Implementation of Artificial Neural Network in Electric Motor Control using Brain-Computer Interface

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Abstract. Brain-Computer Interface (BCI) is a technology that integrates analog brain signals to digital computer-based systems for the purpose of analysis, manipulation, and control. With modern machine learning algorithms, Artificial Neural Network (ANN) was used to develop the intelligence in processing brain signals for electric motor control. In this study, supervised and unsupervised learning methods were explored to train the ANN. Guided and unguided thought-task methods were used in manipulating a 5 and an 8 switching control variations of an electric motor. A brain wave filter was designed, and the different brain bands were explored. Significant signal features were obtained and were varied in terms of qualification. Simulation run in an off-line and real-time mode. Results show high control accuracies in using the Gamma band with a supervised learning method. Guided thoughts with 5 switching controls, and 4 features gave better results. Control accuracies varies between off-line and real-time implementations.

1. Introduction

Brain-computer interface (BCI) technology incorporates the human mind to the modern digital computing systems. BCI utilizes brain signals, known as electroencephalogram (EEG) signals, and subject them to different signal processing methods for a wide variety of purpose and objectives. EEG measures and records the electrical activities emitted by the brain using invasive and non-invasive methods. BCI interlinks human thoughts to the physical world with the use of sensors that captures the electrical activities of the brain, and a system that performs analysis, manipulation, and task (or control) implementations [1].

The complexity and full potential of the human brain is still a topic of interest in the modern age. Emitted random signals from the brain poses a great challenge for researchers in terms of processing and interpretations. Signal processing plays a major role in the preparation of raw signals before they are used for task implementations. Filter design is critical in removing unwanted frequencies and attaining quality signals from its raw form [2]. To put intelligence into a control system, machine learning algorithms are required for detection, recognition, and classification. In this study, the artificial neural network (ANN) algorithm was used because of its proven capabilities, and wide implementation in intelligent systems [3], [4].

The aim of this paper is to implement ANN for electric motor control using BCI. The EEG bands were explored as well as the channels of EEG capture. The supervised and unsupervised learning techniques were explored in a guided and unguided thought-task approach to manipulate and control a 5- and 8- switched electric motor. Significance of this study is found in assisting patients who have
permanent disabilities and are unable to move freely and operate nearby electric or electronic devices. This would aid in mitigating depression for people who are disabled by empowering and capacitating them using their active minds.

2. Methodology
A 14-node Emotiv EEG headset was used to read brain wave signals. These nodes include AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4. Each channel can obtain a raw EEG signal, and can be displayed in its partner software, the TestBench, in real time. Electrodes must have a good contact on the scalp in order to have a good signal. Obtained data are in CSV format [5]. For the implementation in this study, only 4 nodes were used which include AF3, AF4, F7, and F8 [6], [7].

The number of switching controls and features were varied. Four combinations were used for both supervised and unsupervised learning methods. The combinations are 8 switching controls with 4 features (8C4F), 5 switching controls with 4 features (5C4F), 8 switching controls with 6 features (8C6F), and 5 switching controls with 6 features (5C6F). These were performed with both guided and unguided thoughts-task approach. Guided thoughts-task mean that the person thinks about a specific thought while the unguided one means that person is free to think of something for a specific switching control.

A total of 20 volunteers, all legal age, participated in this experiment. A study orientation was given before the procedure starts. They filled-up a questionnaire, answered a survey form, and signed a consent letter for ethical considerations. Smokers, coffee drinkers, and the left-handed participants were allowed to join the simulation as long as they are able to meet the following conditions: For the smokers, they should have smoked at least six hours before their participation. For the coffee drinkers, they should have coffee intake at least two hours before their participation.

Supervised and unsupervised learning methods were used to create the ANN. A feed-forward neural network was used in the supervised method while a clustering neural network was used in the unsupervised method to train the system on classifying the switching controls of the electric motor [8]. Expected results will determine which learning method, number of switching controls and features, thoughts-task training approach, and brain wave band are more useful and appropriate for the implementation.

Once identified, the actuation will be performed by the Arduino Uno micro-controller equipped with a Wi-Fi module and relay cards [9]. Processed signals were passed into the controller to actuate the intended motor action.

2.1 Learning Methods
Figure 1 shows the block diagram for the supervised and unsupervised learning methods. This block diagram shows how the “thoughts-task” ANN training method was established. At first, the participants were told to think about a thought corresponding to a control. This thought corresponds to raw EEG signals which are acquired using the Emotiv headset. The raw EEG signals are pre-processed and the features were extracted for training the neural network. For the supervised learning method, a feed-forward neural network was used as a classifier to have a supervised neural network. For the unsupervised learning method, self-organizing map was used to cluster the features which results to an unsupervised neural network.

Figure 2 shows the implementation of the supervised and unsupervised neural networks. For both networks, the EEG response of the participants was obtained using an EEG Emotiv headset. The raw EEG signals were the pre-processed and features were obtained to serve as inputs to the neural network. A fuzzy logic inference system was used for decision making resulting to a control signal that will trigger a specific motor action through the micro-controller. A feedback mechanism was used to acquire new thoughts to be processed.
2.2 Thoughts-Task Approach

The unguided thoughts approach and the guided thoughts approach were used in this study. Unguided thoughts approach allows the participant to think freely about anything for a specific control. Guided thoughts are given suggested actions to think about as shown in Table 1. Two switching sequences were used to guide the participants on what will be the sequence of their thoughts. This also helped in organized and structured data collection. The sequences are shown in Table 2.

Table 1. Thoughts for Switching Controls

| Switching Controls  | Guided Thoughts   |
|---------------------|-------------------|
| No Response (NR)    | Sleeping          |
| ON                  | Jumping Jacks     |
| OFF                 | Snapping          |
| START SWING         | Swinging          |
| STOP SWING          | Firing a gun      |
| SPEED ONE           | Biking            |
| SPEED TWO           | Swimming          |
| SPEED THREE         | Punching          |
Table 2. Switching Sequence for (a) 8 Switching Controls, and (b) 5 Switching Controls

| SWITCHING CONTROLS | Set No |       |       |
|--------------------|--------|-------|-------|
|                    | 1      | 2     |       |
| NR                 | NR     |       |       |
| ON                 | ON     |       |       |
| SPEED TWO          | SPEED THREE |     |       |
| START SWING        | START SWING |   |       |
| SPEED ONE          | START SWING |   |       |
| STOP SWING         | STOP SWING |   |       |
| SPEED THREE        | SPEED ONE |   |       |
| OFF                | OFF    |       |       |

(b)

2.3 Data Collection
Four data sets were gathered from each participant. For the first 2 sets, they have the freedom to think of anything they want as a thought for each control setting. For the last 2 sets, they were guided by the following thoughts as shown in Table 2. There are 8 thoughts for the 8 switching controls in the first and third data set while there are only 5 thoughts for the 5 switching controls in the second and fourth data set. The created function, recordEEG, obtains the signal from the participants by simulating the option variable in MATLAB. It concatenates the 4 brain wave streams from the AF3, AF4, F7, and F8 nodes.

2.4 Experimental Set-up, Data Gathering Tools
The data gathering was performed in an acoustically prepared room. The temperature was kept between 20° – 25°C [10]. The participants were seated on a chair in any way they are comfortable as shown in Figure 3. During the process, the participants should be in a relaxed state and no other external disturbances should be present. The Emotiv EEG headset was used to gather the brainwaves linked to a computer using the EPOC-Simulink Signal Server in MATLAB. Data obtained was monitored using the TestBench.

2.5 Pre-processing
Band pass filtering was used to extract the five frequency bands of the EEG signal from nodes AF4, AF3, F7 and F8. Z-score normalization was used to reduce the variability of the sequence leaving a range of -1 to 1 only. Figure 4 shows the pre-processing block diagram.
A band pass, least-square FIR filter was designed using the Filter Design and Analysis (FDA) Toolbox in Matlab. The order of the filter was defined by three times the fixed ratio value of the sampling rate divided by the lower cut-off frequency. This filter was used to make Alpha filter, Beta filter, Delta filter, Gamma Filter, and Theta filter. The created function `transformSpect` does the filtering and normalization of the raw data, obtains power spectrum with the parameter of `winhamming` from the filtered data, and acquires half of the power spectrum.

2.6 Feature Extraction

Features were extracted from the filtered data. Two sets of features were considered. The first set is composed of six features and these are kurtosis, entropy, and skewness of the Power Spectral Density and Discrete Wavelet Transform Vectors [11], [12]. The second set is composed of four features which is focused on the kurtosis, entropy, skewness, and singular value decomposition of the Power Spectral Density Vector [13], [14]. The created function `FeatureExtraction` for 6 features and 4 features obtains the feature extracted data of the filtered data. The created function `dwtMaker` obtains the DWT low pass coefficient of the alpha filter. It uses `symlet24` type of wavelet that instantiates a 24-coefficient Symlet wavelet object.

2.7 Artificial Neural Network

The data gathering method was the same for both learning methods considering the unguided thoughts and guided thoughts approach. The supervised method used a feed-forward neural network technique because it uses a target value in getting the right category.

However, the unsupervised method uses self-organizing map neural network using clustering method since it groups the pattern and creates its own cluster. After creating the network, the output will be implemented in the neural network for training.

2.8 EEG Classification

After the supervised neural network, EEG signals were classified using the Fuzzy Inference System (FIS) with a centroid defuzzification method [11]. It returns the center of area under the curve. The 5 switching controls has a different fuzzy logic from the 8 switching controls.

The range values were chosen in order to set a tag for each motor controller. It is also possible to change the range values as long as the gap between each switching control is equal. The features were fed to the feed-forward neural network along with the range values. The data is expected to be exactly in between each range, however, if not, the system is self-adjusting based on the highest value acquired. The highest value was divided by the number of switching controls and the result was used as the range of the membership functions.

In the unsupervised learning method, the neural network makes its own pattern and will also generate its own cluster for that specific category based on the EEG data that was trained; and if the new EEG data is fed into the neural network, it will only find the closest cluster or the exact cluster. Through this, the thought of the person can be identified which control they are thinking.
2.9 Hardware Design
In assembling the hardware, the ATMEGA328, ESP8266, EX2 12V relay card, 12V automotive relay, DB9 connectors, and electric fan were used. The Tx and Rx pin of both ATMEGA328 and ESP8266 should be connected together to utilize the TCP/IP between the computer and ATMEGA328. After the computer sent an indicator to the ATMEGA328, certain digital pins connected to the EX2 12V relay card will either go logically high or low, depending on the command that was sent from the computer. A high digital pin that was sent to the EX2 12V relay card will close the connection connected to the normally opened side of the relay. In the normally opened side of the EX 12V relay card, another relay is connected to it which is the 12V automotive relay that will also either on or swing the electric fan. DB9 connectors were used to connect the EX2 12V relay card to the 12V automotive relay though only the 5 pins on the DB9 were used. Figure 5 shows the hardware implementation of the system.

![Hardware Implementation Diagram](image)

3. Results and Discussion
The ranking method was used to determine which band is to be used. Based on the results as shown in Table 3, 5C4F shows the highest accuracies compared to the other set of combinations. For the 5C4F guided thoughts, the most effective bands to be used are Gamma, Beta, and Delta guided thoughts; while for 5C6F, the most effective bands to be used are Alpha and Theta. For the 5C4F unguided thoughts, the most effective bands to be used are the same as 5C4F except Beta. The mean of 5C4F and 5C6F for both guided and unguided were calculated. Through this result, it shows that 5C4F for both guided and unguided has the highest mean.

Table 4 shows the results of the band ranking method. The Gamma band outranked the other bands in this particular implementation. This is supported by [15] as Gamma-band activity is present in various cerebral functions which includes, memory, perception, attention, synaptic plasticity, consciousness, and motor control. It is also found with visual stimulation and in movement or motor tasks. The action thoughts elevated this above the rest of the bands.
Table 3. Supervised Control Accuracy (a) Guided Thoughts, (b) Unguided Thoughts

| BAND  | 8C6F | 8C4F | 5C6F | 5C4F |
|-------|------|------|------|------|
| Gamma | 43.1%| 38.8%| 96.5%| 100% |
| Beta  | 31.3%| 35.0%| 84.0%| 89.0%|
| Alpha | 56.6%| 47.2%| 90.5%| 86.0%|
| Theta | 54.7%| 55.3%| 81.0%| 80.5%|
| Delta | 44.4%| 44.7%| 77.0%| 77.5%|

Table 4. Band Rankings According to Accuracy

| RANK | Supervised-Unguided 5C4F | Supervised-Unguided 5C4F | Supervised-Guided 5C4F | Supervised-Guided 5C4F | OVERALL |
|------|--------------------------|--------------------------|------------------------|------------------------|---------|
| 1st  | Gamma                    | Alpha                    | Gamma                  | Gamma                  | Gamma   |
| 2nd  | Theta                    | Beta                     | Beta                   | Theta                  | Alpha   |
| 3rd  | Alpha                    | Gamma                    | Alpha                  | Alpha                  | Beta    |
| 4th  | Delta                    | Theta                    | Theta                  | Delta                  | Theta   |
| 5th  | Beta                     | Delta                    | Beta                   | Delta                  | Delta   |

3.1 Graphical User Interface

Figure 6 shows the graphical user interface of the BCI system with 5 switching controls. There are 10 buttons available: start, load network, on, off, swing, stop, no response, save network, clear, and lock button. Initially, the system is locked for security purposes. The user must press the unlock button in order for the other buttons to function. The thoughts for each switching controls will be recorded by clicking the controls buttons (on, off, swing, stop, or no response). The recording time is 10 seconds per switching control. Then, recorded data will be processed and a neural network will be created and saved. This is repeated every time a new recording is performed. This is a system that customizes its response according to the user.

![Smart Control](image)

Figure 6. Graphical User Interface of the System

Since the learning method, the thoughts-task training approach, the number of controls and features, and the filter band to be used were identified, these were implemented in a BCI system. Test trials were done on 10 volunteers given 12 trials with a time limit of 2 minutes. This is to prevent the participants from thinking for a long time. The sequences shown in Table 2b were followed. The testing of this system was made at the same location where the data gathering happened. Table 5 shows the results.
The relax state (NR-No response) is highly recognized by the system. The task of creating a thought to think about in order to run the motor might have impacts in the other switching controls such as to turn on and off the motor or to make it swing and stop swinging.

| SWITCHING CONTROL | ON       | OFF       | SWING     | STOP      | NR       |
|-------------------|----------|-----------|-----------|-----------|----------|
| ACCURACY          | 80.14%   | 81.39%    | 80.69%    | 81.05%    | 92.5%    |

4. Summary, Conclusion and Recommendation

The implementation of ANN in electric motor control using BCI is completed in this study. Two different neural networks, feed-forward back-propagation and self-organizing maps, were used. EEG signals were obtained from 20 participants while they were thinking of a thought for a specific switching control. These EEG signals were pre-processed and sent to a neural network for classification.

A “thoughts-task” ANN training approach was developed, and it describes the supervised and unsupervised learning methods. Switching control actions were thought either in an unguided or guided manner.

The performance of supervised and unsupervised ANN training methods was compared in terms of accuracy. Four sets of combinations (switching controls and features) were considered: 5C4F, 5C6F, 8C4F, and 8C6F. For a cutoff accuracy of 70%, 8C4F - supervised, 8C6F - supervised, and all of the combinations under the unsupervised learning methods were disregarded leaving the 5C4F and 5C6F for both unguided and guided thoughts candidates for the BCI system.

A ranking method and averaging of accuracies were used to determine the EEG signal band to be used. Results show that the Gamma band fits this implementation more than the other bands. Accuracies that belong to the 5C4F and 5C6F supervised methods (unguided and guided approach) were averaged to determine which of the two will be considered. As a result, guided supervised 5C4F has the highest average accuracy.

For control purposes, it is recommended to use EEG headsets with lesser number of nodes like the Emotiv Insight. This will lessen set-up time and can readily provide raw data without removing the data from excess nodes. Deep learning algorithms are also recommended to automatically extract feature and classify in a single block. Other learning algorithms can also be used such as k-means, support vector machines, and adaptive learning methods.

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