edit7(_T(""))
		, m_edit8(_T(""))
		, m_edit9(_T(""))
{
		m_hIcon = AfxGetApp()->LoadIcon(IDR_MAINFRAME);
```

APPENDIX 3.10

```
}

void CAcquisitionDlg::DoDataExchange(CDataExchange* pDX)
{
		CDialogEx::DoDataExchange(pDX);
		DDX_Text(pDX, IDC_EDIT3, m_edit3);
		DDX_Text(pDX, IDC_EDIT1, m_edit1);
		DDX_Text(pDX, IDC_EDIT4, m_edit4);
		DDX_Text(pDX, IDC_EDIT5, m_edit5);
		DDX_Text(pDX, IDC_EDIT6, m_edit6);
		DDX_Text(pDX, IDC_EDIT7, m_edit7);
		DDX_Text(pDX, IDC_EDIT8, m_edit8);
		DDX_Text(pDX, IDC_EDIT9, m_edit9);
}

BEGIN_MESSAGE_MAP(CAcquisitionDlg, CDialogEx)
		ON_WM_SYSCOMMAND()
		ON_WM_PAINT()
		ON_WM_QUERYDRAGICON()
		ON_EN_CHANGE(IDC_EDIT4, &CAcquisitionDlg::OnEnChangeEdit4)
		ON_WM_TIMER()
		ON_BN_CLICKED(IDOK, &CAcquisitionDlg::OnBnClickedOk)
END_MESSAGE_MAP()


// CAcquisitionDlg message handlers

BOOL CAcquisitionDlg::OnInitDialog()
{
		CDialogEx::OnInitDialog();
		// Add "About..." menu item to system menu.
		// IDM_ABOUTBOX must be in the system command range.
		ASSERT((IDM_ABOUTBOX & 0xFFF0) == IDM_ABOUTBOX);
		ASSERT(IDM_ABOUTBOX < 0xF000);
		CMenu* pSysMenu = GetSystemMenu(FALSE);
		if (pSysMenu != NULL)
		{
				BOOL bNameValid;
				CString strAboutMenu;
				bNameValid = strAboutMenu.LoadString(IDS_ABOUTBOX);
				ASSERT(bNameValid);
				if (!strAboutMenu.IsEmpty())
				{
						pSysMenu->AppendMenu(MF_SEPARATOR);
						pSysMenu->AppendMenu(MF_STRING,
```

APPENDIX 3.11

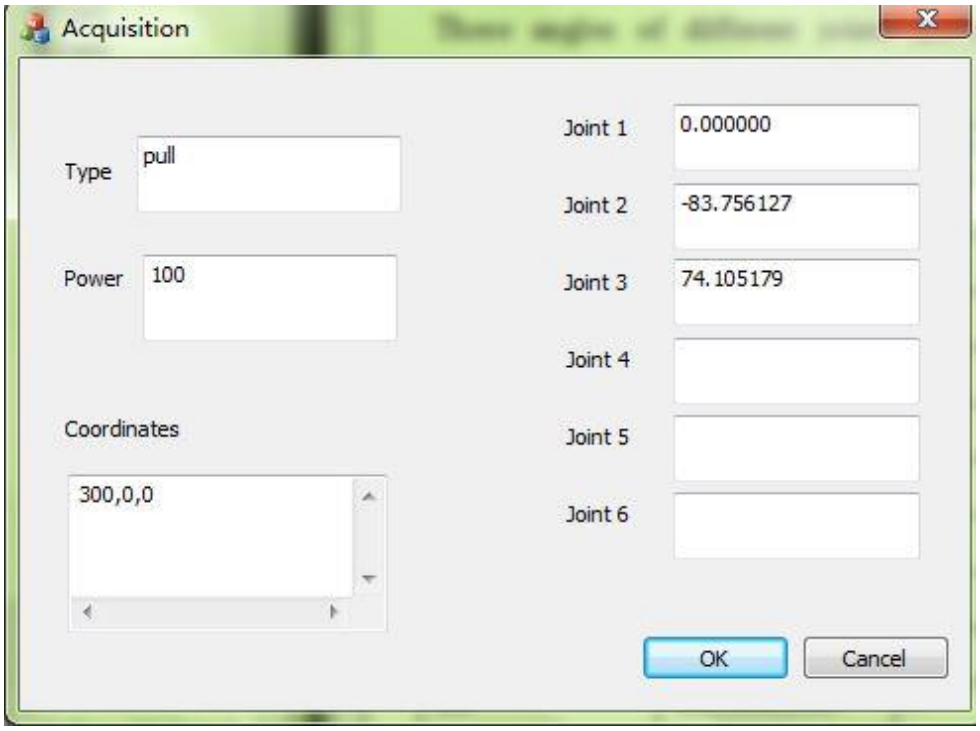
```
IDM_ABOUTBOX, strAboutMenu);
                        }
        }

        // Set the icon for this dialog.  The framework does this automatically
        //  when the application's main window is not a dialog
        SetIcon(m_hIcon, TRUE);                         // Set big icon
        SetIcon(m_hIcon, FALSE);            // Set small icon

        // TODO: Add extra initialization here

        return TRUE;  // return TRUE  unless you set the focus to a control
}

void CAcquisitionDlg::OnSysCommand(UINT nID, LPARAM lParam)
{
        if ((nID & 0xFFF0) == IDM_ABOUTBOX)
        {
                CAboutDlg dlgAbout;
                dlgAbout.DoModal();
        }
        else
        {
                CDialogEx::OnSysCommand(nID, lParam);
        }
}

// If you add a minimize button to your dialog, you will need the code below
//  to draw the icon.  For MFC applications using the document/view model,
//  this is automatically done for you by the framework.

void CAcquisitionDlg::OnPaint()
{
        if (IsIconic())
        {
                CPaintDC dc(this); // device context for painting

                SendMessage(WM_ICONERASEBKGND,
reinterpret_cast<WPARAM>(dc.GetSafeHdc()), 0);

                // Center icon in client rectangle
                int cxIcon = GetSystemMetrics(SM_CXICON);
                int cyIcon = GetSystemMetrics(SM_CYICON);
                CRect rect;
                GetClientRect(&rect);
```

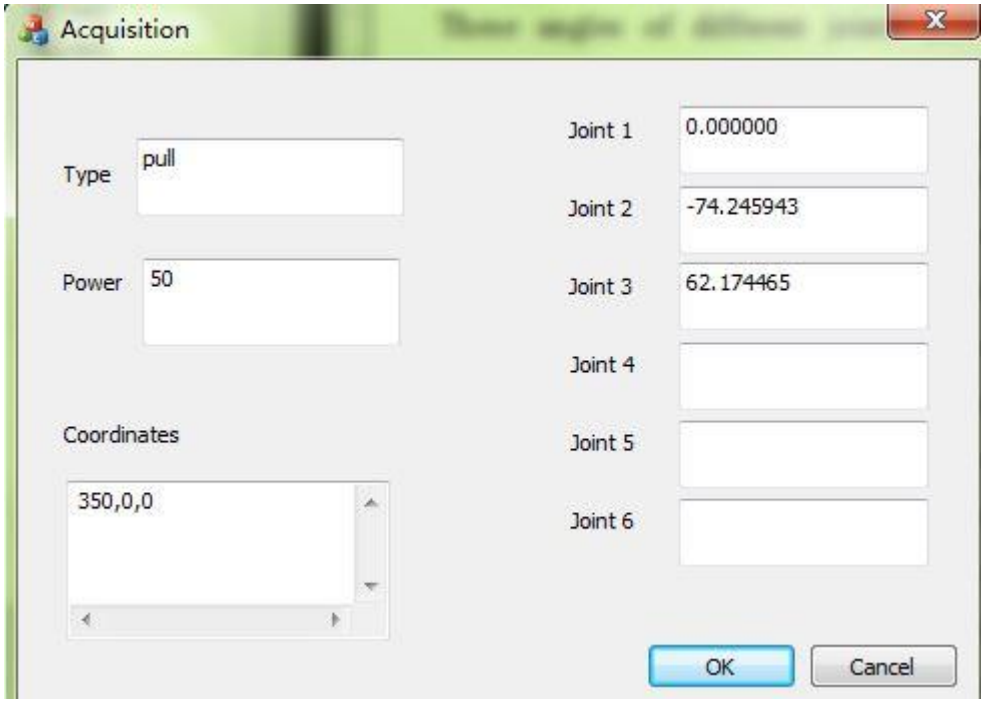
APPENDIX 3.12

```
                int x = (rect.Width() - cxIcon + 1) / 2;
                int y = (rect.Height() - cyIcon + 1) / 2;

                // Draw the icon
                dc.DrawIcon(x, y, m_hIcon);
        }
        else
        {
                CDialogEx::OnPaint();
        }
}

// The system calls this function to obtain the cursor to display while the user drags
//  the minimized window.
HCURSOR CAcquisitionDlg::OnQueryDragIcon()
{
        return static_cast<HCURSOR>(m_hIcon);
}


void CAcquisitionDlg::OnEnChangeEdit4()
{


}
void CAcquisitionDlg::OnTimer(UINT_PTR nIDEvent)
{

        SetDlgItemInt(IDC_EDIT2, AcquisitionThread::m_dPower);
        m_edit1= AcquisitionThread::Direction;
        m_edit3= AcquisitionThread::Coordinates;
        m_edit4= AcquisitionThread::Angle1;
        m_edit5= AcquisitionThread::Angle2;
        m_edit6= AcquisitionThread::Angle3;
        UpdateData(false);
        CDialogEx::OnTimer(nIDEvent);
}

void CAcquisitionDlg::OnBnClickedOk()
{
        SetTimer(1, 2000, NULL);
}
```

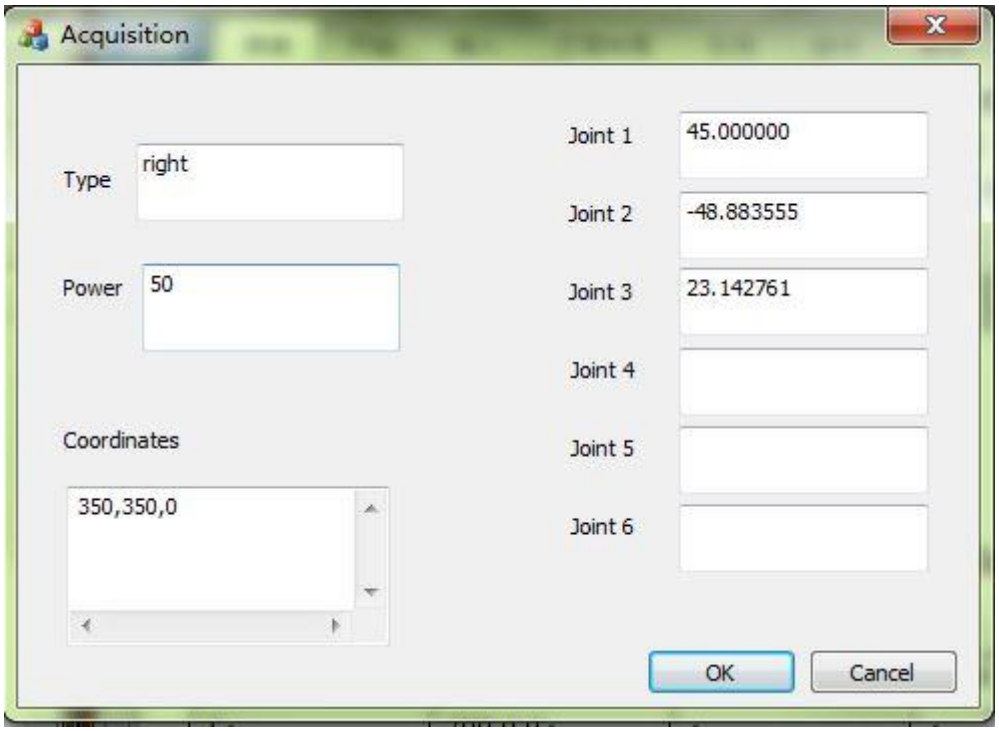
APPENDIX 4.1

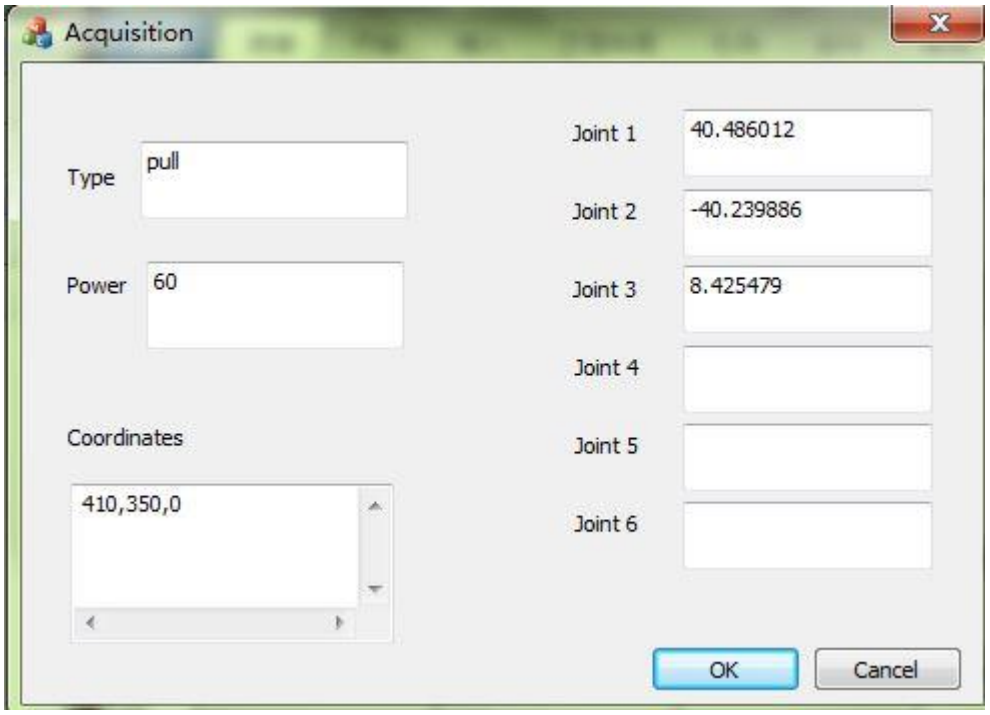
The results of steps in the testing of MFC application



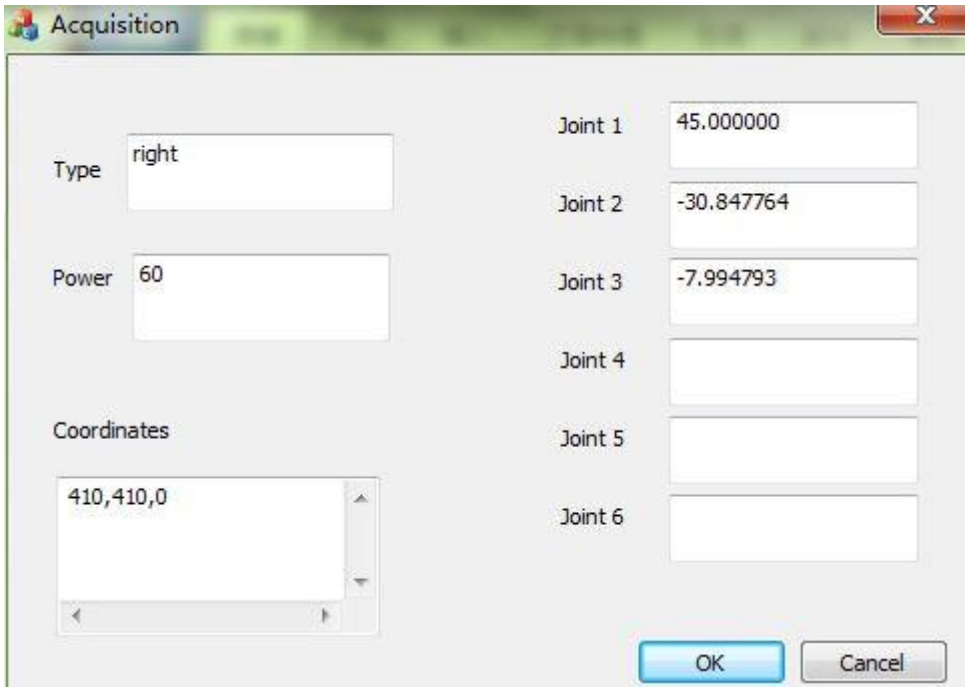


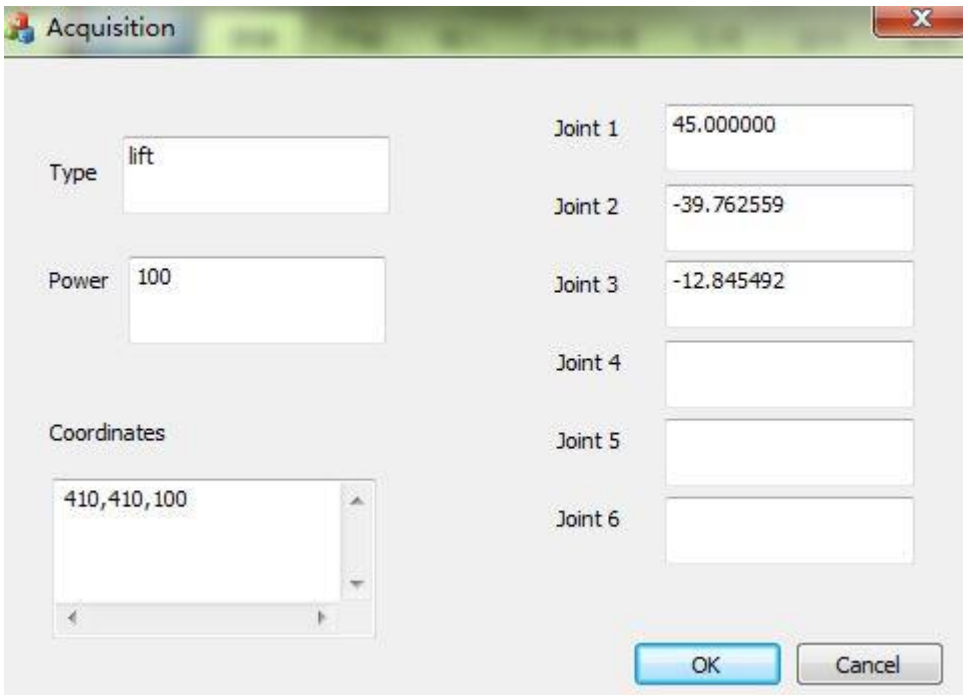
APPENDIX 4.2


Acquisition
Type
right
Power
50
Coordinates
350,350,0
Joint 1
45.000000
Joint 2
-48.883555
Joint 3
23.142761
Joint 4
Joint 5
Joint 6
OK
Cancel

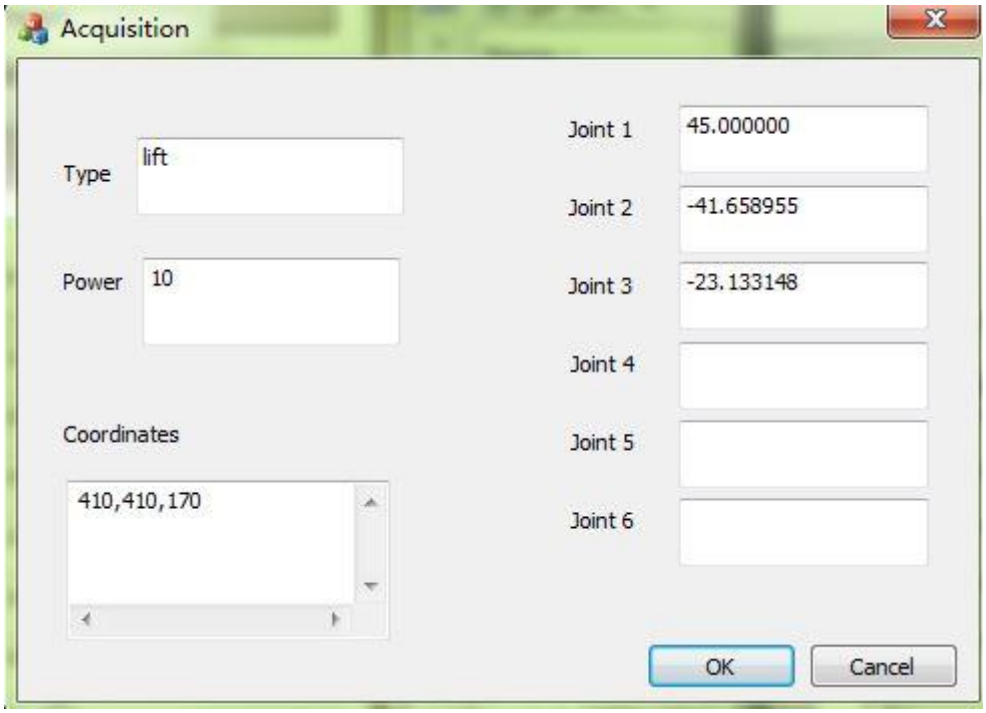

Acquisition
Type
pull
Power
60
Coordinates
410,350,0
Joint 1
40.486012
Joint 2
-40.239886
Joint 3
8.425479
Joint 4
Joint 5
Joint 6
OK
Cancel

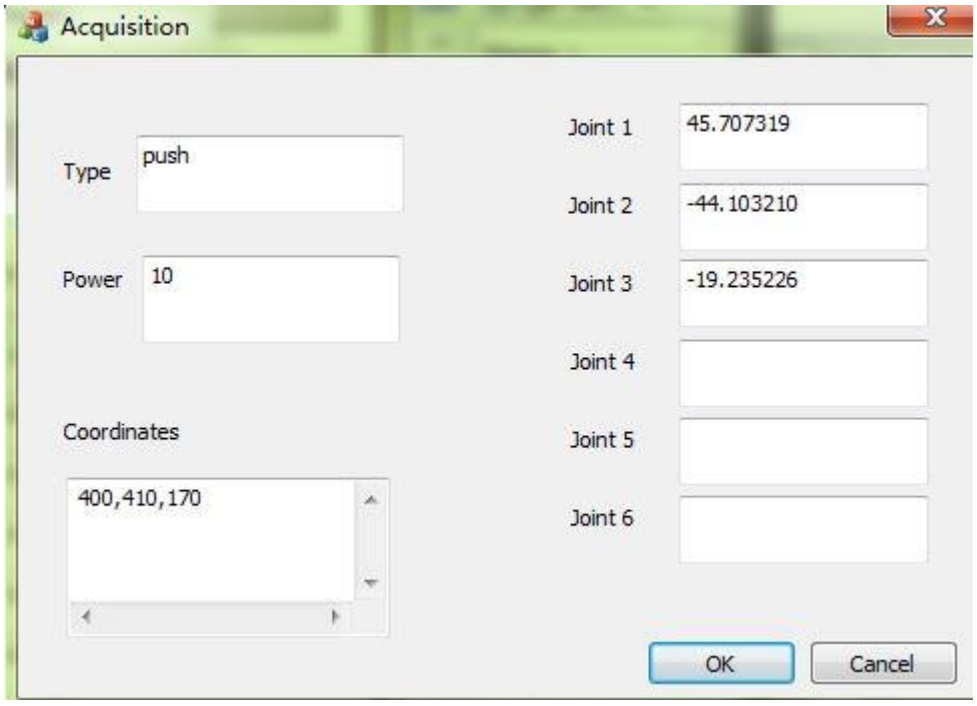
APPENDIX 4.3


Acquisition
Type
right
Power
60
Coordinates
410,410,0
Joint 1
45.000000
Joint 2
-30.847764
Joint 3
-7.994793
Joint 4
Joint 5
Joint 6
OK
Cancel

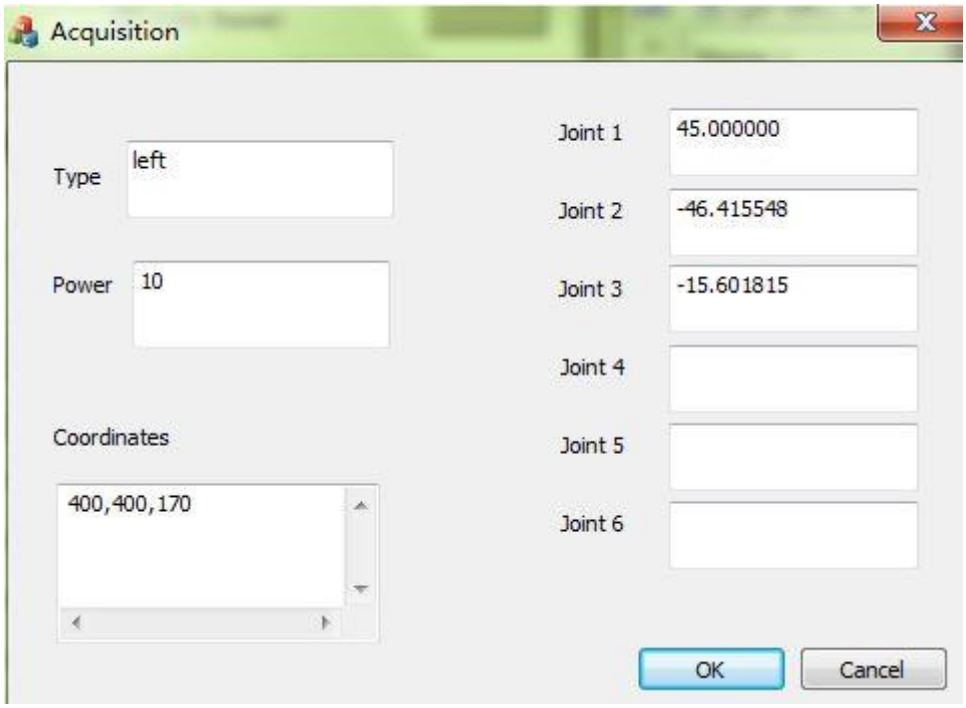

Acquisition
Type
lift
Power
100
Coordinates
410,410,100
Joint 1
45.000000
Joint 2
-39.762559
Joint 3
-12.845492
Joint 4
Joint 5
Joint 6
OK
Cancel

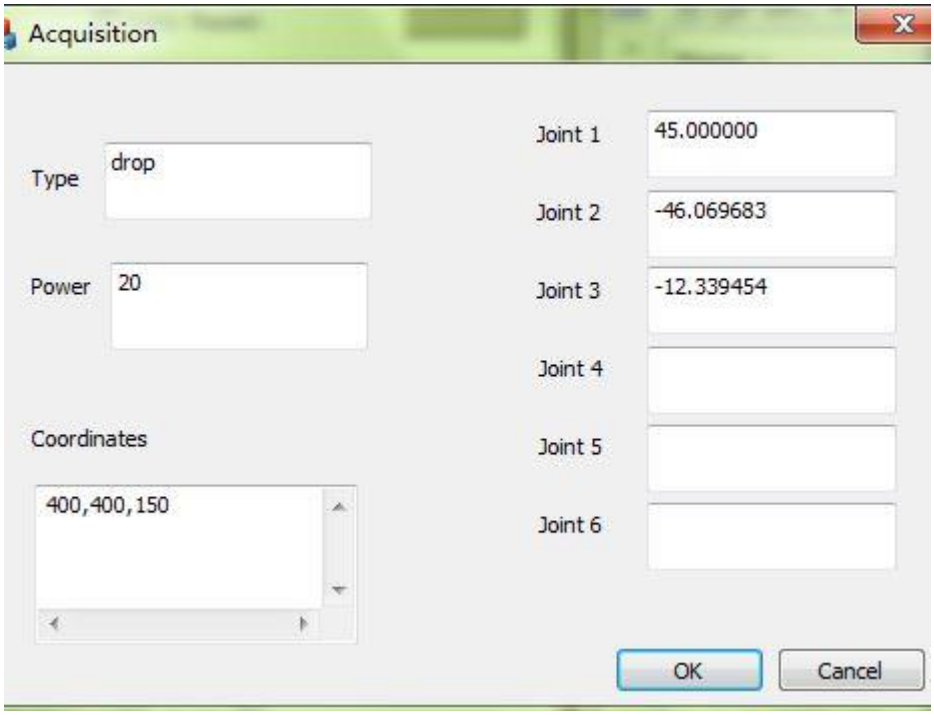
APPENDIX 4.4


Acquisition
Type
lift
Power
10
Coordinates
410,410,170
Joint 1
45.000000
Joint 2
-41.658955
Joint 3
-23.133148
Joint 4
Joint 5
Joint 6
OK
Cancel


Acquisition
Type
push
Power
10
Coordinates
400,410,170
Joint 1
45.707319
Joint 2
-44.103210
Joint 3
-19.235226
Joint 4
Joint 5
Joint 6
OK
Cancel

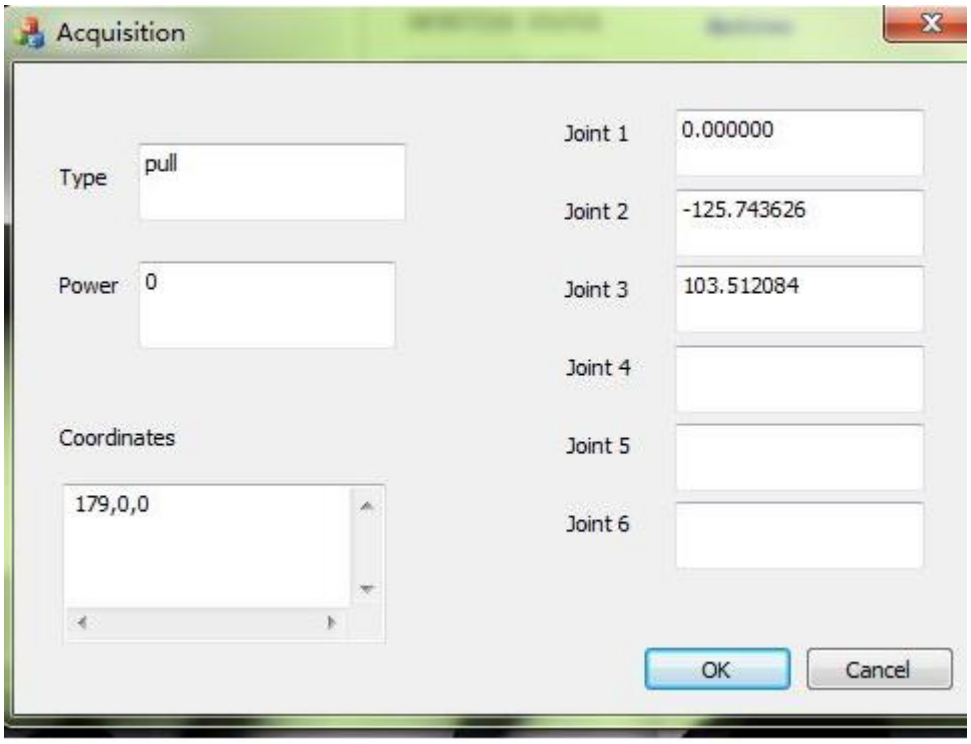
APPENDIX 4.5

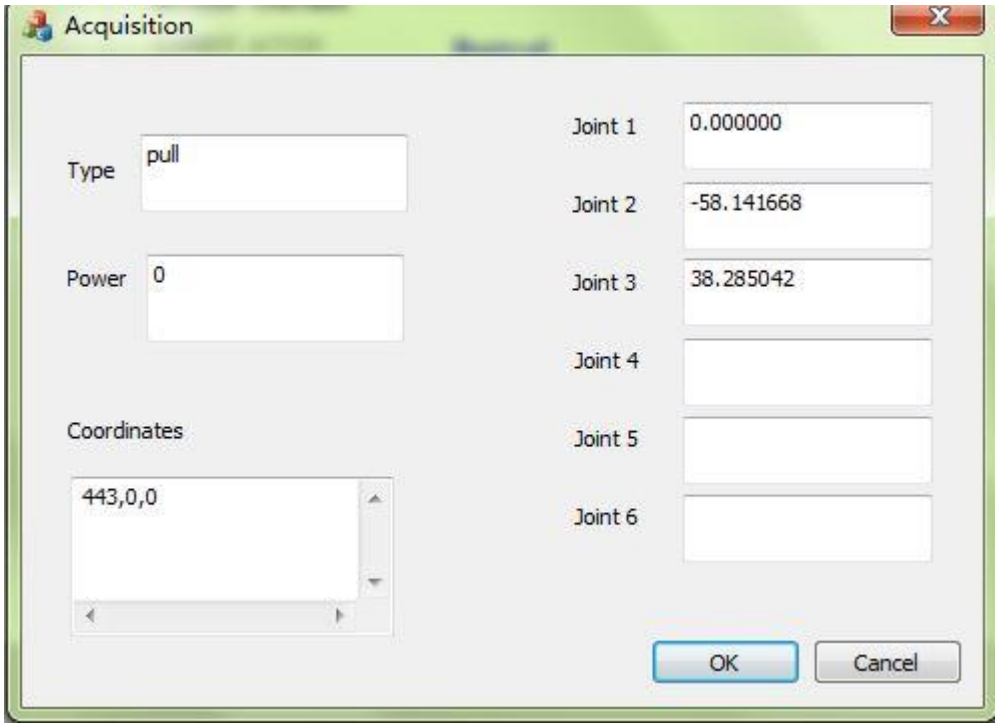

Acquisition
Type
left
Power
10
Coordinates
400,400,170
Joint 1
45.000000
Joint 2
-46.415548
Joint 3
-15.601815
Joint 4
Joint 5
Joint 6
OK
Cancel


Acquisition
Type
drop
Power
20
Coordinates
400,400,150
Joint 1
45.000000
Joint 2
-46.069683
Joint 3
-12.339454
Joint 4
Joint 5
Joint 6
OK
Cancel

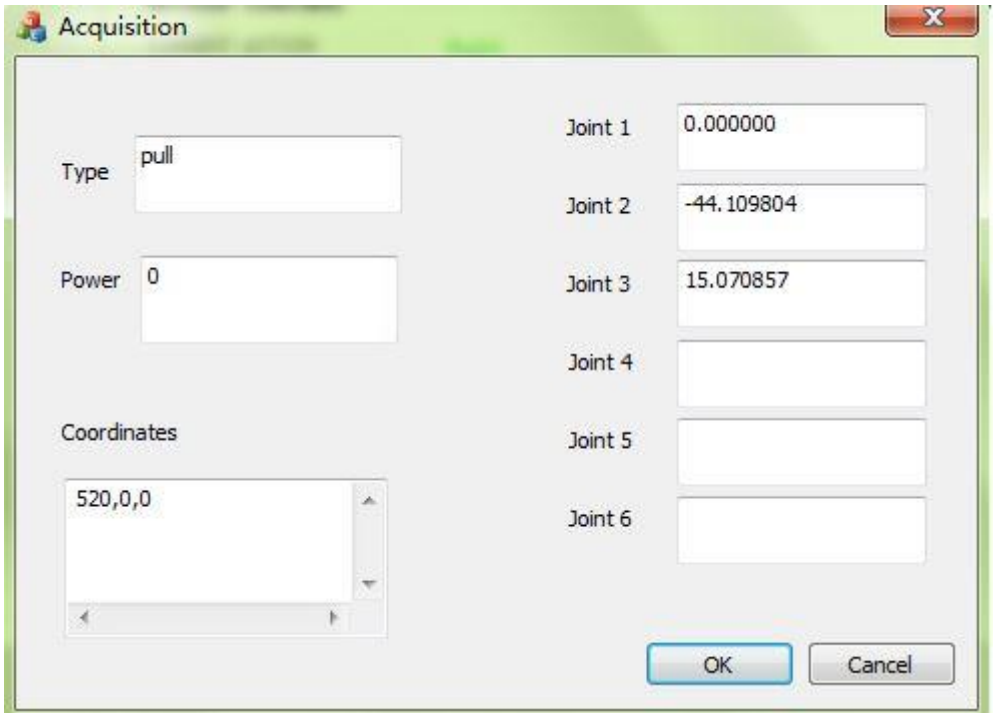
Appendix 5.1

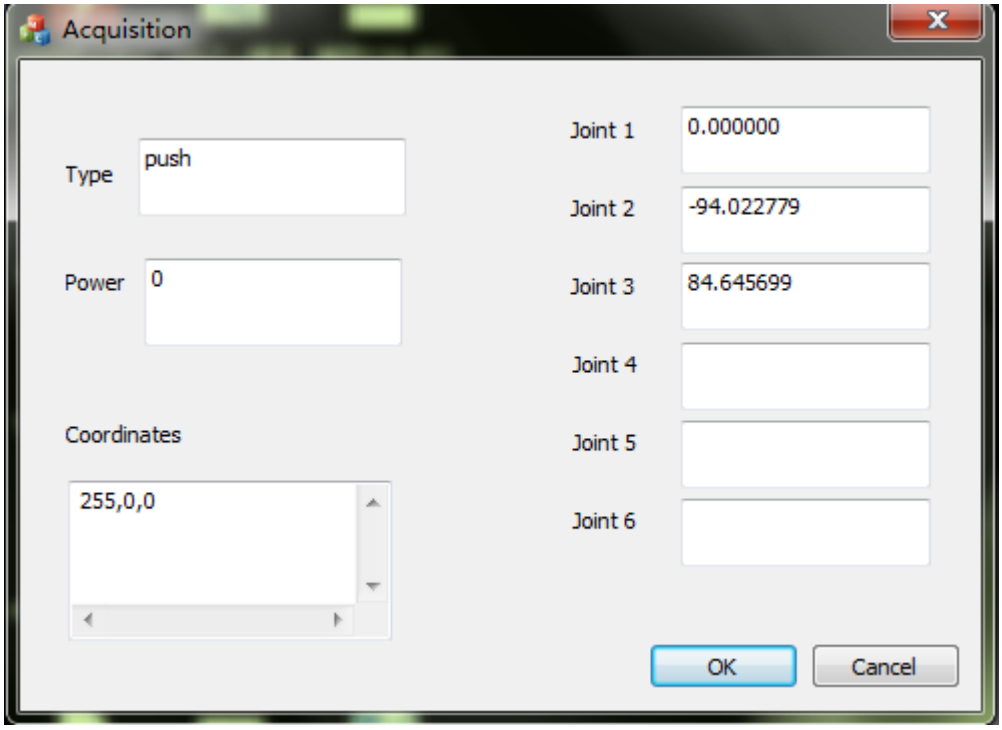
The results of the experiment of designed BCI system with human thought



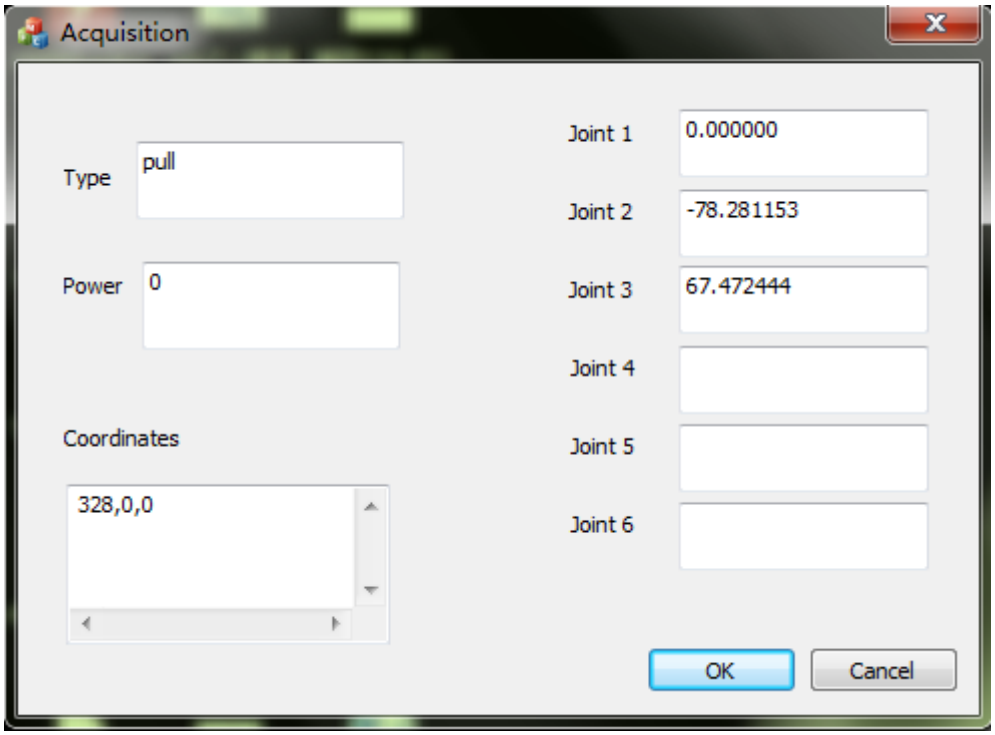


Appendix 5.2


Acquisition
Type
pull
Power
0
Coordinates
520,0,0
Joint 1
0.000000
Joint 2
-44.109804
Joint 3
15.070857
Joint 4
Joint 5
Joint 6
OK
Cancel


Acquisition
Type
push
Power
0
Coordinates
255,0,0
Joint 1
0.000000
Joint 2
-94.022779
Joint 3
84.645699
Joint 4
Joint 5
Joint 6
OK
Cancel

Appendix 5.3


Acquisition
Type
pull
Power
0
Coordinates
328,0,0
Joint 1
0.000000
Joint 2
-78.281153
Joint 3
67.472444
Joint 4
Joint 5
Joint 6
OK
Cancel