A 12-Channel, real-time near-infrared spectroscopy instrument for brain-computer interface applications

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Abstract— **A continuous wave near-infrared spectroscopy (NIRS) instrument for brain-computer interface (BCI) applications is presented. In the literature, experiments have been carried out on subjects with such motor degenerative diseases as amyotrophic lateral sclerosis, which have demonstrated the suitability of NIRS to access intentional functional activity, which could be used in a BCI as a communication aid. Specifically, a real-time, multiple channel NIRS tool is needed to realise access to even a few different mental states, for reasonable baud rates. The 12-channel instrument described here has a spatial resolution of 30mm, employing a flexible software demodulation scheme. Temporal resolution of ~100ms is maintained since typical topographic imaging is not needed, since we are only interested in exploiting the vascular response for BCI control. A simple experiment demonstrates the ability of the system to report on haemodynamics during single trial mental arithmetic tasks. Multiple trial averaging is not required.**

I. INTRODUCTION

UNLOCKING the brain and understanding better its capabilities, functioning, and pathologies is at the forefront of biological science research currently. In an attempt to tap into the brain's numerous simultaneous processes during particular mental operations, some success has been attained in exploiting these processes for controlling augmentative devices to improve the quality of life of those with seriously impaired functional expression [1].

It has been advised, at least for certain subjects, that implementation of non-invasive modalities would be a more prudent approach to first tackle the issue and demand for a brain-computer interface (BCI) by an individual [2]. Several groups have dedicated research to the area, many opting for the more utilised agent of electrophysiology of the brain, namely surface electroencephalography (EEG) [3]. Other BCI modalities have been explored such as functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG). However these are less

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practical due to their size and the ambient requirements.

Another method of brain imaging, termed near-infrared spectroscopy (NIRS), has been developed over the last 3-4 decades and its permissibility for use in a BCI has been suggested by several research groups now pursuing the optical BCI (OBCI) modality [4]-[9]. The ability of NIRS to inspect brain state in amyotrophic lateral sclerosis (ALS) has also been demonstrated recently [4], [10]. It has also been reported that an OBCI may be a suitable tool in stroke rehabilitation [11]. Indeed it has also been mooted that an OBCI may have applications as a complementary interrogatory method allying with, in particular, EEG [12], [13]. For instance, the supplementary direct localisable abilities of NIRS could be harnessed alongside the high temporal resolution of EEG.

In this paper we wish to describe a dedicated 12-channel NIRS instrument for BCI applications. The device is capable of real-time acquisition of functional activity that is relayed in vascular haemodynamic concentration changes. The instrument is supported by a LabView® interface platform that synchronises, displays, and processes haemodynamic data.

Current embodiments of NIRS-BCIs are limited in terms of online real-time capability or in the case of real-time applicability, they are limited in the area of tissue they can interrogate. Our current device has improved SNR and localisation by having multiple channels as well as utilising multiple wavelength sources for increased spatial resolution. In addition, tissue interrogation paradigms are very flexible since independent sources and detector-fibres are not constrained to fixed optode arrangements on the head. Thus, custom-made holders are/can be made for experiment-specific irradiation patterns. Consequently, instrumentation can be minimized for subject comfort.

II. OPTICAL BCI BACKGROUND

A. Optical Brain-Computer Interface

A brain-computer interface is simply a device that presents a user with a viable communication aid for translating/transducing thoughts (e.g. cognitive, motor control) into observable gestures, for example, moving a cursor on a computer screen. An optical NIRS-BCI is a device that exploits the change in optical properties of focal cortical brain tissue during functional activation for such communication.

B. Near-Infrared Spectroscopy

NIRS is essentially a tool whereby matter is penetrated by NIR radiation and the resultant absorption and scattering effects are observed so as to deduce the matter's composition.

Assumptions are made about the absorbing molecules (chromophores) involved in brain imaging. In cortical tissue and other superficial cranial layers some chromophores can be considered constant absorbers. The main constant absorbers of NIR light that are found in brain tissue are melanin, water, lipids, and cerebrospinal fluid (CSF). At normal concentrations in blood, plasma can similarly be treated as a colourless liquid in comparison to haemoglobin absorption. Haemoglobin and various respiratory enzymes, in particular cytochrome-c-oxidase (ccOXY), are the varying chromophores of interest which indicate cerebral blood oxygenation and tissue oxygenation [14].

With any mental action performed, neuronal responses are manifested in various regions of the brain. With this, neighbouring vascular responses ensue (neurovascular coupling) whereby a combination of increases in cerebral blood flow (CBF), cerebral blood volume (CBV), and cerebral metabolic rate of oxygen consumption (CMRO$_2$) lead to an overall localised increase in oxy-haemoglobin (HbO) and a relatively smaller localised decrease in deoxy-haemoglobin (HbR). Again, varying haemoglobin is the main marker of tissue oxygenation dynamics. A modified version of the Beer Lambert Law can be used here to determine HbO and HbR concentration changes:

$$\Delta c_{HbO} = \frac{\alpha_{HbR_{760}}\dfrac{\Delta A_{880}}{B_{880}} - \alpha_{HbR_{880}}\dfrac{\Delta A_{760}}{B_{760}}}{\alpha_{HbR_{760}}\alpha_{HbO_{880}} - \alpha_{HbR_{880}}\alpha_{HbO_{760}}};$$

$$\Delta c_{HbR} = \frac{\alpha_{HbO_{760}}\dfrac{\Delta A_{880}}{B_{880}} - \alpha_{HbO_{880}}\dfrac{\Delta A_{760}}{B_{760}}}{\alpha_{HbO_{760}}\alpha_{HbR_{880}} - \alpha_{HbO_{880}}\alpha_{HbR_{760}}}$$

$$(1)$$

where Δc_{HbO} and Δc_{HbR} are determined concentration changes in HbO and HbR respectively; ΔA_{880} and ΔA_{760} are recorded wavelength specific light intensities; B_{760} and B_{880} (constants) are the product of the direct inter-optode spacing and the tabulated dependent differential pathlength factors. α represents the specific tabulated extinction coefficients for either HbO or HbR at each specific wavelength [14].

III. SYSTEM DESCRIPTION

A. Overview

The 12–channel (24 LEDs, 3 detectors) continuous wave NIRS (cwNIRS) system at NUI Maynooth has a new interfacing and processing paradigm that makes use of a software based demodulation scheme. This is to replace the dual channel system by Coyle [13] where they envisaged an extension to the capabilities of the first prototype, in order to interrogate a larger surface area of the cerebral cortex to ultimately increase the throughput of the optical BCI [15].

Instead of the analogue based lock-in detection techniques used until now [11]-[13], [15]-[16], a LabView® (*National Instruments* graphic programming language) centered workstation controls all aspects of the instrument from driving LEDs, performing spectral analysis to visualisation. All processing, feedback, and synchronisation is dealt with by various LabView® virtual instruments.

The main components of the cwNIRS device are the sources and driving electronics, detectors, coupling optics, mechanical harnessing, and the data acquisition and processing unit. These are illustrated in Fig. 1.
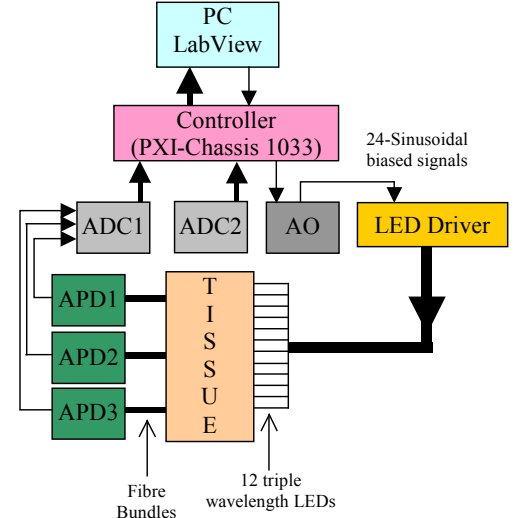

Fig. 1: Data flow diagram of the cwNIRS tool for accessing brain state. Abbreviations are expanded in the main text.

The remainder of Section III is used to describe the instrument in terms of its optical components, electronic components, and software interface. Section IV reports on the haemodynamic signals obtained by the device along with a brief description of their significance. Finally, Section V concludes the paper with a discussion.

B. Optical Components

1) Light Source

Custom-made, high power (5mW-17mW), triple wavelength NIR-AlGaAs-LEDs (Opto Diode Corp: APT0101) were integrated into the device. When applied correctly, they allow sufficient photons to penetrate the cerebral cortex and reflect back after intercepting the localised cortical haemodynamic traffic. Only two of the three dyes per LED are currently being used, with 760nm to resolve HbR and 880nm for resolving HbO (800nm dye is not being used). With 30nm and 80nm spectral bandwidth at 50% maximum (full width half maximum), chromophore crosstalk is avoided, at least optically. An 8° beam angle with perpendicular application of the LEDs to the scalp augments the irradiance reaching the cortical surface. The co-location and lensing of the dyes in each LED package helps improve precision during measurements.

2) Detector

The avalanche photodiode (APD) detector chosen to collect the back-reflected photons (Hamamatsu, C5460-01) is/has being used by other NIRS groups [17], [18], which has a high sensitivity (0.005nW) and excellent noise-equivalent power (NEP) of $20fW/Hz^{1/2}$. With high attenuation (7-9 orders of magnitude) in biological tissue, NIR light is said to accomplish traversing ~8cm of tissue from the source before being fully absorbed [19]. The APD with an active area of 3mm requires glass fibre optic bundles (Edmund Optics, NT40-644) of similar diameter and a large acceptance angle to guide the photons from the scalp to the detector. The APD requires only a ±12V regulated DC supply to generate the high internal voltage (~200V) necessary for the avalanche-multiplication process.

3) Mechanical Optode Holder

A major contributor to the overall signal integrity is the mechanical restraining of the sources and fibre optics to the subjects scalp, all the while maintaining subject comfort. Many configurations of optode coupling have been implemented including a dedicated mechanical mounting system constructed by Coyle [20]. However, in its development and to support a multi-channel system, we fashioned brass tubing in felt and hot melt glue to house the sources and detectors in a 1 detector, 6 source '*optet*[1]'. The 6 LEDs encircle the detector with a 30mm radial spacing (See Fig. 2). This allows quick localising of more active channels, which, once identified, will then allow for replacement of the optet with 1-3 LEDs and a single detector, for the final BCI design. In this way the number of independent BCI channels can be increased to augment the OBCI's throughput, inspecting, with minimal sources and detectors, only the areas of maximal activity for each cortical function (e.g. cognitive, motor, visual).

C. Electronic Components

1) LED Driver

An LED Driver was constructed to provide a stable current-to-intensity source to drive the 12 triple wavelength LEDs. The overall system is scalable to accept many more LEDs, the only constraint being the modulation bandwidth available to separate the sources. All LEDs are modulated (sinusoidal) in the range 1kHz-20kHz, each driven at a maximum of 100mA (~160mW). A genetic algorithm based application was written for selecting frequencies with minimal overlap and harmonic distortion in the 19kHz range.

2) Data Acquisition and Processing Unit

The entire cwNIRS system is integrated within a single workstation running LabView®. This interfaces with devices for signal acquisition (NI-PXI4462), and waveform generation (NI-PXI6723) for the LED driver. The PXI4462 is a 24-bit, 4-channel, 204kHz simultaneous sampling rate analogue-to-digital (ADC) converter. The PXI6723 is a multifunction digital-to-analogue converter (DAC) with 32-analog output channels (AO). Two ADCs and one DAC are housed in a PXI-1033 chassis, which is used to buffer and synchronise data transfer to the workstation via a PCI-Express card. All cards are operated and synchronised to the same 10MHz master clock via a trigger line on the chassis backpane, ensuring robust data timing. The PXI chassis has a further 2 empty slots for either ADC or DAC to allow for system scaling of sources/detectors.

D. Software Interface

Source selection by demodulation is performed in software as inspired by the work of Everdell [17]. Using Fast-Fourier Transform (FFT) demodulation, the amplitude of each dye's carrier signal is extracted from the bulk data, thus separating the 12 dye's light intensities (6 LEDs, 2 dye per LED) reaching each detector. The signal processing pipeline continues within LabView®, where the data is downsampled to 20Hz. Next, filtering and calculation of haemoglobin concentration changes is performed. Classification of BCI activation events, and user feedback with BCI device control can subsequently be carried out in real-time. During an experiment, the user is provided with visual or auditory prompts for, for example, mental arithmetic tasks. The resultant BCI classification of trials is then either reported to the user in training, or used to perform some communication control. In addition, success rates are fed back to the user.

IV. SYSTEM VALIDATION

A short experiment was carried out to verify that the system could indeed report on the cerebral haemodynamics of the user. In future experiments these will be exploited to classify intentional functional activity, for application in a BCI to provide communication aid.

Two subjects (mean age 25 years old) took part in the experiment. Both subjects had previous experience with an optical BCI. All 12 LEDs, but only 2 detectors, were placed on the frontal lobe in two optets of 6 sources and 1 detector each. They encapsulated cortical tissue around F7-Fp1 and F8-Fp2 of the 10-20 electrode placement system (see Fig. 2).

The subjects were asked to perform mental arithmetic exercises during synchronous predetermined trials which simply entailed successively subtracting (for each subtraction the minuend is the result of the previous subtraction) two whole randomised numbers (the minuend was a 4-digit number, the subtrahend a 2-digit number between 16 and 22). The initial rest period was fixed at 30s and the remaining rest periods were randomised between 15s-30s, in an attempt to curtail habituation, stimulus expectation, and low blood oscillation (Mayer Wave) synchronisation. Stimulus periods were fixed at 15s. Each

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[1] We term a single source and detector an 'optode'. We term an optode with multiple spatially disparate sources an 'optet'.
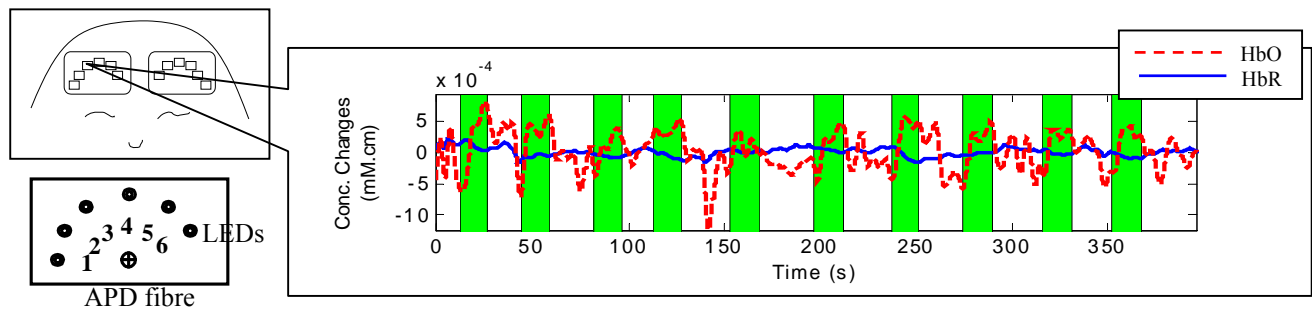
Fig. 2: Ten trials of mental arithmetic tasks from subject 1 on channel 3. During the stimulus periods (shaded regions), activity in the left frontal cortex is indicated by increased haemodynamics, in particular, an increase in HbO and a decrease in HbR. The optet arrangement used is shown on the left.

subject performed 2 sets of 10 trials within the same session.

Both subjects reported similar results. Fig. 2 shows the non-averaged response from subject 1 on channel 3 after band pass filtering (0.05Hz-0.2Hz). This non-averaged analysis is illustrated to report the possibility of an OBCI to determine single trial functional activations, in real-time. After locating the channels with maximum activation, the number of LEDs per optet would be typically be reduced, perhaps to 1-3 LEDs. Differences in neighbouring channels were also observed demonstrating that the cwNIRS system reports spatially varying haemodynamics.

I. DISCUSSION

A 12-channel cwNIRS instrument has been constructed and described here for use in an optical BCI. Since the device uses single source-detector pairing the spatial resolution is ≤ inter-optode spacing of ~30mm with detector sensitivity of 0.005nW. Irradiance of ~5mW-17mW provides adequate cerebral penetration, and the data acquisition (24-bit 204kS/s ADC) allows for sensitive analysis of haemodynamics, as reported in Fig. 2. A 10MHz shared clock ensures synchronisation between data collection and generation, also allowing for accurate data time-stamping. Software demodulation schemes allow for ease of expansion of the device. The flexible LabView® interface allows for rapid prototyping of BCI paradigms, also allowing speedy testing of signal processing techniques. The system can also be used with HomER (see [12]) to produce offline topographic mapping of interrogated cerebral tissue.

Future work will consist of running a series of experiments to test the performance (baud rate, computational overhead speed) of an optical BCI using cognitive/other mental tasks.

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