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PAPER

Towards Design and Implementation of an EEG-Based BCI TV Remote Control

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ABSTRACT

BCI is a rapidly growing field within biomedical engineering as it enables a direct connection between the central nervous system and an external device. BCI detects brain signals using biosensors (electrodes) installed on the head's scalp or implanted inside the brain. EEG is a non-invasive method for detecting and monitoring the brain's activity. Using EEG-based BCI in the medical field can significantly help disabled people to perform daily activities. In this context, it is very important to support and enable paralysed people to interact with multimedia devices like televisions by developing suitable solutions. This paper proposes an EEG mind-controlled TV remote control system prototype. The proposed prototype uses affordable hardware components to perform its task. A quantitative questionnaire has been conducted to identify the system's functional and non-functional requirements. The system can send four different signals to power on/off, change the channel, raise and reduce the volume of the TV. The system has been tested by 20 subjects. The testing results show that the accuracy of the system is 74.9%. Despite the system being able to control only four TV functions, the system is scalable, and more commands can be added in the future. Also, using Raspberry Pi in the system gives a great possibility to eliminate the computer and to use Raspberry Pi directly with the headset. This paper demonstrates the approach's feasibility and opens the route for enhancing the system and using EEG-based BCI with more and different devices.

KEYWORDS

brain-computer interface, EEG, disabled people, remote control, Raspberry Pi

1 INTRODUCTION

Many attempts have been made in the past years to enable paralysed patients with neurological diseases like Amyotrophic Lateral Sclerosis (ALS) or injury of the spinal cord to express themselves and communicate with their environment using their brain commands [1].

In the last few years, the use of the mind's power to control devices has become a very interesting and very good research topic in the medical field, with practical

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applications in entertainment and home automation, such as controlling TVs, LEDs, air conditions, etc, to be used by disabled people for whom these technologies may serve as their only means of communication within their environments and to the outside world [2].

Brain waves are electrical signals that are commonly sinusoidal with different ranges of amplitude [3]. Brain-computer interfaces (BCIs) work as a direct link between the brain of a human and an external device [4], where BCI devices can detect these signals and transform them into commands used in different applications and allow people to control different devices. BCIs can help paralysed people control external devices through brain commands. New advancements in the Internet of Things and smart and home automation may increase the use of BCI applications in daily home living activities [1].

BCI can be one of two types: invasive or non-invasive. The invasive way is when an electrode chip is implanted inside the brain by surgical invasion, like Electrocorticography (ECoG). Non-invasive BCIs include techniques like Electroencephalography (EEG), Magneto Encephalograph (MEG), etc., which are used to detect and collect these with lower signal quality than invasive methods. In non-invasive techniques, the electrodes, with or without conductive gel, are placed on the scalp. In both types of BCI, the electrical brain signals produced by neurons are transferred to the computer to translate them into data [5].

BCI use has been applied to fields other than medicine, such as cognitive training, learning systems [6], entertainment, etc., for normal users [1].

The most used method for detecting the brain's electrical activity is the non-invasive EEG technique. To enable the patient or user to control an external device or interact with software in real-time, the brainwaves detected by EEG must be interpreted and converted into commands. Furthermore, EEG can be used in the medical diagnosis of diseases or disorders [7]. The EEG technique is accurate, cost-effective, and provides the patient full control. It also lets the user take the EEG device off when feeling inconvenienced [8].

Recent advancements in commercial EEG devices such as headsets and headbands [9] provide an affordable and accessible way to investigate and develop applications in different fields [10]. With recent advances in smart TVs, users can interact with their voice or motion. As TVs have developed rapidly, the next generation of TV interfaces may be expected by customers, where these TVs may be more intuitive and natural. Eventually, an interesting possible goal for intuitive interactions is to understand and identify the intent of the user to enable him/her to control a TV by thinking [11].

Regarding the statement of the problem related to TV control, TVs using conventional remote controls require physical interaction such as pressing buttons and may not offer the desired degree of accuracy and convenience for disabled people, especially for severely paralysed people, such as patients with locked-in syndrome (LIS) or completely locked-in syndrome (CLIS). Using technologies like voice commands in controlling TVs could be a good alternative to the traditional TV remote control, but voice control is not always accurate, especially if the disabled person or patient speaks fast or cannot speak the required language or speaks with a strong accent (most systems support only English), which may lead to command execution errors. Also, voice control cannot be applied to all disabled people, such as those with speech impairments. Eye-tracker technology may provide a possible solution, but it has some limitations, like the "Midas touch" problem [12], which is an issue that occurs if the patient's gaze direction does not match his/her desire, which causes incorrect output or command. Mind-controlled TV is a solution that can provide easy and intuitive control for disabled people. Several successful research attempts have been made to implement mind-controlled TV systems. Some of these systems are not implemented using hardware and not tested in real environments; other systems have poor functionality, where only one control command is included. More research and investigation will certainly be done, as this is a new field of research.

In this context, the main purpose of the research presented in this paper is to design and implement an EEG-based BCI TV remote control that uses human brain thoughts to control the TV. This should help in designing and developing a new generation of smart TVs as new inventions and technologies are emerging and being used. To the best of our knowledge, the novel idea of using Raspberry Pi in the implementation of an EEG-based BCI remote control with four commands has been presented in this paper. This BCI application is quite promising and has great potential in setting goals for scientific research, especially for paralysed people with special needs in general or for healthy people's entertainment.

2 LITERATURE REVIEW

The use of commands extracted from the brainwaves for controlling TVs is reported in the literature of different research and applications. Brain signals can be detected using many EEG headsets or electrodes, such as the EMOTIV™ Insight headset that has been used in this TV remote control.

The following paragraphs introduce several solutions to the issues of mind-controlled TV remote control. Most literature introduces several utilities and techniques that address and deal with aspects of remote control.

In 2013, Kim et al. [11] introduced an EEG-based BCI TV channel control system using P300. The 46-inch TV screen was divided into four video previews, where each part displayed a particular programme. Eight subjects took part in the experiment, where each subject was asked to concentrate and chose one of four TV channels to watch. The distance between the subject and the TV was three meters. The system had good accuracy when using an EEG headset with 16 electrodes, which give robust and stable signals, as well as when using a 3-electrode EEG headset. In terms of functionality, the system was weak, where the only function was channel selection, and it could not be used as a remote control for other basic functions, such as power on/off and volume control.

In 2014, Lin and Hsieh [13] proposed a wireless EEG system to control the channel selection of the TV. They used a Neurosky EEG chip to obtain brain signals from the scalp. A tablet PC was used as the main controller, and an Android application was developed. Bluetooth and infrared emitter were used to communicate with the TV. Seven men tested the system, and the results showed that most subjects got high accuracy.

In 2016, Alomari [14] suggested an EEG universal system for TV remote control. The system depends on integration between mental commands and facial expression commands. The author used an EEG dataset available online on PhysioNet. He used Discrete Wavelet Transform (DWT) to analyse the EEG records from the dataset and to extract the features. These extracted features were then used as inputs to Support Vector Machines (SVMs) and Neural Networks (NNs), which the author used to generate the needed decision rules. The results showed that the system has good performance accuracy. Although the proposed system offers five control functions, it was not implemented and tested to validate its functionality. The author proposed using an EEG headset to record EEG signals, but he used a dataset available online.

In 2018, Zaki et al. [10] proposed a system to remotely control a TV using a BCI headset. They used an EMOTIV™ EPOC headset with 16 electrodes to detect the brain waves, Raspberry Pi III, and an IR receiver/transmitter to implement the system. The system can only turn the TV ON or OFF, without any other functions. Although this system has only one control command, using Raspberry Pi provides great flexibility and the possibility to improve the design of the system and still use only Raspberry Pi to perform other system functions. More research is needed to validate the possible functions.

In 2022, Kaongoen et al. [4] proposed a novel method to interact with home appliances using EEG signals obtained from the area around the ear of the user. They used a specially made EEG-based BCI headphone to detect EEG signals. Eleven subjects tested the system in which the target was an interactive simulated television that was created for the experiment. A subject could control the TV by moving the mouse cursor toward three different circles. The channel could be changed by performing speech imagery of the words next and back (left circle), the volume could be changed by imagining the words up and down (right circle), and the TV could be turned on or off by imagining word power (bottom circle). Speech imagery is a mental task that one can perform by imagining speaking of a certain word without generating any sound. The system achieved high accuracy in offline training. Only a few subjects were capable of using this TV control system with fast command execution and high accuracy. The system has an interesting novelty in that it provides powerful performance by using a combination of speech-imagery tasks with the custom-made ear-EEG device. The headphone-shaped ear-EEG device gives the user the comfort and wearability that some traditional EEG headset does not offer. However, the system has not yet been fully implemented to be tested in a real environment.

In 2022, Velasco-Alvarez et al. [15] proposed a BCI system to control some home devices (including TV), Whatsapp, and Spotify applications using voice commands through Google Assistant. The system enables the user to control a device, such as a TV, by using thoughts to pick an element from a matrix to generate text, which will is converted to a voice command. EEG was detected using 8 electrodes placed on the scalp, and the signals were amplified using the acti-CHamp amplifier. The TV commands included power ON/OFF, volume ON/OFF, increase or decrease volume, change channel, and set timer to turn off the TV. The system was successfully tested by 12 healthy subjects (males and females) and showed good accuracy. It system could be useful for patients despite the possible difficulties in learning and using the system to control devices. The system can be considered complex, as it consists of several parts, including an EEG sensor, BCI speller software which is used to spell out the text, virtual assistance (Google Assistance) running on a smartphone, a Google Nest device, and an infrared-emitting controller. Integrating several parts or devices required careful integration of hardware and software components to prevent or reduce errors, which can occur when converting the brain's thoughts into commands. Also, it may be difficult for users to send control commands; thus, they have to pay attention when selecting the required items from the matrix of the BCI speller.

A combined BCI and eye-tracking system was presented by Wang et al. in 2022 [16]. They aimed to help ALS patients control home appliances using a MindWave Mobile EEG headset that contains one electrode to detect EEG signals; a pair of eye-tracking glasses which are used to detect the gaze point; and an intelligent Human-Computer Interaction (HCI) screen, which can help to control appliances using voice commands. An experiment was conducted to test the system with 10 subjects (5 males and 5 females). Using a “you only look once” algorithm for object detection with voice commands provided a high accuracy, as the experimental results revealed. In terms of accuracy, the “Midas touch” problem [12], from using eye-tracker technology, may emerged. It was also found that using one electrode to detect EEG signals may cause a weak or unstable signal and using BCI with eye-tracking technology and HCI screen to control home devices can be complicated and can lead to errors or misinterpretation in the execution of commands.

In 2023, Uyanik et al. [17] proposed a BCI home and wheelchair-control system in a virtual environment. A virtual home and wheelchair environment was implemented using the Unity engine. This environment contains different kinds of appliances that can be controlled by brainwaves, such as lights and TV. A NextMind sensor was used to detect brainwaves. The virtual control menu for the TV included power ON/OFF, next/previous channel, and volume UP/DOWN. The system was tested on 15 healthy participants and successfully showed that all participants accomplished their tasks interacting with different devices. One drawback may be that the system was not tested in a real environment. Testing in a real environment is important for recognizing problems that may not have emerged in the virtual environment or earlier phases of testing, and monitoring real system behaviour is also important, as the real environment is different and more complex than a simulated environment.

Table 1 shows related research on mind-controlled TV remote control, noting the strengths and weaknesses and how this work is different from ours.

Table 1. Related research

Similar work	Strengths	Weaknesses	How Our Work Is Different
“Toward Realistic Implementation of Brain-Computer Interface for TV Channel Control” [11]	– High accuracy, 16 electrodes EEG headset as used.	– Implemented using unaffordable components. – Poor functionality; only the channel selection function was supported.	– Implemented using affordable components. – More control functions are included, TV power ON/OFF, channel change, and volume UP/DOWN.
“A BCI Control System for TV Channels Selection” [13]	– Good accuracy – TV power ON/OFF, channel change, channel number, channel table, and volume UP/DOWN control functions are included.	– The EEG acquisition module was complex and contained several parts.	– One-piece convenient EEG headset that may be simply used by the end-user.
“Mind Controlled Universal TV Remote Control” [14]	– Implemented using affordable components. – Five control functions were proposed: TV power ON/OFF, channel Next/Previous, volume UP/DOWN	– No real-time EEG data were collected (a dataset available online was used) – No hardware implementation of the system. – The system was not tested in a real environment. – Open eye movement was mandatory to enable control.	– Real-time EEG data obtained from subjects has been used in this system. – This is not a simulated system; hardware implementation of this system’s prototype has been done. – The system has been tested on 20 subjects in a real environment to validate its functionality.

(Continued)

Table 1. Related research *(Continued)*

Similar work	Strengths	Weaknesses	How Our Work Is Different
"Home Automation using EMOTIV: Controlling TV by Brainwaves" [10]	– High accuracy, 16 electrode EEG headset was used.	– Implemented using unaffordable components. – Poor functionality; only the TV power ON/OFF control function was supported. – The system was not tested in a real environment.	– Implemented using affordable components. – More control functions are included: TV power ON/OFF, channel change, and volume UP/DOWN. – The system has been tested on 20 subjects in a real environment to validate its functionality.
"A novel online BCI system using speech imagery and ear-EEG for home appliances control" [4]	– High accuracy custom-made ear-EEG device was used. – TV power ON/OFF, channel Next/Previous, and volume UP/DOWN control functions were included.	– No hardware implementation for the remote control (except for the ear-EEG device); an interactive simulated TV was displayed on a computer screen.	– This is not a simulated system; hardware implementation of this system's prototype has been done. – The system has been tested in a real environment on real TVs to validate its functionality.
"Brain-computer interface (BCI)-generated speech to control domotic devices" [15]	– Accurate – Remote control functions included power ON/OFF, volume ON/OFF, increase or decrease volume, change channel, and set timer to turn off the TV. – Could be used to control different devices.	– Implemented using unaffordable components. – Complicated system, where brainwaves could not be used directly to control a device. The user had to select an item from a matrix to generate a text that was converted into voice commands to be used by Google Assistant to control a device. – The EEG data acquisition module was complex.	– Implemented using affordable components. – EEG brainwaves can be used to control a TV directly without the need for intermediate techniques.
"An Eye Tracking and Brain-computer Interface Based Human-environment Interactive System for Amyotrophic Lateral Sclerosis Patients" [16]	– Accurate – Could be used to control different devices.	– Using one electrode to detect EEG signals caused a delay and instability in the signal recording. – Poor functionality; only the TV Power ON function were supported. – The system could be complex due to the use of eye tracking with BCI, and the use of an HCI screen that converts brainwaves and eye behaviour into commands to control home appliances. – Using an eye tracker may cause a "Midas touch".	– More control functions are included: TV power ON/OFF, channel change, and volume UP/DOWN. – No need for using other techniques with BCI or to use HCI-supported devices. – The "Midas touch" problem cannot happen.
"Brainy Home: A Virtual Smart Home and Wheelchair Control Application Powered by Brain Computer Interface" [17]	– Accurate – Implemented using affordable components. – Could be used to control different devices.	– No hardware implementation for the remote control (except for the EEG headset); an interactive simulated environment was displayed on a computer screen. – The system was not tested in a real environment.	– This is not a simulated system, hardware implementation of this system's prototype has been done. – The system has been tested in a real environment on real TVs to validate its functionality.

The literature review shows that TV and BCI integration is a modern and promising trend of research. This field of research can be expanded to involve BCI control in a real smart-home environment to control many devices. Furthermore, it has been observed that improvements are required to enhance the efficiency of control and reduce the system's cost. This paper presents a solution that uses Raspberry Pi and eliminates any extra modules. Linux Infrared Remote Control (LIRC) has been used to decode infrared signals, which offers the great possibility of being able to simulate any remote control.

3 QUANTITATIVE QUESTIONNAIRE

A survey with quantitative questions was created to determine the functional and non-functional requirements of the user for the TV mind-controlled remote-control system. The approach of sampling was purposive. This questionnaire is an important step towards designing and implementing the prototype of the system presented in this paper.

3.1 Sampling

For the purpose of a comprehensive survey, we targeted people from a different range of backgrounds, ages, education levels, and professional experiences. Twenty participants took part in the study. The questions of the survey were divided into two groups. Each group contained multiple-choice questions, which allowed the participants to select an answer for each case, and open-ended questions. In the first group of questions, background information was collected, while the second group's purpose was to identify the user's functional and non-functional requirements of the system.

3.2 Analysis of the results

In this paper, a quantitative-based method was used to identify the requirements of the user and how the user interacted with the EEG-based BCI TV remote control. To analyse the answers of the survey participants, IBM® SPSS® Statistics v.29 was used. The questions were associated with the interests of users considering their suggestions, and the literature review conclusions.

The first category of the survey included general questions for participants, such as the profession of the participant (40% engineers, 25% teachers, 15% students, 10% biologists, 5% retired corporal, and 5% housewives). Regarding participants' ages, 15% of the participants were between 18 and 30 years, 25% were between 30 and 40 years, 15% were between 40 and 50 years, 15% were between 50 and 60 years, and 30% of the participants were above 60 years. Regarding the education level of the participants, 35% of them had a bachelor's degree, 30% had a master's degree, 20% had a PhD degree, and 15% had a high school degree.

Various questions concerning the user's functional and non-functional requirements of the system were included in the second category of the survey. The most significant functional requirement of the mind-controlled TV remote control is to have the basic commands that let the person run and interact with the TV; therefore, the respondents answered the question "How important is it to have the basic commands of the mind-controlled TV remote control (Power on/off, volume up, volume down, change the channel)?". The majority of respondents (55%) felt it was "very important", 30% answered "important", and 15% answered "neutral". Figure 1 shows the respondents' answers to this question.

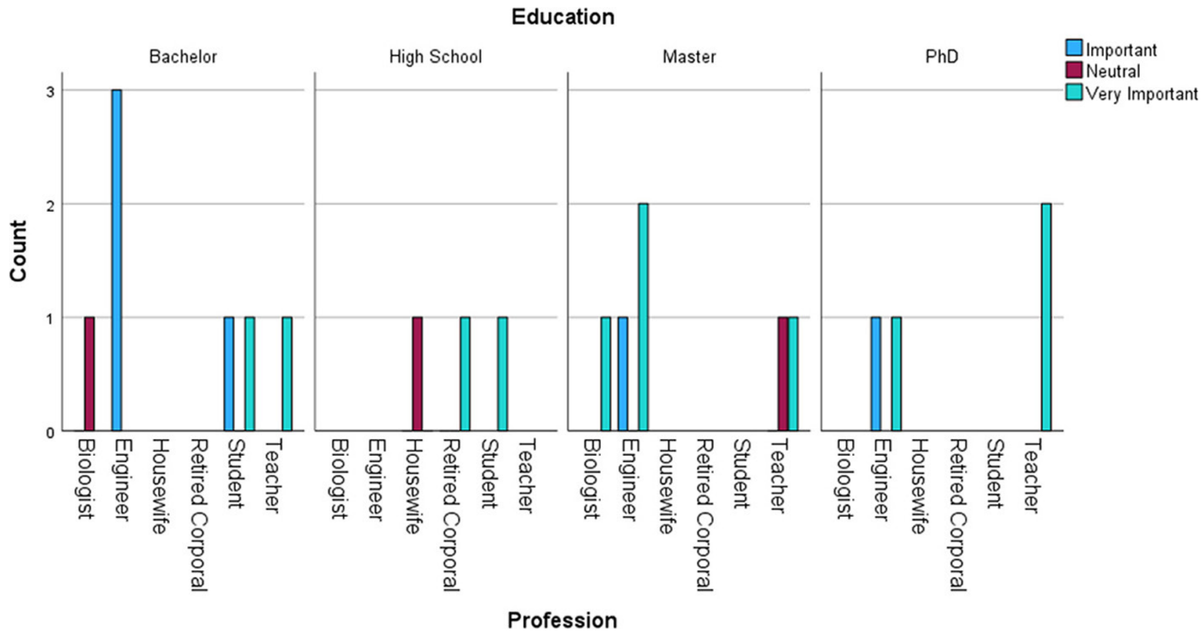

Fig. 1. Results related to the basic commands of the system

Most of the participants emphasised that the user should learn and train how to use the system. Questions concerning non-functional requirements such as safety, performance, reliability, usability, and flexibility were also included in the survey. For safety requirements, 40% of the respondents felt that these requirements were "very important", 40% felt it was "important", 15% of them selected "neutral", and a small number of the respondents (5%) indicated that it was "not very important" (see Figure 2). The system is safe to use since EEG non-invasive method have been used, which do not require surgical procedures.

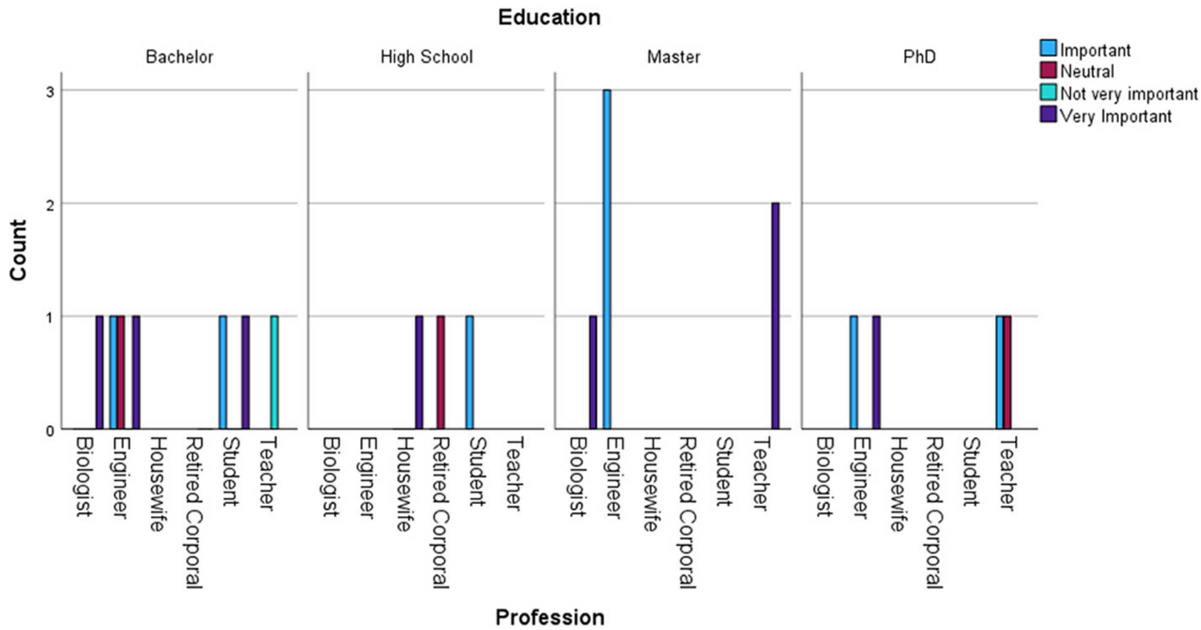

Fig. 2. Results related to the safety requirements of the system

The second question was "How important are the performance requirements (accuracy) for the system?". Most respondents (88%) felt it was "very important", 15% of them chose "important", and 5% of the respondents felt "neutral" (see Figure 3).

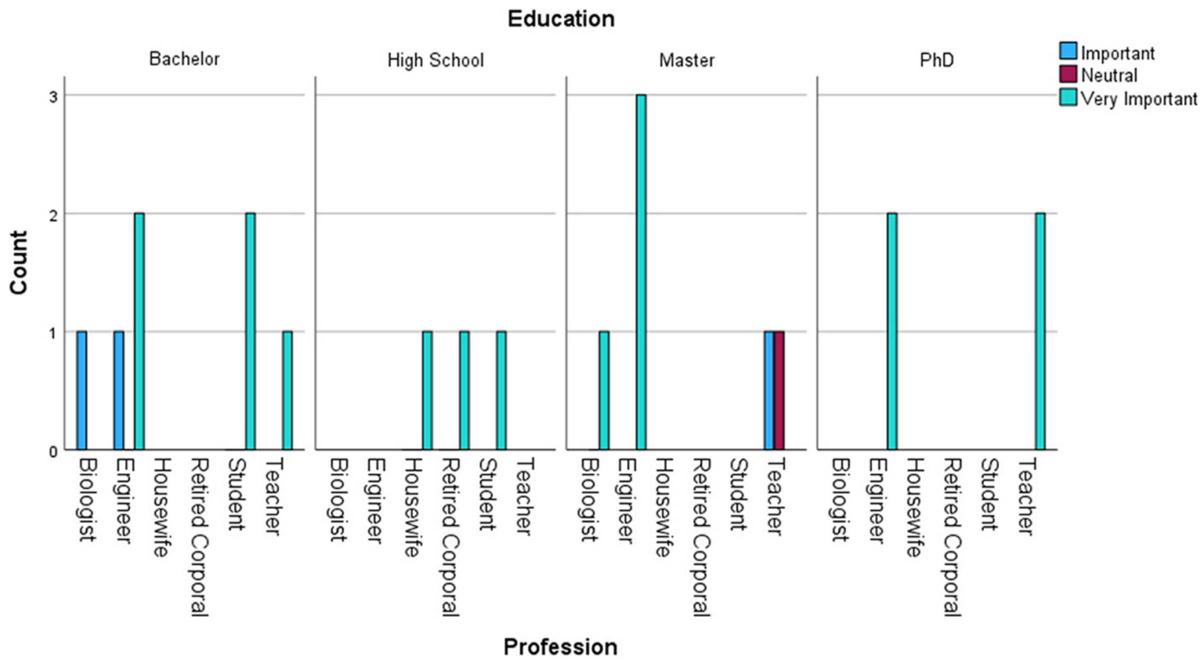

Fig. 3. Results related to the performance requirements of the system

The third question was "How important are the usability requirements for the system?". Only 30% of the respondents considered it "very important", 40% of the respondents felt it was "important", 25% of the respondents selected "neutral", and the remaining respondents (5%) considered it not "very important" (see Figure 4).

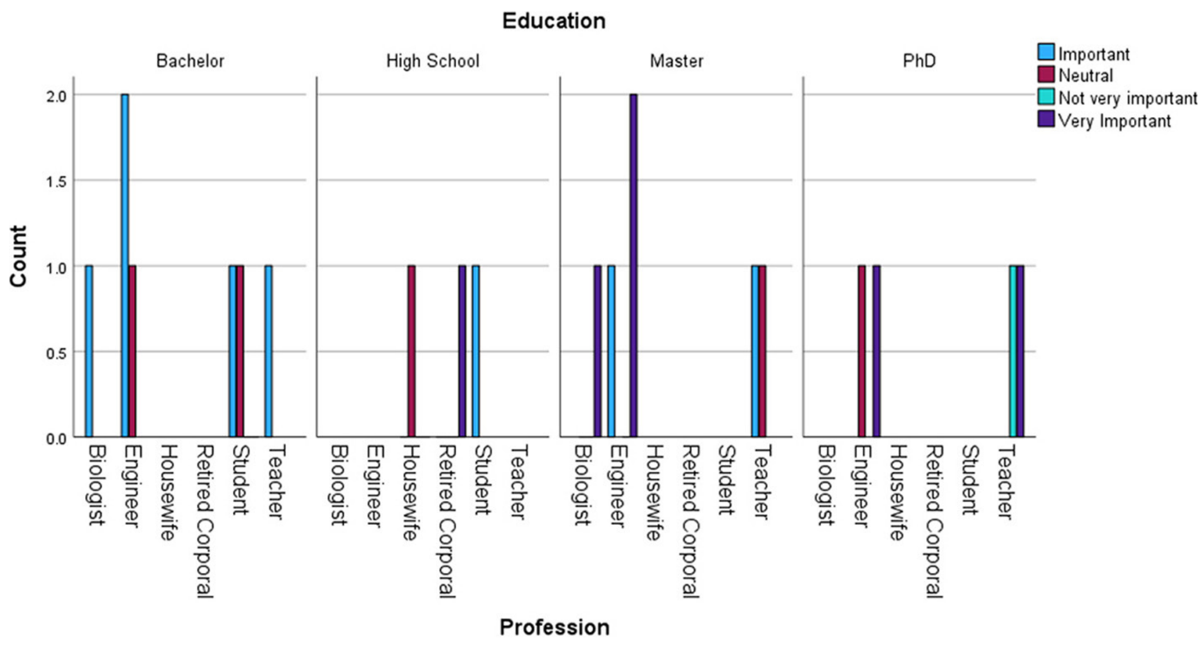

Fig. 4. Results related to the usability requirements of the system

The reliability requirements refer to the ability of the system to be partially or fully operational when needed. The related question was "How important are the reliability requirements for the system?". The choice "very important" was chosen by 25% of the respondents, "important" was chosen by 45%, 15% chose "neutral", 10% chose "not very important", and 5% of the respondents considered it "completely unnecessary" (see Figure 5).

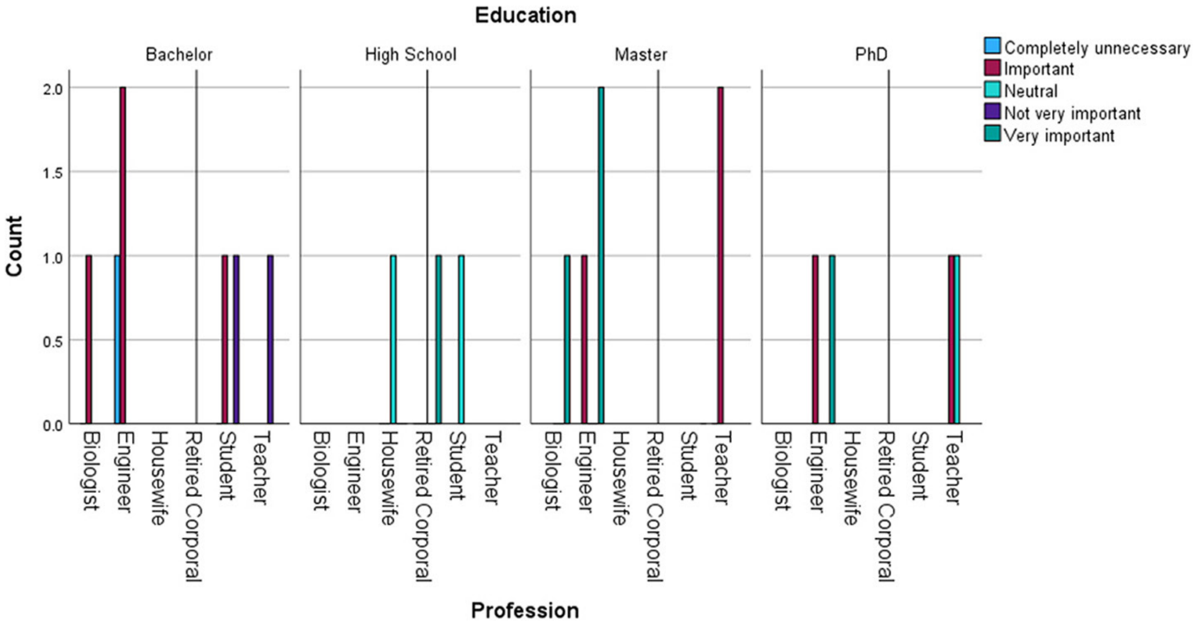

Fig. 5. Results related to the reliability requirements of the system

The flexibility requirements can be defined as the ability of the system to be modified according to different environments or users' expectations. For the question "How important are the flexibility requirements for the system?", the answers were as follows: 35% "very important", 25% "important", 30% "neutral", 5% "not very important", and 5% "completely unnecessary" (see Figure 6). This TV remote control system can be adapted or modified; for instance, additional control commands can be added.

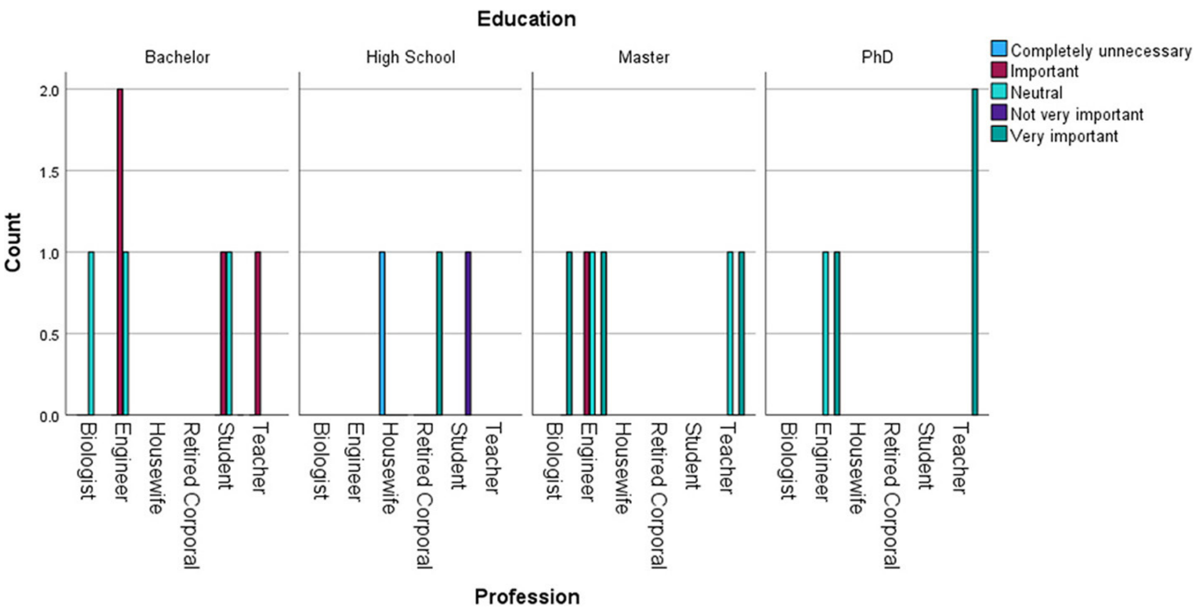

Fig. 6. Results related to the flexibility requirements of the system

The proposed system's prototype should be designed based on functional and non-functional requirements that have been determined from the analysis of the participants' answers. Some requirements should be considered in the design and implementation of the system. The following requirements are common interests among participants:

- Train the paralysed user or healthy user to use and control the mind-controlled TV remote control.
- The system should have the basic commands to control the TV with the ability to add more commands and functions. (Two suggestions from the participants: the ability to find the remote if it is lost, and select audio language of the channel.)
- The system should be accurate.
- Safety requirements should be included in the system.
- Performance requirements should be included in the system.
- Usability requirements should be included in the system.
- Reliability requirements should be included in the system.
- Flexibility requirements should be included in the system.

4 MATERIALS AND METHOD

In this work, the EEG technique was selected to control TV due to its high temporal resolution and continuous dynamic neural activity [8]. A schematic representation of the EEG-based BCI TV remote control system is presented in Figure 7.

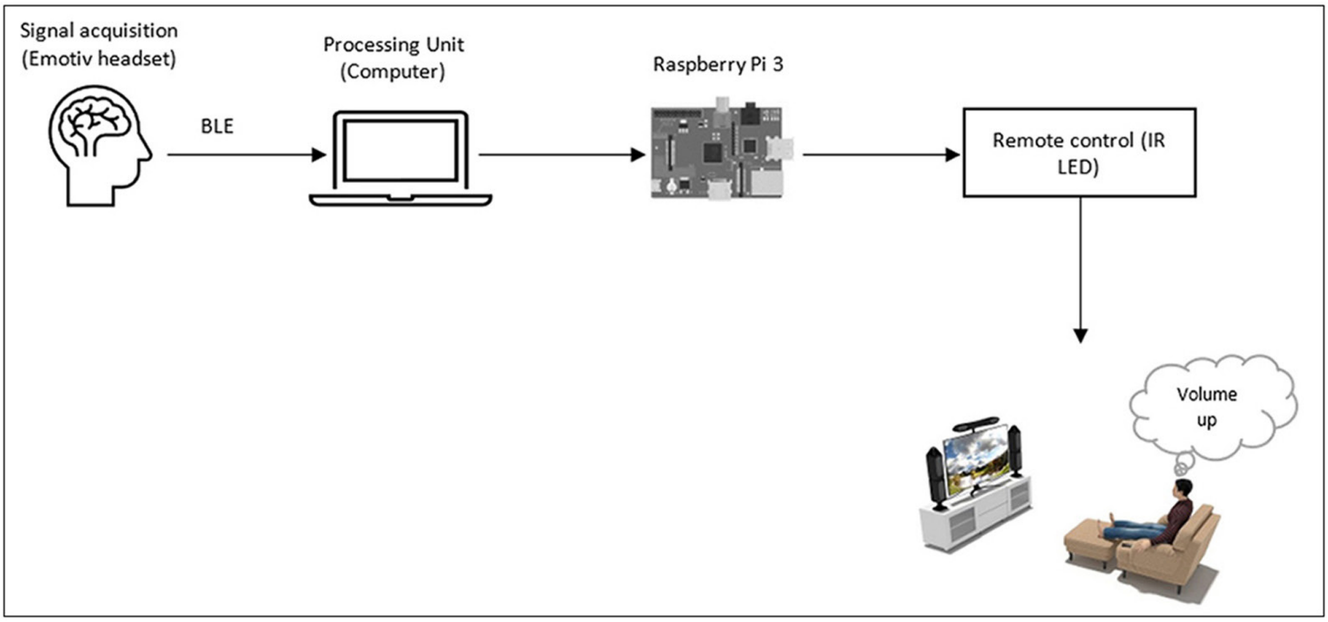

Fig. 7. System architecture

4.1 EEG headset

The "EMOTIV™ Insight headset" device was used in this system. It is 5-channel neuroheadset that contains semi-dry polymer sensors. The sampling rate of the headset is 128 Hz per channel. This device is used for experiments and was specially designed for BCI use and research, detecting and filtering EEG signals, and then sending the EEG data wirelessly to the computer for further processing [5]. Whole-brain sensing is offered by this mobile EEG headset, which uses advanced electronics to produce robust and clean signals. The EMOTIV™ Insight headset is compatible with computers, phones, and tablets. It uses 2.4 GHz wireless (with a dongle) or Bluetooth Low Energy (BLE) to connect. Also, it has a LiPo battery 450 mAh, which was developed for 8 hours of operation. The electrodes are positioned according to the 10–20 system shown in Figure 8, where the electrodes must be positioned on the head's scalp to detect the neuronal activity.

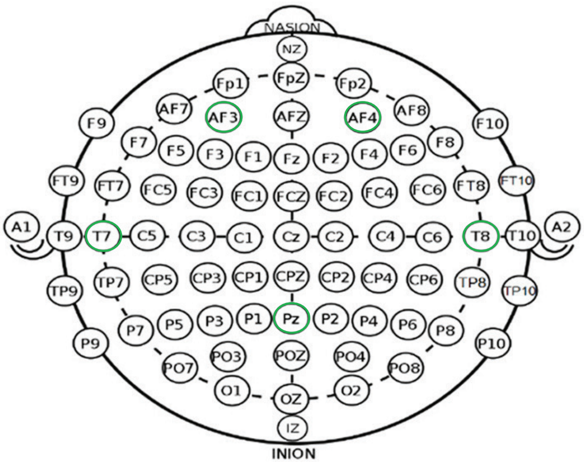

Fig. 8. Emotiv™ Insight electrodes [18]

4.2 Computer

The tasks of the computer (processing unit) were to receive the EEG brain signals, process these signals and transform them into commands, perform training tasks, and send commands to the Raspberry Pi. These operations were performed using Emotiv™ Cortex API, which currently supports Windows and Mac operating systems. Python programming language was used in this system [8].

4.3 Raspberry Pi III

Raspberry Pi III Model B is a cheap, efficient, and fast single-board computer that offers high performance and execution level that makes it a great option for various control research or projects. Using Raspberry Pi in the proposed system may eliminate the need for a computer as a processing unit. The LIRC package was installed on Raspberry Pi III since its supports Raspbian Linux OS (see Figure 9).

4.4 Other components

VS1838B IR receiver is a commonly used high-speed, high-sensitivity, and low-power photodiode, which makes it an excellent choice as an Infrared receiver for building remote-control-systems projects. It is a cost-effective and easy-to-use IR receiver that well matches the embedded electronics and can be used with common IR remotes (see Figure 9) [19].

An Infra-Red Light Emitting Diode (IR LED) is a device specially designed to transmit infrared rays. These rays are invisible to the human eyes because it is not in the range of visible electromagnetic radiation spectrum [20]. This IR LED emits 940-nm wavelength light, which is the electromagnetic radiation spectrum range of IR. This IR LED is commonly used in the remote control of TVs, VCRs, cameras and various other kinds of electronic devices (see Figure 9) [20].

The BC547 transistor is an NPN transistor used to amplify power and signals or may be used as a switch. The base terminal's small current controls the emitter's large current and base terminal. The biasing of this transistor is where it operates in a constant DC voltage in the region of its characteristics (see Figure 9) [21].

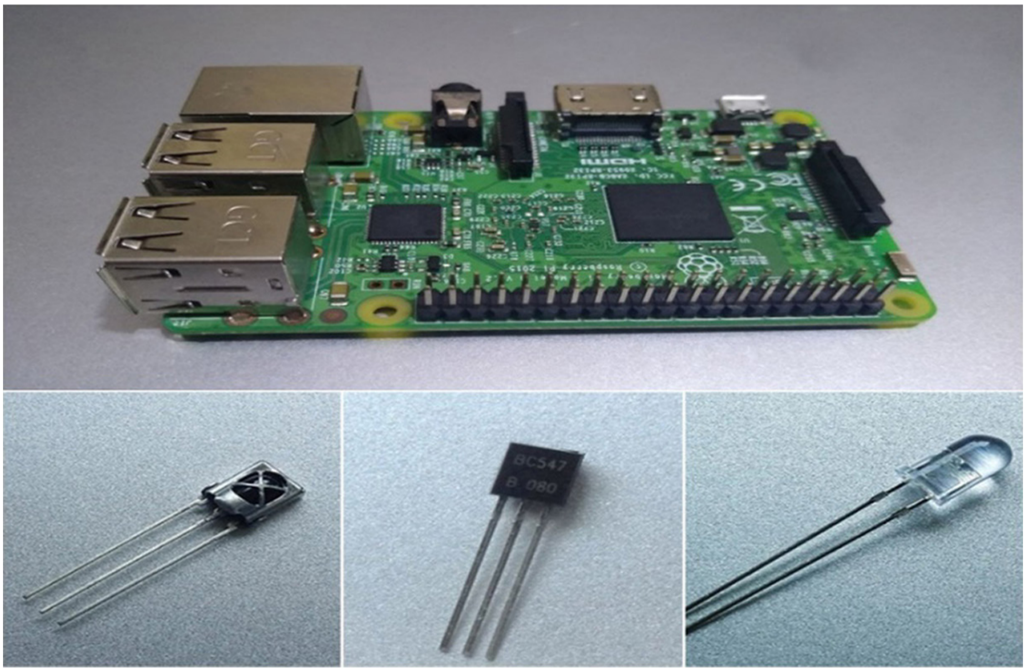

Fig. 9. Raspberry Pi 3, VS1838B IR receiving, IR emitting LED, and BC547 transistor

5 IMPLEMENTATION OF THE SYSTEM

This remote-control system comprised four essential parts: (1) the EMOTIV™ Insight" neuro-headset, (2) the processing unit, containing the EMOTIV™ Cortex API and Python programming language, (3) the Raspberry Pi III, and (4) the remote-control circuit.

5.1 Hardware implementation

The circuit diagram of the system is shown in Figure 10. The implementation of the proposed system starts with connecting the computer to the Raspberry Pi via Bluetooth to send control commands. The IR receiver has 3 pins, where the Vcc pin is connected to the 5V GPIO pin of the Raspberry Pi, the signal pin is connected to the GPIO18 pin, and the ground pins of both devices are connected. The collector of the BC547 transistor is connected to the 22Ω resistor, which is connected to the IR LED's cathode, in turn. The LED's anode is connected to the 3.3V pin of the GPIO, while the emitter is connected to the ground. The base pin of the transistor is connected to a 6.8kΩ resistor to protect the transistor from being damaged. The other terminal of the resistor is connected to the GPIO22 pin (see Figures 10 and 11). The Raspberry Pi is connected to an external 5V power source via a USB cable.

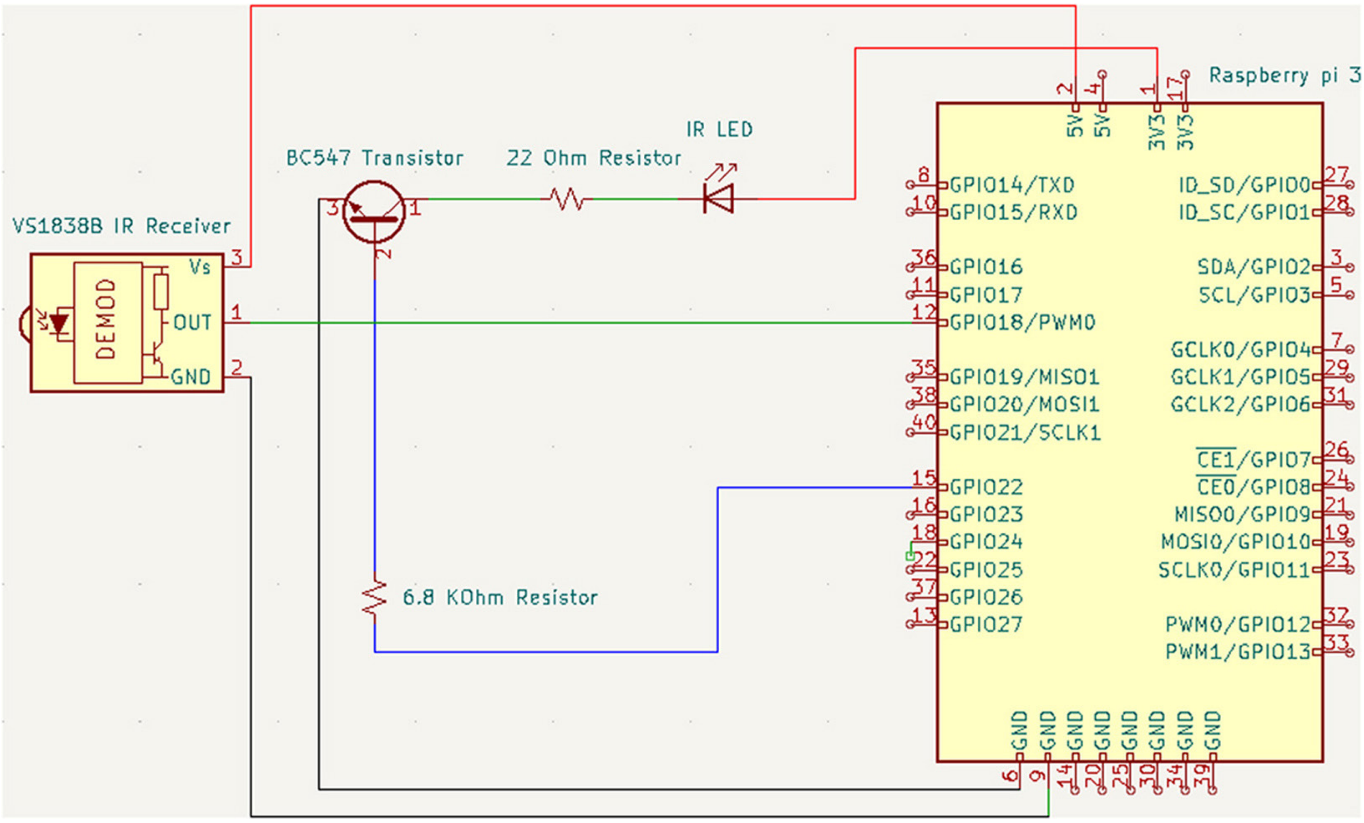

Fig. 10. Circuit diagram of the system

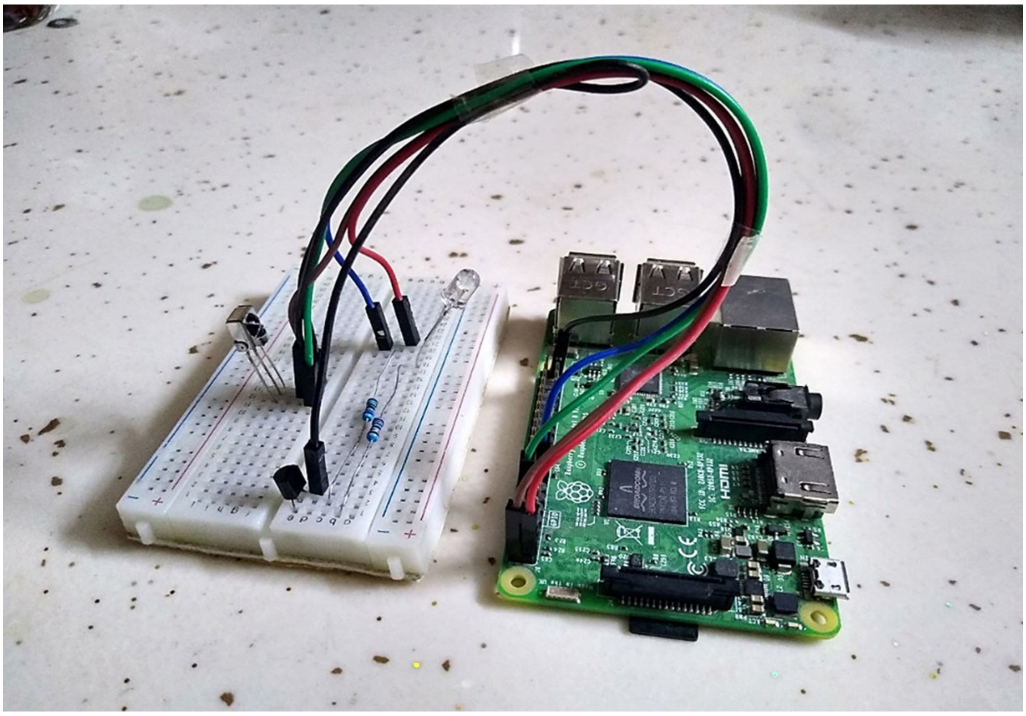

Fig. 11. System implementation

5.2 Software implementation

A new model for research development systems has been launched by Emotiv™, called Cortex API. This API is based on WebSockets and JavaScript Object Notation (JSON), where multiple platforms and languages are supported by this service [22]. In this system, Cortex API was installed on the computer and accessed using Python, using the advantages that Emotiv Cortex API offers. A full duplex connection was established by a Websocket to enable a connection with bidirectional channels that run on a single socket. After connection to the service, requests made through JSON messages received responses from the Cortex API. After successfully logging in and authenticating with the Emotiv service, the streaming service could be accessed [22].

Sampled signals of EMOTIV™ EEG were sent wirelessly to the computer for processing. After processing, the signal was transmitted to the Raspberry Pi to control the TV. To decode and send IR signals, the LIRC package was used. LIRC was installed on Raspberry Pi, as it offers great functionality and flexibility and is an excellent tool for IR remote-control applications. To provide the necessary information, IR signals received by the device drivers were decoded using LIRC. LIRC allows controlling many devices such as computers, IR mouse, TV, and satellite receivers [23]. Figure 12 shows the software activity diagram of the system.

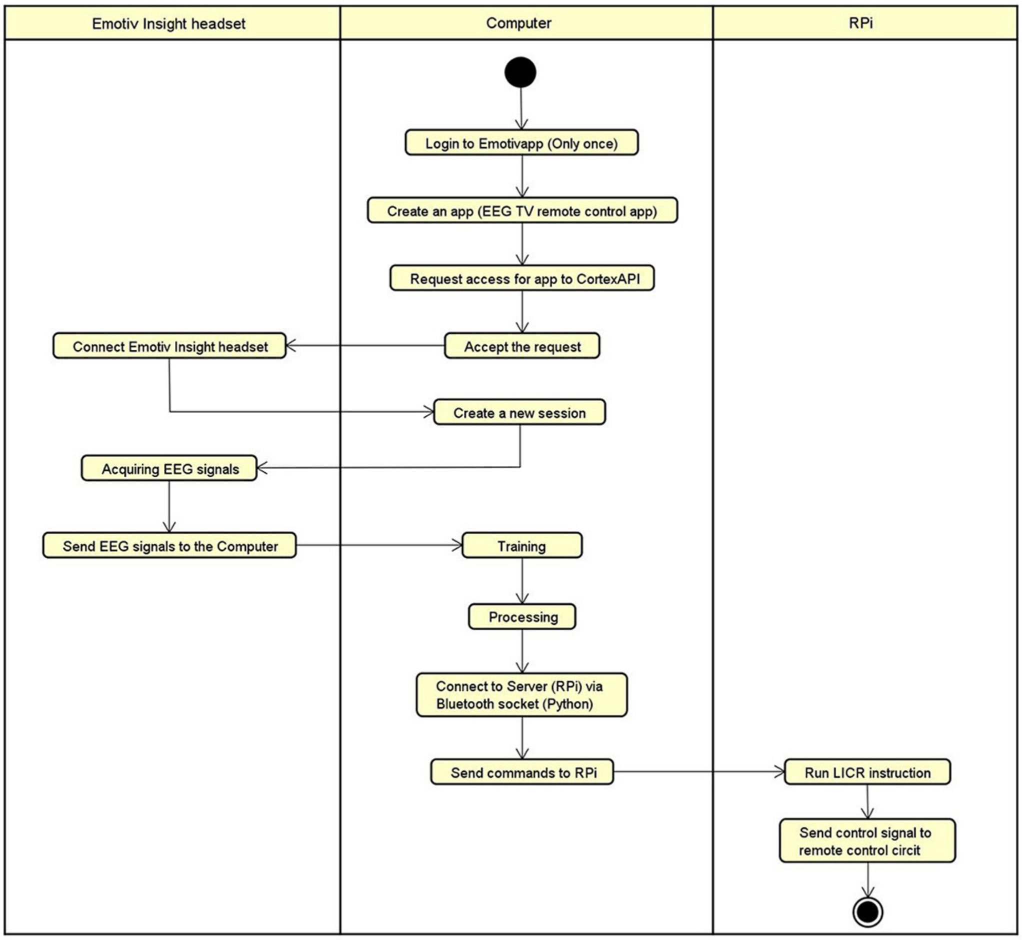

Fig. 12. Software activity diagram

The training session started by asking the subjects to wear the Emotiv™ Insight EEG headset and to be relaxed during the session. The session included recording the EEG data of the subjects using the EmotivBCI cortex service while they performed a specific speech-imagery task. Subjects were asked to perform four different speech imagery tasks: "power", "volup", "voldown", and "change channel". The neutral mental state was also considered by recording a short period of the subject's brain activity while he/she was not performing any command. This data was processed by Emotiv™ Cortex API and used to create a model that was used to identify the speech imagery words that were recorded before. The training session took 25–40 minutes. The computer connected to the Raspberry Pi via Bluetooth in a client-server model. The Raspberry Pi acted as a server, where a Python script was written to build a server used to communicate with the client where the server script was automatically run when the Raspberry Pi was turned on. The computer acted as a client, where Python code was written to communicate with the Raspberry Pi by establishing a socket. Python scripts were used on both Raspberry Pi and the computer. Python script on Raspberry Pi was used to control the GPIO pins, thus sending IR signals through IR LED.

6 TESTING, RESULTS, AND DISCUSSION

The testing was conducted using EEG signals detected from 20 subjects. The system was tested on three different brands of televisions: SONY® [24], SHOWNIC® [25] and SAMIX® [26]. Since configuration files for these TV remotes are not available in the LIRC remotes database, LIRC provides a great possibility to register new remotes easily by creating a configuration file for the required remote control. The configuration files were created using LIRC through an IR receiver, which was responsible for detecting IR signals from the TV remote control.

The LIRC package was installed on Raspberry Pi since its supports Linux OS. After installation, LICR needed to be configured to work correctly and without faults with hardware and software. The GPIO pins were selected from the config.txt file dtoverlay=gpio-ir,gpio_pin=18, dtoverlay=gpio-ir-tx,gpio_pin=22.

To conduct the experiment, each subject had to wear the EEG headset and sit on a chair in front of the powered-OFF TV with the remote control circuit next to him/her (see Figure 13). First, each subject was asked to power ON the TV by thinking of the corresponding word that he/she was thinking of during the training session. After the TV was successfully turned ON, the user was asked to raise the volume, reduce the volume, change the channel, and power OFF the TV, respectively. Each subject was asked to try to control the TV fifteen times (attempts) for each command (power, volume up, volume down, change the channel) and to write down the number of successfully delivered commands (the successful attempts that enabled them to control the TV). When the subject thinks of one of these commands, the computer sends the control command to the Raspberry Pi via a Bluetooth connection to run the Python script, which contains the commands to send the corresponding IR signal to the TV, for example, irsend SEND_ONCE samix volup.

Fig. 13. Conducting the experiment

Figure 14 is a representation of the results in Table 2 and shows the number of successfully delivered commands (successful control attempts or success rate) for each subject during the experiment. The results of the test were analysed using IBM® SPSS® Statistics v.29. Analysis of results revealed that there were some bad responses which may have been caused by a lack of focus during the experiment. Also, the responses of males were slightly more successful than females' responses, possibly because the quality of the EEG signal of some female subjects was slightly lower due to females' thicker hair.

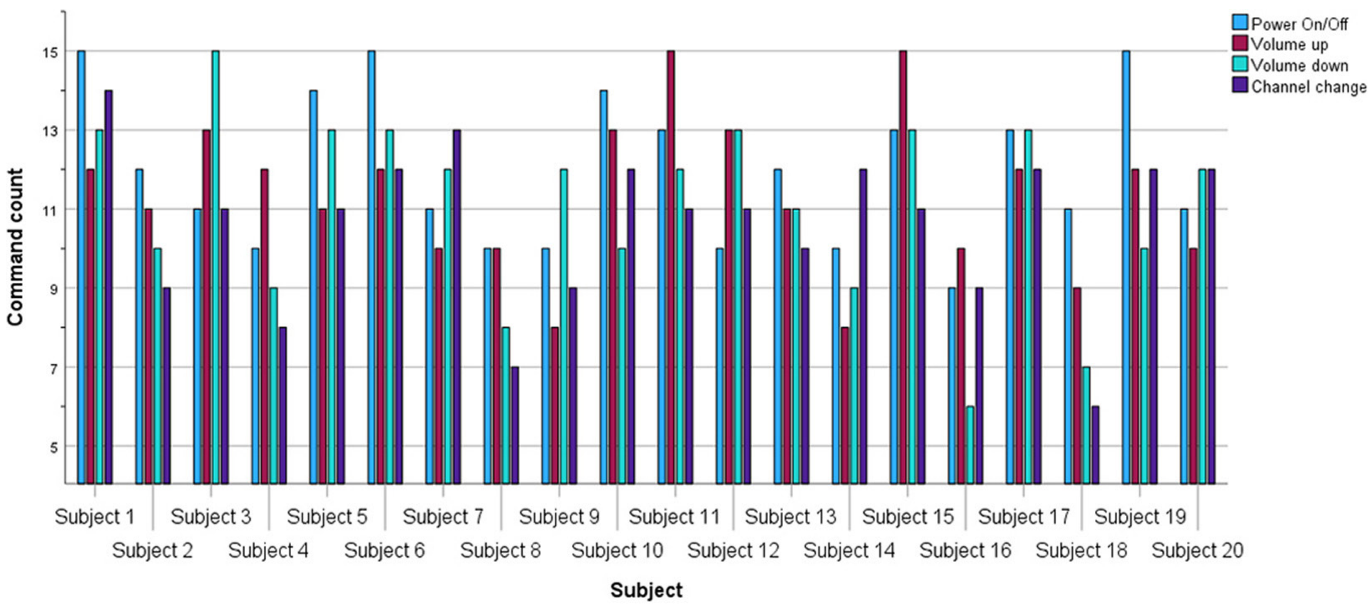

Fig. 14. Number of success delivered commands (success rate) in the experiment

Figure 15 shows the histogram average of the success rate (successful control attempts) in the experiment. For example, three subjects have an average success rate between 9.5 and 10. The total average success rate was 11.237, while the test reveals that the total accuracy of the system was 74.9%. The amount of dispersion was calculated using standard deviation for all sets of values (for each subject individually), where the maximum/minimum values were 2.22/0.58, respectively. On average, the standard deviation of the experiment was low, with the average standard deviation for all values being 1.511. Dispersion can be noticed in subjects 3, 18, and 19 due to notable variance in the values of the successful commands for the four commands, as can be seen in Table 2.

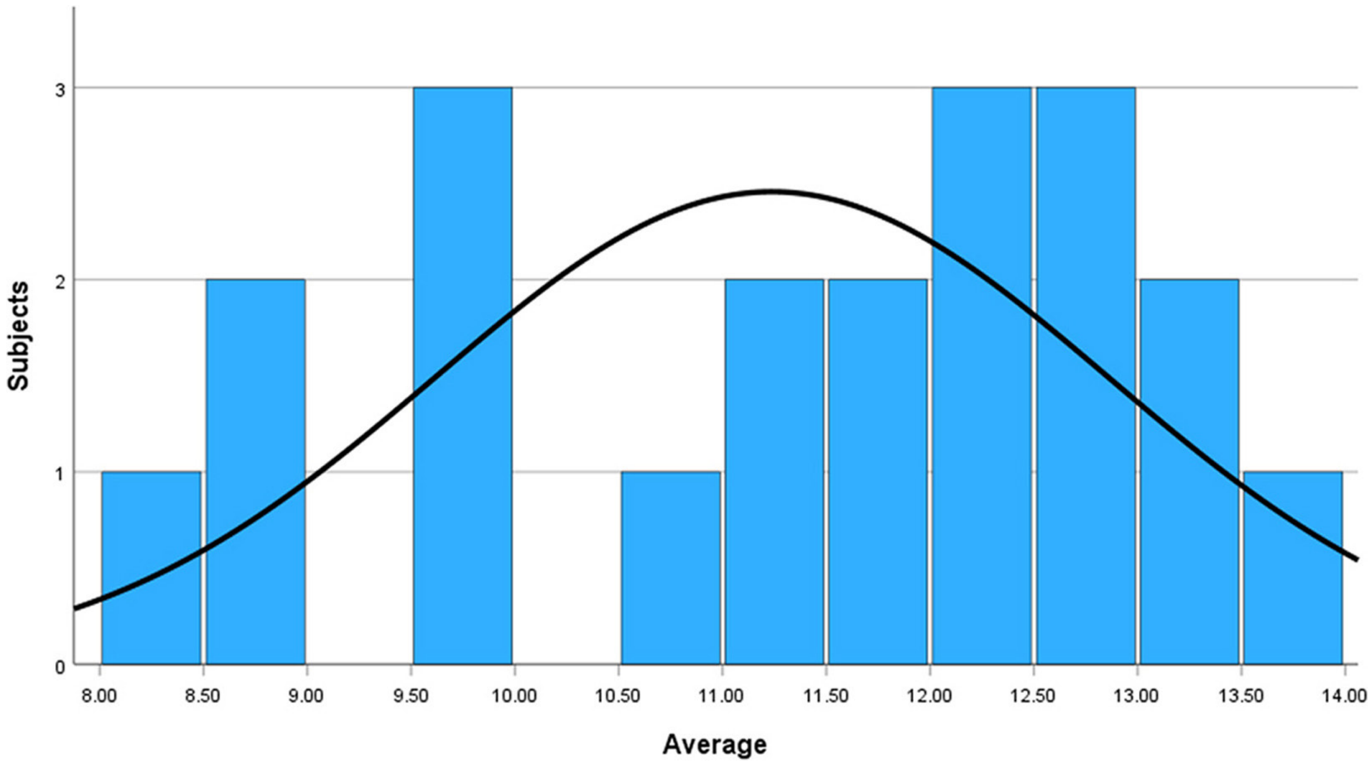

Fig. 15. Histogram of the average success rate of the results

Table 2 shows the number of successfully delivered commands (the successful control attempts) of each command for each subject during the experiment, the average success rate, and the standard deviation of the successfully delivered commands as well as the total average and the total standard deviation. The subjects reported that mental tasks were easy to use to control the TV, and most of them could maintain their focus when performing tasks. Subjects 12, 15, and 16 reported that they felt the headset was uncomfortable after some time of use. It might take some time for people who have never used BCI systems to be more familiar with using such systems. Although these observations could be limitations of the work, the experiment was conducted successfully, and all four functions implemented in this system worked with good accuracy.

Table 2. Results of testing

Subject	Power ON/OFF	Volume Up	Volume Down	Channel Change	AVG	STDEV
Subject 1	15	12	13	14	13.5	1.2909
Subject 2	12	11	10	9	10.5	1.2909
Subject 3	11	13	15	11	12.5	1.9148
Subject 4	10	12	9	8	9.75	1.7078
Subject 5	14	11	13	11	12.25	1.5
Subject 6	15	12	13	12	13	1.4142
Subject 7	11	10	12	13	11.5	1.2909
Subject 8	10	10	8	7	8.75	1.5
Subject 9	10	8	12	9	9.75	1.7078
Subject 10	14	13	10	12	12.25	1.7078
Subject 11	13	15	12	11	12.75	1.7078
Subject 12	10	13	13	11	11.75	1.5
Subject 13	12	11	11	10	11	0.8164
Subject 14	10	8	9	12	10	2.1602
Subject 15	13	15	13	11	13	1.6329
Subject 16	9	10	6	9	8.5	1.732
Subject 17	13	12	13	12	12.5	0.5773
Subject 18	11	9	7	6	8.25	2.2173
Subject 19	15	12	10	12	12.25	2.0615
Subject 20	11	10	12	12	11.25	0.9574
Total AVG					**11.2375**	
STDEV AVG						**1.51182**

7 CONCLUSION AND FUTURE WORK

The applications of EEG-based BCI remain a goal of modern research, particularly in the biomedical domain. The purpose of our research was to propose the design and implementation of a TV remote-control system controlled by the mind. The system can be used by patients with quadriplegia, locked-in syndrome, etc., who cannot hold or use remote control, or by healthy people for entertainment. Also, this work is a forward step that opens the way to control more home appliances through BCI. A survey with quantitative questions was conducted to determine the functional and non-functional requirements of the system, which helped in the design development of the system. The performance of our BCI system was comparable with other works presented in the literature review. Compared with the existing state of art, the results of this work were obtained from 20 males and female subjects of different ages between 19 and 79 years, who tested the prototype in a realistic environment in order to obtain all possible opinions and feedback regarding the use of the system and to detect the possible shortcomings of the system's prototype. Related systems in previous work have been tested on fewer subjects (11 or 8 subjects [11] and 7 subjects (males only) between 20–25 years old [13]). In related works, like in [14], the system has not been tested by people. Our test shows promising results, as the accuracy of the system was 74.9%. The accuracy could likely be improved by increasing the training time. The system is cost effective compared with most similar works and has good accuracy for all of its four control commands. This remote control system's prototype was implemented using widely available and simple electronic components, and it is scalable, so more control functions can be added, and the use of the computer as a processing unit should not needed in the future. As the experimental results reveal that this system could be appropriate for TV control applications in a real home environment, similar remote control for satellite receivers could be easily implemented since they are already widely used with TVs at home. Also, the use of the system can be expanded to control more home devices, such as air conditioners. Although this remote control has only four control functions, this paper demonstrates that our goal of building a prototype of the an EEG-based BCI TV remote-control system was successfully achieved.

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