Hybrid EEG-EMG based brain computer interface (BCI) system for real-time robotic arm control

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DOI: 10.5185/amlett.2019.2171
www.vbripress.com/aml

Abstract

Nowadays, bio-signal based BCI systems are widely being used in healthcare systems and hence proven to be an effective tool in rehabilitation engineering to assist disabled people in improving their quality of life [**1**]. In this research work, handicapped people with above hand amputee have been targeted and hence non-invasive EEG and EMG biosensors are used to design wireless hybrid BCI system. The presented hybrid system is able to control real-time movement of robotic arm via combined effect of brain waves (attention and meditation mind states) and wrist muscles movements of healthy arm as command signal. The system operates the robotic arm within 3 degree of freedom (DOF) motion which corresponds to movement of shoulder (internal and external rotation), elbow (flexion and extension) and wrist (Gripper open and close) joint. It has been experimentally tested on 4 subjects with upper limb amputee (having one healthy arm) after training period of one day. On receiving the input signals from EEG and EMG sensors, subjects have successfully controlled the movements of the robotic arm with accuracy of 70% to 90%. In order to validate the obtained results, a potentiometer has been fixed on robotic arm and angular motion of shoulder and elbow joint is recorded (actual motion) and compared with results of the BCI system (required motion). The comparison shows high resemblance between actual and required motion which reflects the reliability of the system. In addition, apart from robotic prototype, its 2D modelled is also designed on visual studio. The presented preliminary experimental results show that the motorized prosthetic prototype movement due to mind and muscle control is in accordance with the 2D modelled virtual arm permitting to improve its real-time adoption for rehabilitation. Copyright © 2019 VBRI Press.

Keywords: Rehabilitation engineering, Electroencephalogram (EEG), Electromyogram (EMG), Brain Computer Interface (BCI) system, robotic arm.

Introduction

In the European Union, number of disabled people is increasing at alarming rate and has reached about 37 million [**2**]. Therefore, for disable people with neuromuscular disorders such as spinal cord injury, brainstem stroke, amyotrophic lateral sclerosis, cerebral palsy or multiple sclerosis, an effort should be made to facilitate them with different kind of mobility and communication systems which allow them to build connection with world in more comfortable manner [**3**]. However, designing such systems need sophisticated methods and technologies with higher accuracy, reliability and safety as they have to directly interact with disabled human user. Thus, several control techniques have been investigated and various types of bio- signals are used in each technique depending on its function. EMG is one of the commonly used bio-signals used in bio- robotics applications such as prosthetics [**4, 5**], exoskeletons [**6, 7**] and wheelchairs [**8, 9**]. However, EMG based control methods are not preferred to use alone because of muscle fatigue problem which effects and disturbs the EMG signal amplitude [**10, 11**]. On the other hand, brain computer interface (BCI) system has acquired a great interest in the field of bio-robotics. A BCI is a communication channel which allows a patient to directly use his brain activity (EEG signals) to control automated systems like prosthetic arm [**12**]. Hence this method is also feasible for a paralyzed people who cannot move their certain body parts but can still control their thoughts, which can be used to perform specific maneuvers. Use of EEG based control approach can be found in several bio-applications [**13-18**]. Though, EEG based systems are not fully suitable for bio-robotics applications due to low accuracy, low reliability and low user adaptability [**19-21**]. Consequently, to overcome the problems and issues related to both EMG and EEG based control strategies, a hybrid system could be a better approach which uses both the methods and makes overall system more accurate and reliable. In [**22-24**] it has been shown that accuracy of the system increases by using hybrid approach as compared to situations when EMG and EEG based approach were used separately Several researches have been made in controlling robotic or prosthetic arm by using EEG and EMG signals but they contain some limitations. In [**25**], a motor driven prosthetic arm was controlled with only 1 DOF (arm extension and flexion), whereas in [26] only three actions were performed by prosthetic arm i.e. flexion, extension and pinch. Moreover, in [**26**] the accuracy of designed BCI system was also not so high. Additionally, in [**27**] only opening and closing of prosthetic hand is controlled. In [**28, 29**] robotic arm is controlled by hybrid BCI system that uses multichannel EEG system, which is not comfortable for patients and its setup also requires some expert for positioning electrodes on head. Thus in our work we have considered and overcome all these constraints and designed highly accurate hybrid BCI system to control robotic arm with 3 DOF motion. Also, we have used single channel EEG biosensor instead of multichannel, which makes overall system less complex, more comfortable for patients and cost effective. In the proposed hybrid system firstly, EMG and EEG signals are acquired by myo arm band and single channel Mindwave mobile headset respectively which are connected to computer via Bluetooth wireless communication. The acquired raw bio-signals are then processed and classified with the application developed in MATLAB and processed signal is used to control virtual prosthetic limb programmed on visual studio. Finally, computer is linked to Arduino Uno via serial communication which transmits signal to control the motorized prosthetic hand.

Materials and methods

The BCI system aims to control the movement of targeted body area in the similar fashion as the normal body moves in response to the bio signals acquired from muscles and brain [**30**]. In the presented research the implemented BCI system uses patient's bio potentials (EEG and EMG signals) in simultaneous manner to control the movement of robotic arm. The schematic representation of overall methodology adopted in designing hybrid EEG-EMG based BCI system has been shown in **Fig. 1**. The proposed system mainly comprises of four main modules i.e. signal detection & acquisition, signal processing, signal transmission, mapping signal to robotic arm & 2D virtual arm and system validation.

In the first module, EMG and EEG signals are acquired from patient's arm and scalp respectively. EMG is a technique used for recording and evaluating the electrical activity generated by muscles. Generally, muscles activities can be detected by two methods [**31**]: (i) invasively by using a needle based electrode; inserted directly into the muscle and (ii) noninvasively by positioning a surface electrode over the targeted muscle. In this work, noninvasive technique has been employed and raw EMG signals are detected by using Myo arm band **(Fig. 2a)** which has eight integrated sensors to obtain the EMG signals generated by myoelectric activity of human arm. In addition, it also has an integrated accelerometer, gyroscope and magnetometer for complete gesture recognition of hand gestures **(Fig. 2b)** [**32, 33**] along with built-in Bluetooth module for wireless data transmission to the external unit. Along

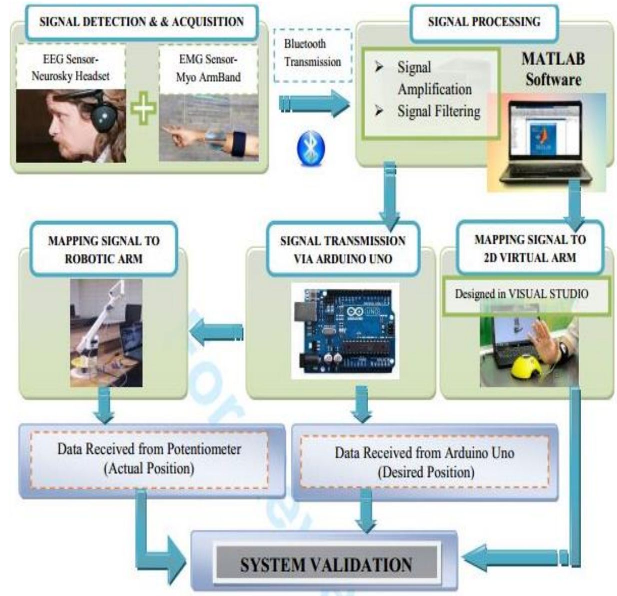

Fig. 1. Methodology of Hybrid EEG-EMG based BCI system.

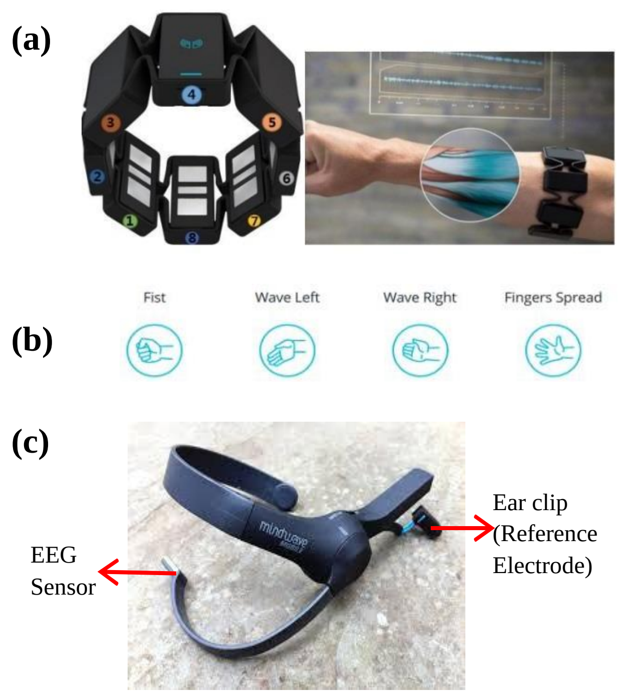

Fig. 2. (a) Myo arm band (EMG Sensor) (b) Myo arm hand gestures (c) Neurosky mind wave mobile headset (EEG Sensor).

with EMG, EEG is also used in the proposed hybrid BCI system. EEG records the electrical activity from the scalp, produced by activation of brain cells [**34**]. Here Neurosky single channel mind wave mobile headset **(Fig. 2c)** is used for detection of raw EEG signal. Neurosky Mindset is wireless, portable, lightweight and non-invasive device, which includes a headband with three mounted sensors (dry electrodes) along with a Bluetooth unit for data transmission. The two electrodes (reference and ground) are placed onto the earlobe and third EEG recording electrode is located on the forehead. It reads electric signals generated by neural activity in the brain and provides information about user's levels of "attention" and "meditation" on a scale of 0 to 100 [**35**]. Hence by combined effect of hand gesture (from EMG signal), attention and meditation values (from EEG signal) the movement of robotic arm will be controlled. At area of contact between body and electrodes, there exist several obstacles like skull, skin and many other layers which weaken and distort the electrical signal. Hence, in the second section the acquired raw EEG and EMG signals are filtered and amplified in MATLAB. The processed signals then act as an input for control system of robotic arm prototype and 2D virtual robotic manipulator programmed on visual studio.

The processed data then needs to be transmitted to Arduino Uno microcontroller which controls robotic arm via real time brain and myoelectric signals. Thus, in third unit, a serial communication is established between computer and Arduino Uno to perform signal transmission. In Arduino, attention and meditation values are classified into different ranges and different variables are assigned to hand gestures, attention and meditation ranges (table S1 and S2). As robotic arm has to perform 6 different actions therefore in Arduino six combinations of EMG and EEG signals are programmed (Table S3). Thus, when the user performs specific hand gesture along with certain level of focus or meditation, the robotic arm preforms a pre-defined action.

In next module, a generated signal from Arduino controls the movement of robotic arm. The robotic arm prototype has 3 degree of freedom (DOF) motion and its joints represent the human wrist, elbow and shoulder joints **(Fig. 3a)**. The robotic elbow joint performs extension and flexion motion of arm (varying between 0 to 120 degrees), robotic shoulder joint executes medial and lateral rotation of shoulder (varying between 0 to 150 degrees) whereas robotic wrist joint corresponds to opening and closing of gripper. Each joint is connected with a servo motor and SG90 9g micro servo is used to control the movement of gripper while MG996R servo is used for moving shoulder and elbow joints. Hence these servo motors receive the input command from Arduino which allows them to derive the robotic arm to its desired position.

Finally in order to validate the system response, a, a linear taper potentiometer "480-5885-ND" (angular position sensor) is connected to Arduino and positioned on the robotic arm in order to measures the actual angular position of the robotic arm [**25**]. In addition, a virtual 2D robotic hand manipulator has also been designed using Microsoft Visual Studio which consist of shoulder joint, elbow joint and a claw **(Fig. 3b)**. Processed signals from MATLAB are also mapped on virtual robotic arm which moves according to provided input. Thus, the motion of robotic arm manipulator is compared with action of virtual robotic arm to analyze if the movements are in correct accordance. Lastly, the data from potentiometer (actual position) and controller output (desired position) is compared to verify the accuracy and reliability of the system.

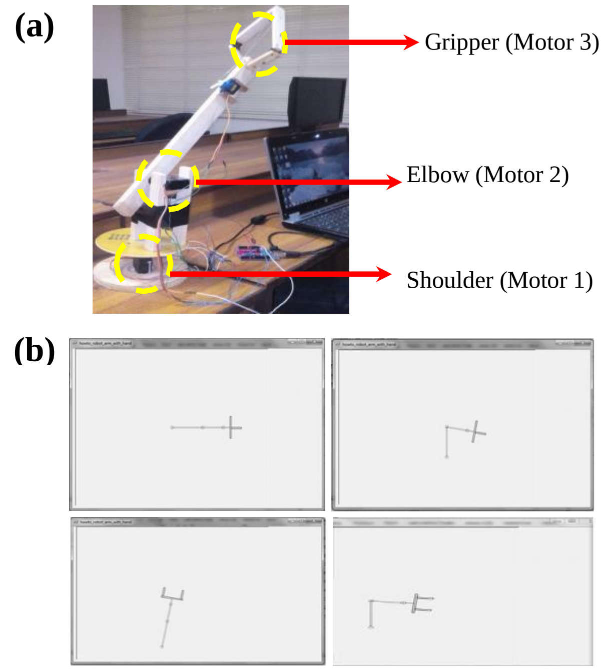

Fig. 3. (a) Robotic Arm Prototype (b) 2D Modelled Robotic Arm.

Experimental results and discussion

The developed BCI system has been experimentally tested and verified by a group of subjects (2 males and 2 females), who controlled the movement of robotic arm by combined influence of their mind thoughts and healthy hand movements. The following criteria were used in selection of experimental subjects: (1) Must have upper limb amputee only on one hand (2) Second hand must be completely fit and healthy (3) Don't have stress or other mental disorder. Before maneuvering the robotic arm, the subjects' brain is trained for one day to self-control the "attention" and "meditation" mind levels. In order to have high attention value the participant has to be focused on specific thought i.e. greater the focus, the higher will be the attention value. On the other hand, to keep the meditation value high the subject has to keep his mind in more relaxed state. Then, the subjects are also trained to combine specific hand movement (for EMG signal) with their mind level (for EEG signal) to perform pre-determined action. The action perform by robotic arm are not solely dependent on the attention and meditation value but also govern by the hand movement, so as a combine result from these three inputs one action is performed. Since it is hard to achieve the same level of attention and meditation every time, therefore, a range has been defined (Table S1) which makes the initial training easy for the people.

Some of the actions performed by subjects are shown in **Table 1** and it confirms that all the performed operations matches the conditions set in Arduino program (Table S3). Additionally, the information about tasks given to subjects and accuracy by which tasks have been performed are shown in **Table 2** (results of 2 random subjects are displayed). It illustrates that accuracy varies between 70% to 90% depending on the subject's mind state and their training level. The angular motions performed by elbow and shoulder during tasks execution is presented in **Fig. 4**. Furthermore, processed signals from MATLAB are also send to virtual arm which accomplish the actions depending on EMG and EEG signal inputs **(Fig. 3b)**. It has been observed that motorized robotic prototype and virtual arm performed the same task simultaneously on providing same input (processed signal); which shows that all actions are executed correctly by the hybrid BCI system. Additionally, in order to validate the obtained results, the potentiometer is mounted on robotic arm that is used as "angular position sensor" to determine the actual angular movement of elbow and shoulder joint. The obtained actual angular position is compared with desired angular position data provided by Arduino microcontroller. In comparison graphs **(Fig. 4)**, overlapping of actual and desired positions show that robotic arm has accurately performed the anticipated actions.

Table 1: Experimental Results of Hybrid EMG-EEG based BCI System.

Subject	Attention (0-100)	Meditation (0-100)	Hand Motion	Action (2D modelled and 3 DOF robotic arm)
1	64	100	Fist	Gripper Close
	32	41	Fist	Shoulder Movement towards Right
2	100	84	Wave right	Downward Elbow Movement
	36	28	Wave right	Upward Elbow Movement
3	41	96	Wave left	Shoulder Movement towards Left
	89	76	Wave right	Downward Elbow Movement
4	100	100	Finger spread	Gripper Open
	92	100	Fist	Gripper Close

Table 2. Overview of Tasks Execution Accuracy by the Subjects.

SUBJECT 1			
ELBOW MOVEMENT		**SHOULDER MOVEMENT**	
COMMANDS GIVEN	**COMMANDS EXECUTED**	**COMMANDS GIVEN**	**COMMANDS EXECUTED**
Up	Up	Right	Right
Down	Down	Left	Right
Up	Up	Right	Right
Up	Down	Right	Right
Down	Down	Left	Left
Up	Up	Right	Left
Down	Down	Left	Left
ELBOW MOTION ACCURACY: 86%		**SHOULDER MOTION ACCURACY: 71%**	
SUBJECT 2			
ELBOW MOVEMENT		**SHOULDER MOVEMENT**	
OMMANDS GIVEN	**COMMANDS EXECUTED**	**COMMANDS GIVEN**	**COMMANDS EXECUTED**
Up	Up	Right	Right
Down	Up	Left	Right
Down	Down	Right	Right
Up	Up	Left	Left
Up	Up	Left	Left
Down	Down	Right	Right
Up	Down	Left	Left
Down	Down	Left	Left
ELBOW MOTION ACCURACY: 75%		**SHOULDER MOTION ACCURACY: 87.5%**	

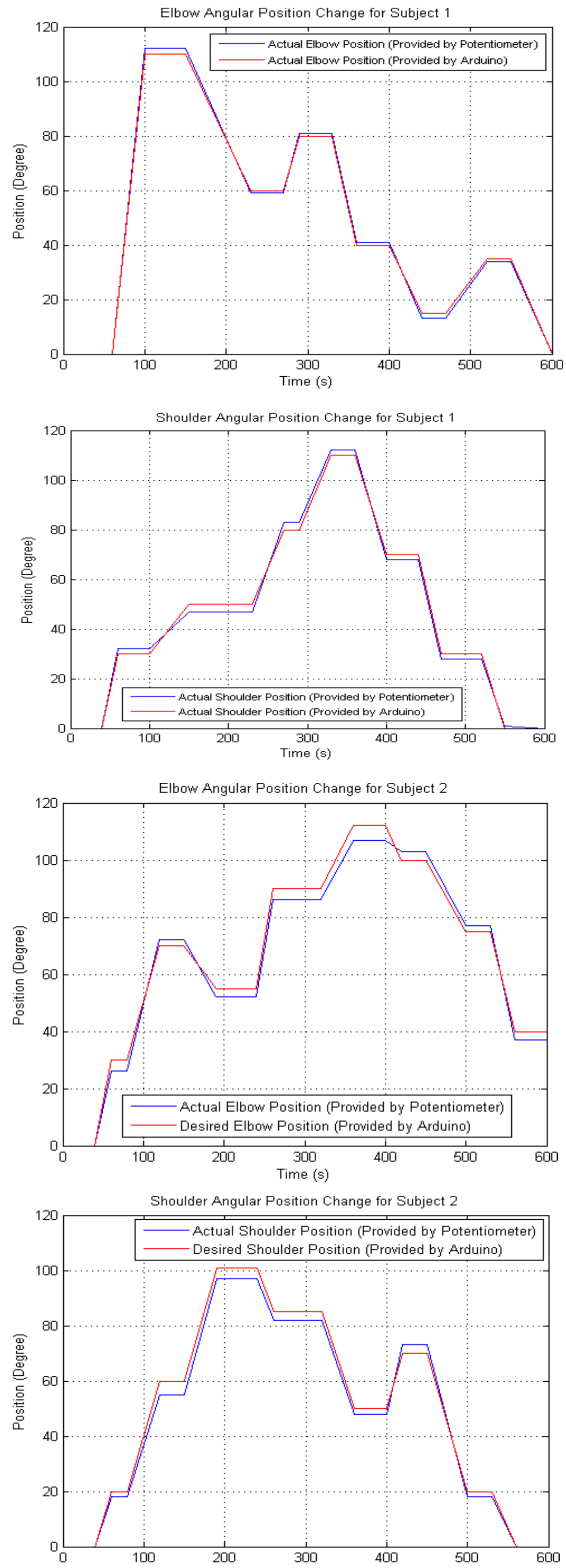

Fig. 4. Validation Test Results of: (a) Elbow Angular Position for Subject 1 (b) Shoulder Angular Position for Subject 1 (c) Elbow Angular Position for Subject 2 (d) Shoulder Angular Position for Subject 2.

Conclusion

The presented research demonstrates a novel method of rehabilitation for disabled people by creating a BCI system with non-invasive biosensors to operate the robotic limb with 3 DOF range of motion. The shoulder, elbow and wrist joints are replicated on robotic arm prototype and are controlled by patient's EEG and healthy arm EMG signals. The system is tested by four subjects after undergoing an extensive training for a day, each subject was asked toper form the desired action several times to validate the repeatability and accuracy of the resulted action performed by robotic arm. The experimental results have testified the reliability of the system by comparing the system response with position feedback from linear potentiometer. Moreover, simultaneous movement of 2D modeled robotic arm with real prototype has also validated the correct accomplishment of robotic tasks. Furthermore, from obtained results it is also observed that system accuracy of different subjects lies between 70% and 90%. All subjects have reported that they did not feel any difficulty in maneuvering robotic arm and it was also easy for them to control meditation and attention values along with hand movements. However, they cannot move the robotic arm with precise angles i.e. they can move only in right, left, up, and down direction with gripper open and close, irrespective of specific angles. Hence it shows that one of the factors on which system accuracy depends is patient's training i.e. how perfectly subject's brain is trained for controlling and synchronizing mind levels with hand motion for specific action. Thus, in future more intense and long lasting training would be provided to subjects and system behaviour will be monitored in terms of controlling the arm with precised angles. In addition, further research will be carried out to design a self-reliant portable BCI system that will use Raspberry pi instead of Arduino microcontroller and will actuate the prosthetic arm independently without any need of external controlling unit.

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