A low-cost, open-source, BCI-VR prototype for real-time signal processing of EEG to manipulate 3D VR objects as a form of neurofeedback

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Abstract— **In this paper we present a low-cost and open-source brain-computer interface (BCI) virtual-reality (VR) prototype for real-time signal processing of Electroencephalography (EEG) event-related desynchronization and synchronization changes (ERD/ERS) within the Precentral Gyrus (Motor Cortex), which allows the user to manipulate a 3D object within a Virtual Reality Environment as a form of immersive neurofeedback. This BCI-VR system prototype was functionally tested on multiple participants and demonstrated live before an audience during the 2017 'Hack the Brain' at the Dublin Science Gallery. The availability of a low cost, effective, BCI-VR solution targeted at researchers and developers, which is capable of analysing a subject's BCI performance and presenting neurofeedback VR to a level acceptable for academic and industry experimentation, has the potential to open up this field to much wider range of researchers and could help increase the functional outcomes for stroke rehabilitation.**

Keywords— BCI, VR, Brain Computer Interface, Virtual Reality, Motor Rehabilitation, Event-Related Potentials, open-source

I. INTRODUCTION

A brain-computer interface (BCI) is a closed-loop system composed of six steps: brain activity measurement, pre-processing, feature extraction, classification, translation into a command, and feedback. Neurofeedback is a very important component, because when information is visually returned back to the user about the success or failure of an intended act, evidence shows that this observation can modify sensorimotor activity and improve neural plasticity [1] such as in the case of motor rehabilitation and improved patient outcomes in cases of stroke [16], which is the commonest cause of acquired disability in Ireland [5].

The benefits of BCI neurofeedback therapy has been shown in numerous case studies utilizing both Evoked potentials and Event related desynchronization\synchronization (ERD \ ERS) and the results are often long lasting, because neurofeedback actually changes the way the brain itself works [1]. Several prototypes have enabled users to navigate in virtual environments via EEG. Healthy participants have explored virtual spaces [9][16], manipulated virtual objects [7], and patients with spinal-cord injuries have controlled wheelchairs through virtual spaces [8]. In these studies, subjects who utilise Virtual Reality Environments make less mistakes and report to researchers that BCIs based on VR feedback are simpler to master and more enjoyable to use [9][12][16].

These benefits may occur because VR enhances vividness and mental effort, which may lead to more distinct brain patterns and improve pattern recognition performance. Nevertheless, VR technologies provide motivating, safe, and controlled conditions that enable improvement in BCI learning, as well as the investigation of the brain responses and neural processes involved, while testing new virtual prototypes [12]. The principal benefits of the BCI-VR environment in a therapy setting are believed to be [19]:

1) A 3D virtual environment can "immerse" the patient to the degree that they will demonstrate appropriate limb and postural corrections in response to VR perturbations.
2) The illusion of the 3D VR coupled with the patients' ability to directly manipulate the VR display will produce a considerably stronger learning environment than conventional therapy approaches.
3) The ability of the patient to explore, interact and make errors in the VR environment will provide a facility for motor re-learning unparalleled outside of a VR setting.
4) The novelty and intrinsic appeal of such an interaction will also provide a powerful motivation factor for rehabilitative exercise.

Continuing research into BCI-VR technology and the interpretation of brain signals in order to develop limb, hand and movement rehabilitation could increase the functional outcome of stroke rehabilitation [2]. In an Irish context the Economic and Social Research Institute (ERSI) has estimated the cost to the economy of stroke related serious physical disability as being in excess of €500 million annually. Thirty thousand Irish people have a stroke-related disability and a further 8,000 will suffer a stroke this year alone [5].

In this study we investigated if it was possible to provide neurofeedback in the form of Virtual Reality through a low-cost, open-source, BCI-VR prototype, in order to make this

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area much more accessible and affordable to a wider range of researchers working in stroke rehabilitation.

The remainder of this paper is organised as follows: Section 2 discusses the methodology we employed to design and develop the prototype. The experiments and results are presented in Section 3, which is followed in Section 4 by conclusions and directions for future work.

II. METHODOLOGY

The methodology we employed was to design and build the hardware for the low-cost, open-source, BCI-VR prototype, and to develop the software application for real-time signal processing using a training and prediction function focused on the ERD/ERS sensorimotor rhythms from the Precentral Gyrus (Motor Cortex) for the manipulation of a simple 3D object within a basic Virtual Reality Environment. Further on, we tested and validated the prototype.

A. Equipment

We focused exclusively on using low cost, off-the-shelf, tools and technologies to develop the prototype system. An OpenBCI Cytron Biosensing Board (Fig. 1) provided the bio-sensing microcontroller used to sample the users electrical brain activity (EEG), and OpenViBE, a free open-source software platform, was used to design, develop and run the BCI modules for acquisition, pre-processing, processing and visualization of the acquired brain signal data.

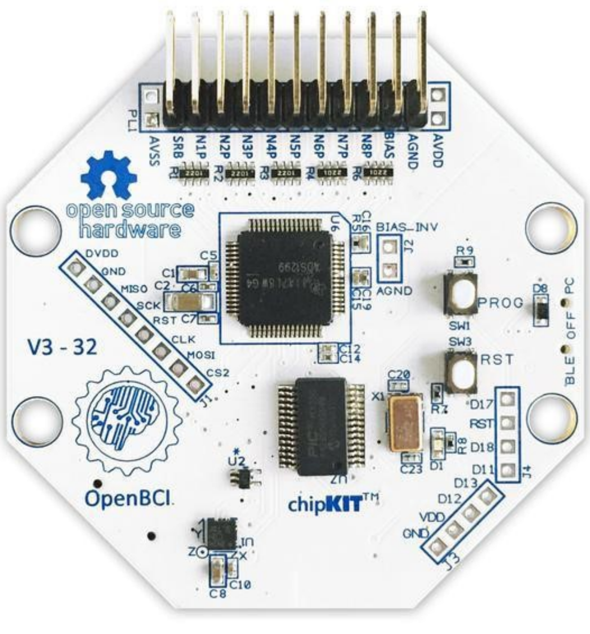

Fig. 1. OpenBCI Cytron Board *[13]*

The Virtual-Reality Peripheral Network (VRPN) provided a device-independent and network-transparent interface to connect the OpenViBE application to an OSVR Hacker Development Kit 2 (Fig. 2), used to render the 3D VR scenes to the user. Finally, we used the Unreal Game Engine and development environment to create the 3D VR environment.

Fig. 2. OSVR Hacker Development Kit 2 [15]

B. EEG Signals

The BCI-VR system needs to record activity directly from the brain non-invasively, and the system must be under intentional user control, i.e. the user must actively determine to perform a mental task to accomplish a desired goal with the system [4]. In order to achieve this, we focused on two EEG rhythms, the Rolandic mu rhythm in the alpha range of 7-13Hz (Fig. 3), and the sensorimotor rhythm (SMR) in the mid-beta range of 13-15Hz associated with the motor-cortical areas directly related to the brain's motor output channels.

A subject's movement, or the preparation for movement, is commonly associated with a short-duration decrease of amplitude in both mu and beta rhythms nearly a full second beforehand known as an event related desynchronization (ERD) seen at central electrode sites, as identified in the international 10:20 system. The mu recovers to baseline level within a few seconds while the beta displays a brief event-related synchronization (ERS) ending after the movements execution [14].

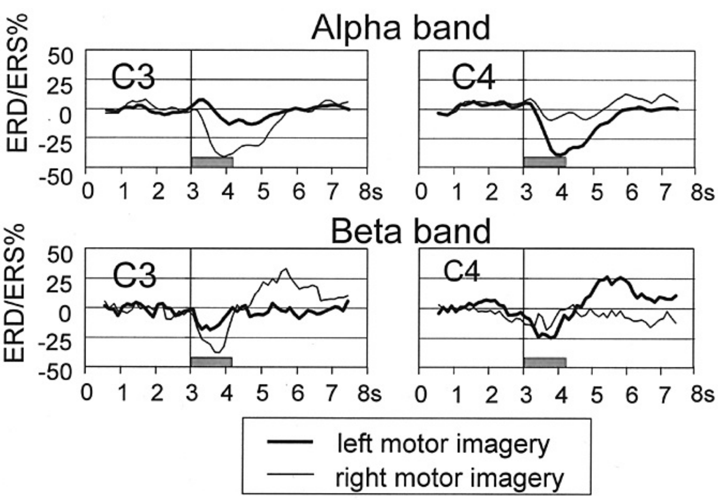

Fig. 3. An average ERD/ERS curves recorded over left and right sensorimotor cortex C3 and C4 electrode locations during motor imagery in the alpha and beta range showing a band power increase (ERS) and decrease

(ERD) with respect to the baseline while a gray bar indicates the time period of the cue presentation. [14]

For the BCI-VR system electrodes were positioned at: F3, F4, C3, Cz, C4, P3, P4. The ground electrode was positioned on the left ear lobe A1 and the bias electrode was positioned on the right ear lobe A2 (Fig. 4).

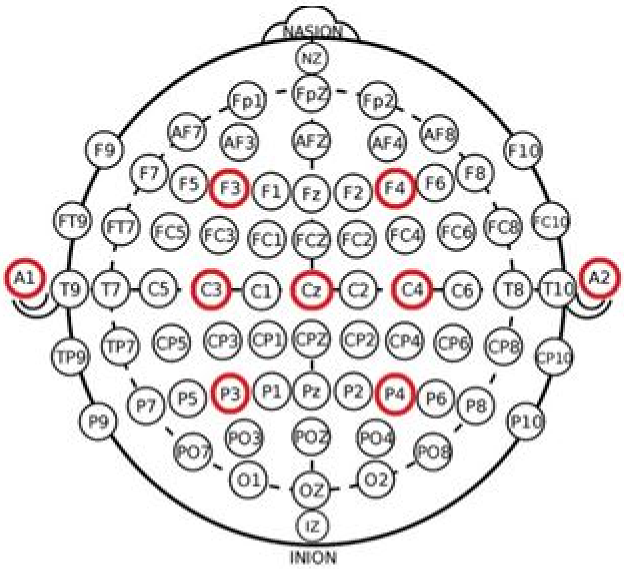

Fig. 4. The 10/20 Electrode Setup *[18]*

The resulting signals have specific temporal, frequential and spatial features, making them generally suitable for automatic identification.

C. Design

In order to design a BCI two phases are required: an offline training phase, which calibrates the system, and an online phase which uses the trained BCI to recognise mental states and translate them into commands for a computer [17]. In the BCI-VR system we implemented a set of scenarios, based on templates provided with OpenVibe, to utilise a Graz BCI which targets motor imagery of the subject's hand movements and computes the spatial filters to efficiently discriminate the EEG signals using a Common Spatial Pattern (CSP).

The BCI follows a closed-loop process composed of several steps which involve brain activity measurement to obtain signals reflecting the user's brain activity, followed by pre-processing to clean and denoise the input data and feature extraction, followed by classification to assign a class to a set of features corresponding to a mental state. A command is associated to this identified mental state in order to control the application and feedback is provided to the user about the identified mental state [10].

To achieve this, the following software elements were utilised:

1) Acquisition: First step is to acquire EEG data while the subject imagines right and left-hand movements. This is composed of 40 trials of 20 left and 20 right instructions with the order randomized within a session and the acquired training signal data written into a General Data Format (GDF) file.

2) Trainer: This is a pre-processing step before feature extraction and classification which maximises the difference between two signal class matrices using a Common Spatial Pattern (CSP) on the subject-specific frequency bands. The CSP method creates spatial filter coefficients according to the Common Spatial Pattern algorithm which maximize the variance of one class while simultaneously minimize the variance of the other.

3) Classifier: The most favourable frequency bands are then obtained from the resulting pre-processed training signals using logarithmic Band Power (BP) for feature extraction. The features are identified by filtering the signal in the alpha/beta frequency bands and selecting four seconds of signal half a second after the instruction was shown to the user (Left and Right). The signal is then split into blocks of 1 second every 16th second and the logarithmic band power is computed by squaring it, averaging it over the time-window and computing its logarithm. The matrices are then be converted in feature vectors which are then passed to the Linear Discriminant Analysis (LDA), which identifies the signal class, i.e., "left" or "right", depending on the hand chosen for the imagined movement and produces a configuration file at the end of the experiment which will be used during online sessions.

4) Controller: The controller can now be used online. Firstly, the previously produced CSP spatial filter is used prior to feature extraction. Then during the feature extraction, the signal is again filtered in the alpha/beta range and the filtered signal is split into blocks of 1 second every 16th second and the logarithmic band power is computed with the matrices converted into feature vectors. Finally, the feature vectors are classifier with the LDA classifier sending either a negative or positive value for each class which allows the manipulation of the 3D object within the Virtual Reality Environment.

D. VR Tasks

Some of the challenges often encountered in creating a BCI-VR system is to provide a meaningful VR feedback to the user by integrating the stimuli needed for BCI based on evoked potentials as tightly and seamlessly as possible in order not to deteriorate the credibility and thus the immersiveness of the VR environment and designing a VR application that is useful and usable despite the differences between a typical VR and the standard BCI training protocols [11].

The Unreal 3D VR project used for neurofeedback was developed by Toby Steele and Michael McMahon during the 2017 'Hack the Brain' hackathon at the Dublin Science Gallery [18]. The 3D VR comprised of a set of basic shapes, which can be rotated both left and right, and when viewed from the correct angle form a Celtic symbol (Fig. 5), but are unresolved from all other angles (Fig. 6). The online VR neurofeedback takes the live EEG signal data, analyses the subjects right/left motor imagery and provides real-time feedback by using the trained CSP filter and LDA classifier to output commands through the Analog VRPN Server, which can be interpreted by the Unreal Game Engine to control the elements within the Virtual Reality Environment [18].

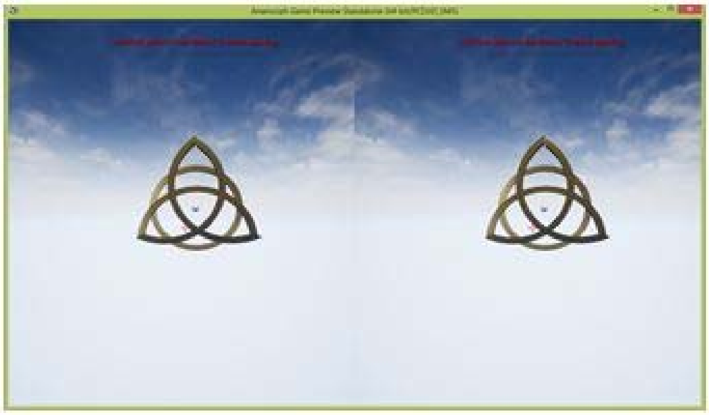

Fig. 5. The Resolved Stereoscopic 3D VR image *[18]*

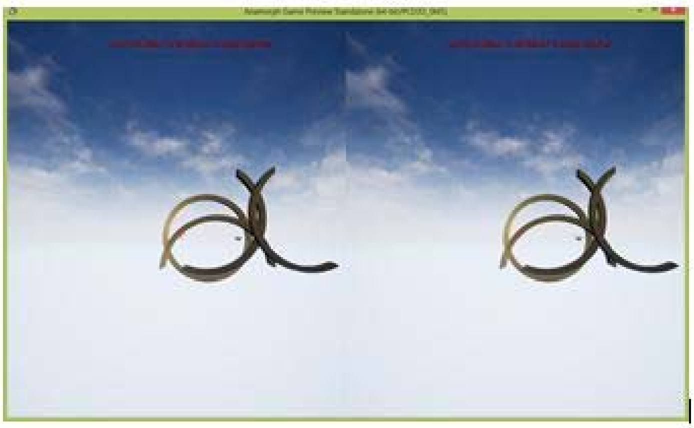

Fig. 6. Unresolved Stereoscopic 3D VR image *[18]*

E. Experiment Setup

The process is explained to all subjects, who sign an informed consent form agreeing that they are aware of the procedure and its purpose. Also, no personal information is collected and after use all data will be destroyed. The cap is placed on the participant with electrodes setup as per the 10/20 diagram ensuring the Cz electrode is placed on the vertex, and the electrodes are connected to the OpenBCI board. Signal verification is done by asking the participant to carry out a few tasks that will generate detectable artefacts such as blinking and clenching the jaw.

The first step in a BCI session is to run the signal acquisition scenario to acquire EEG data from the subject in order to train the classifier to discriminate right and left-hand movements. The scenario starts an instruction sequence which presents left and right arrows to the subject, who is requested to imagine left and right-hand movements when each arrow is displayed (Fig. 7). A cross appears on screen five seconds prior to the arrow, so the subject is aware a training cue is about to appear. A training session contains twenty arrows of each and lasts around seven minutes.

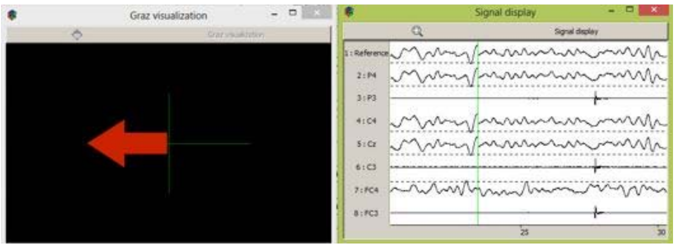

Fig. 7. Running the Acquisition Scenario *[18]*

Once the acquisition file is captured, the training scenario computes the Common Spatial Pattern (CSP) and then the Classifier Scenario trains the LDA classifier. The system is now ready to run the online BCI-VR for real-time signal processing of the ERD/ERS sensorimotor rhythms so the OSVR HDK headset is placed on the subject and the Unreal 3D project is launched.

Finally, the online VR Input scenario is run, which takes the subjects live EEG signal data, analyses the subjects right/left motor imagery and provides real-time feedback by using the trained CSP filter and LDA classifier to output commands through the Analog VRPN Server, which can be interpreted by the Unreal Game Engine to control elements within a VR environment.

The subject tries to resolve the Celtic symbol using both left and right motor imagery and if possible hold the image in a resolved state. An observer can monitor the subject signals through visualizations on the monitor.

III. Experiments & Results

The testing process was focused on human interaction testing and not on the achievement of specific experimental tasks. Following approval by NUI Galway, Discipline of Information Technology, the BCI-VR system was tested on multiple participants at the ‘Hack the Brain’ Hackathon in the Dublin Science Gallery over the weekend of the 10th – 11th June 2017, and was also demonstrated live before an audience on the final day of the Hackathon (Fig. 8). The main findings of the ad-hoc functional testing which occurred during the Hackathon were:

1) It was found that the majority of subjects could control the BCI-VR reporting that the environment responded to their right/left motor imagery.

2) One subject was able to hold the Celtic symbol in place for up to 15-20 seconds at a time.

3) All subjects found the immersive experience of VR to be helpful in focusing on the task when compared to attempting the same task on a monitor.

4) It was found that asking the subjects to imagine playing tennis with the left and right hands in response to left/right signals during the acquisition phase greatly improved the quality of the EEG samples.

Unfortunately, due to the informal nature of a Hackathon we did not record the number of training sessions or feedback trials performed per subject and do not have results to indicate that the setup is providing above chance levels accuracy therefore future experimentation will be necessary to provide more rigorous evaluation of the results.

Fig. 8. Live demonstrate of BCI-VR at 'Hack The Brain' *[18]*

IV. Conclusions and Future Work

Through the development and testing of a prototype we have shown that it is possible to develop a low-cost, open-source, BCI VR prototype and to design a BCI-VR application for real-time signal processing focused on deriving ERD/ERS from the Precentral Gyrus (Motor Cortex), allowing the manipulation of a simple 3D object within a basic Virtual Reality Environment.

The testing process was focused on human interaction testing and not on the achievement of specific experimental tasks; however, the feedback and results from participants was enthusiastic and the BCI-VR system operated as designed.

The research has shown that on the software side there are some excellent open-source products, with the combination of BCILab for development and testing of new BCI methods combined with OpenViBE as a framework for implementing the resulting method plugin being particularly powerful.

On the hardware side the OpenBCI Cyton Biosensing Board and VRPN RDK 2 are both quite affordable. While current VR headsets do require high-end gaming PC's with significant graphics capability, the advent of smartphone-based VR systems such as the Google Cardboard and Samsung Gear VR could significantly reduce this cost issue going forward. Additionally, the cost could be reduced further using more cost effective non-clinical electrodes and cap. The total Bill of Materials for the low cost, open source, BCI-VR system is shown in Table 1:

TABLE 1. Bill of Materials

Bill of Materials (BOM)	
OpenBCI Cyton Board	€406.00
OSVR HDK 2	€325.00
Alienware Aurora (VR Ready)	€1,429.00
g.tec g.GAMMAcap3	€170.00
g.tec g.LADYbirdPASSIVE ring electrode x 8	€272.00
OpenViBE	€0.00 (Open Source)
VRPN	€0.00 (Open Source)
Unreal Game Engine	€0.00 (free for non-commercial work)
Total	**€2,602.00**

This Bill of Materials compares favourably on price to state of the art research systems such as, for example, the Brain Vision acti32Champ System which is commonly used in University Laboratories and retails at €41,000.

The significance of this research lies in two areas. Firstly, patients with a stroke-related disability (30,000 with another 8,000 new patients in Ireland alone), will benefit of the intervention of BCI neurofeedback therapy, often with long lasting effects. This has been shown in numerous case studies. However, medical grade EEG equipment is very expensive and requires highly trained specialists to setup and operate, which prevents widespread usage of BCI neurofeedback therapy. Secondly advances in BCI research is held back by the fact that access to expensive EEG equipment is restricted to hospitals and relatively few University laboratories, even for neuroscience and medical students, and virtually non-existent for other researchers. Wider access would foster greater innovation as researchers and students from other disciplines could potentially discover imaginative and radical BCI applications if affordable prototyping systems were more widely available.

One area for future investigation would involve carrying out controlled experiments using the BCI-VR system on a range of volunteers and produce empirical data based on the subject's ability to achieve specific experimental tasks in a VR Environment. It would also be of value to benchmark the performance of the low-cost, open source BCI-VR system against commercially available medical and research grade equipment in a laboratory setting.

A further area for investigation which could yield benefits for BCI research would be the development of a low-cost BCI device which would combine cap, electrodes and a biosensing chip based on a multichannel ADC converter chip suitable for biopotential measurements, which would be practical for daily routine use by an unconstrained, freely-moving user.

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