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Wearable Brain Cap with Contactless Electroencephalogram Measurement for Brain-Computer Interface Applications

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Abstract— **Many brain computer interfaces (BCI) are based on feature selection from electroencephalogram (EEG) signals. To acquire these signals, a set of electrodes is used, most of the times attached to a brain cap. Several brain cap designs have been presented, as well many different electrodes. So far, all the brain caps are difficult and uncomfortable to wear. Moreover, the electrodes, wet or dry, are also difficult to place. Despite the huge potential that a BCI offers, for disabled and healthy people, new brain caps are required to overcome these two main problems. In this work, a wearable brain cap is presented with the ability to measure the required EEG signals without requiring any electrical contact with the head. The wearable cap is obtained using a flexible polymeric material, with new integrated contactless electrodes. The electrodes may be obtained using a new electroactive gel, which is used to read the EEG signals.**

Keywords: wearable brain cap; contacless sensor; brain computer interface

I. INTRODUCTION

A Brain-Computer Interface (BCI) relies on the measurement of brain activity in order to provide solutions for communication and environmental control without movement. Although a BCI was initially intended for people with severe disabilities (e.g. spinal cord injury, brainstem stroke, etc.), it can also be used as an alternative communication channel by the healthier ones [1].

Over the past two decades, several studies were performed towards the development of these BCI systems, which don't require muscle control [2-4]. Although still in its infancy, BCI is no longer a realm of science fiction, but an evolving area of research and applications. BCI propose to augment human capabilities by enabling people to interact with a computer through a conscious and spontaneous modulation of their brain-waves after a short training period. They are indeed, brain-actuated systems that provide alternative channels for communication, entertainment and control [5]. Nowadays, the typical BCI systems measure specific features of brain activity and translate them into device control signals, generally making use of EEG (ElectroEncephalogGram) techniques.

Essentially 4 modules of hardware/software compose the standard BCI, as illustrated on Fig. 1. The signal acquisition module is generally constituted by a cap, electrodes and proper instrumentation hardware for neural data acquisition. The brain activity is then recorded, amplified and digitized. The recorded and pre-treated signals are further subjected to a series of processing techniques, which can be divided into two modules: feature extraction module and translation module. The first one employs several filters so as to extract significant measures from neural data. These features used include for instance, slow cortical potentials (SCP), Sensorimotor Rhythms (SMR) and P300 evoked potentials [5,6]. Some examples of possible filters to apply are: time (e.g. moving average), frequency (e.g. narrow-band power) and spatial (e.g. Laplacian filters) filters. The next stage, translation module, converts these signals features into device commands that carry out the user intents, by detecting a previously identified EEG pattern. Finally, the actuator module is the sub-system that performs the action correspondent to the outputted command, allowing for the operation of the desired device (e.g. wheelchair, neuroprosthesis, etc.) [5].

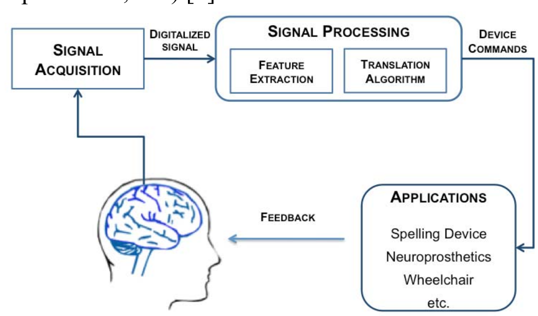


Figure. 1. Basic design and operation of a BCI system.

Many factors determine the performance of a BCI system. These factors include the brain signals measured, the signal processing methods responsible for extracting signal features, the algorithms that translate these features into device commands, the output devices that execute these commands, the neurofeedback provided, and the characteristics of the user as well [5]. The achievement of a superlative combination of these factors is the key to establish the ideal BCI system. The ideal solution would be a contactless measurement of brain activity, allowing the design of a wearable system which would provide a more comfortable and practical device for the user. In fact, the majority of the existent BCI technologies are based on

EEG, which despite being the most straightforward method for measuring bio-potentials, carries strong disadvantages. These are related with the need for an electrolytic paste to promote the impedance reduction as well as with the Signal-to-Noise Ratio (SNR) [7,8]. Likewise, the electrodes with contact carry strong disadvantages since they are of difficult placement, resulting in time-consuming and complex attachment procedures. Concerning the wearability, the existent brain caps are difficult and uncomfortable to wear, disallowing its daily and normal use. In addition, they don't provide a portable and discreet solution for brain activity detection at the user perspective.

Taking this into account, we propose a new solution for the measurement of brain biopotentials, which consists of a wearable device system with integrated sensors – a Wearable Brain Cap.

II. Wearable Brain cap

A. System Description

The Wearable Brain Cap proposed allows the use of a new generation of electrodes that besides being more flexible, allowing for its integration in a wearable device, doesn't require the existence of electrical contact between its surface and the subject scalp. Consequently, the disadvantages concerning the use of the standard EEG tests will be surpassed with the use of contactless electrodes, since there will not be the need for an electrolyte gel neither for time-consuming and uncomfortable attachment procedures. Moreover, oppositely to other techniques, such as Near Infrared Spectroscopy or Magnetoencephalography, with our sensors it's possible to actually measure brain activity as standard potentials, as it happens with EEG. This can be achieved by selecting one-reference methodology, meaning that besides the contactless working electrodes, there will be a reference establishing contact with the subject skin. Fig. 2 depicts a scheme of the one-reference approach proposed.

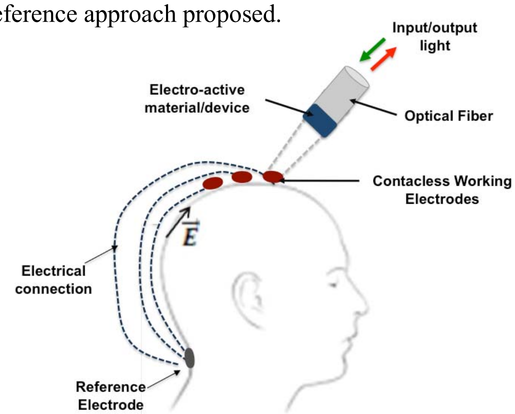


Figure. 2 One-reference approach. The contactless electrode is highlighted.

Usually the reference is placed on the ear lobes, since most of the times they are not influenced by the electrical activity of the temporal lobe and by the muscle activity. On the other hand, in the user perspective, it would be better to place the reference in a more discrete place, since the objective is to use this brain cap as normal daily garment. Therefore, another alternative would be to use the reference electrode on the back neck, as illustrated in Fig. 2. With this approach, the electric field magnitude would most likely be higher, since the distance between the working electrodes and the reference increases, being its detection more easily achieved.

B. Fabrication Technique

The novel fabrication technique used to design our device is based on the multilayer integration of different types of materials, allowing for the integration of several components, e.g. sensors, actuators, optical fibers, electrical wires, antennas. This integration is made concurrently to the deposition and resorting to printing techniques. The layers may be composed of different materials such as polymeric, metal, or synthetic materials. For instance, the fabric could consist of a polymeric material sandwiched in a synthetic layer, and the sensors and actuators, or even other components would be printed, for instance, in the polymeric layer (Fig. 3).

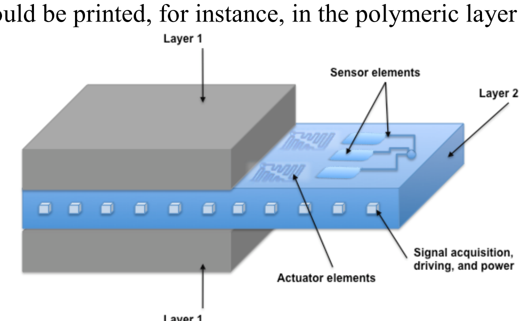
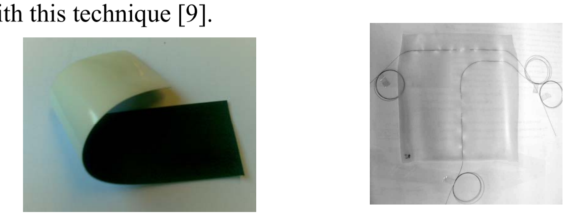


Figure 3. Sandwiched 3-layer scheme of a wearable device fabric.

Thereby, the final result would be, at naked eye, a normal fabric such as common t-shirt, or even a scuba diving suit. In this case, we are able to design a normal and wearable cap or even, if necessary, a normal swimming cap. Fig. 4 shows a sample of the polymeric material as well as a sample fabricated with this technique [9].



a) b)

Figure 4. a) Polymeric material and b) Polymeric foil with optic fiber sensors embedded.

We can see the optic fibers and sensors embedded in the sample material, providing more flexibility to the textile. This facilitates its use in a wearable device and in particular to our wearable brain cap.

C. Contactless Sensor Design

The sensor proposed is a fiber-optic based device which basis of operation relies on the electro-active principle. The main functional stages of our sensor are depicted in fig. 5 and are: optical signal generation; control and modulation; and detection. Briefly, the first stage requires a light source in order

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to obtain an optical signal that will be further modulated and controlled (second stage) trough a series of devices and steps. This second step is dependent on the electric field, and resides in an electro-active component. This can be used simply as a coating material like for example a hydrogel or other piezoelectric material. Afterwards, the modulated light is guided to a photodetector to further analysis.

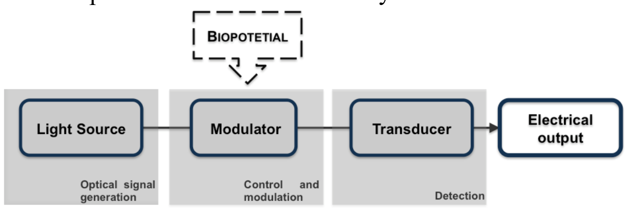


Figure 5. Main functional stages of the contacless sensor.

We propose the use of an electroactive hydrogel as the sensing/modulator component of our sensor – polyacrylamide hydrogel (PAAM). This polymeric material, besides being of low cost, allows for the easy modification of its physical and chemical properties [10,11]. When submitted to an external electric field, PAAM undergoes a bending process, altering its mass and volume properties. Likewise, the input light passing trough this hydrogel will experience modifications, not only regarding the refractive index, but also the amount of light that is transmitted back to the photodetector. A comprehensive study of the properties of PAAM hydrogel is presented in [10].

Fig. 6 shows the configuration proposed for our sensor, where we can see that PAAM would be placed at the end of the optical fiber.

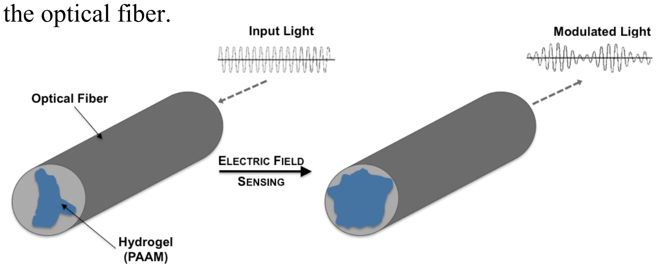


Figure 6. PAAM fiber-based sensor.

The hydrogel is constrained in a cavity at the end of the optical fiber, as near as possible to the subject scalp to increase the detection sensitivity. After the modifications of PAAM properties due to the electric field arousing from the subject brain activity, the input light is modulated, i.e. change of the refractive index and amount of light transmitted.

III. Measurements and Analysis

In order to validate the wearable brain cap system proposed, we studied some parameters trough some experiences. Human scalp EEG experiments were carried in order to have an idea of the typical electric field resultant from brain activity in the relaxed state. Likewise, we performed somes tests to evaluate the electro-active behaviour of the PAAM hydrogel, in order to obtain the minimum electric field that could be detected with its use as a sensing element.

A. Brain Activity Electric Field

The component of E (electric field) in any direction can be expressed as the negative of the rate at which the electric potential (dV) changes with distance (ds) in that direction, i.e.;

$$E = -\frac{dV}{ds}. \qquad (1)$$

Since the electric field can be related with the electrical potential (V), its determination can be achieved by using the EEG standard test.

We have acquired human scalp EEG from a 23-year old subject (male) in order to determine an approximate value of the electric field resultant from brain activity under a relaxed state. The electrodes configuration used to perform the experiment was based on the Fig. 2, i.e. on the one-reference approach. Therefore, we used three electrodes for the recording procedure: one working electrode (position Cz), a reference on the back neck and the subject ground. The results obtained are represented in fig. 7 and were acquired with the recording setup from BrainVision (BrainVision Recorder, BrainVision UK).

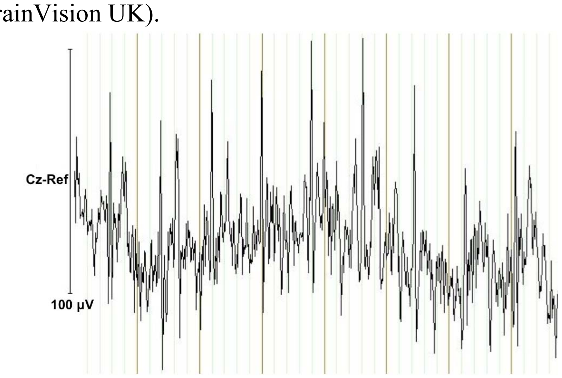


Figure 7. Scalp EEG recorded waves for Cz-Ref.

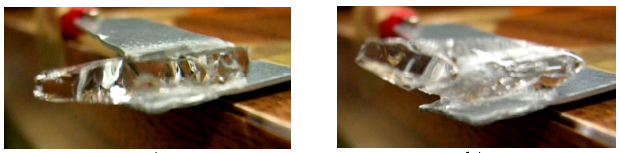
As shown in fig. 7, the scalp potential obtained has a magnitude near 100 µV for a distance between electrodes of 25 cm. Taking this into account and by replacing these values into (2), we determined the corresponding electric field – 4 µV/cm. The results obtained are in conformity with the literature, since the typical values reported range from 50 to 200 µV [12].

B. Electroactive Properties of the Hydrogel

PAAM hydrogel is an electroactive polymer with great sensing capabilities to physical, chemical and biological environments and response to external stimulus in a controllable way. PAAM shows abrupt and vast volume changes as well as bending phenomena when submitted to an external electric field [10].

To produce PAAM hydrogel, Acrylamide 99%, N,N'-methylenebisacrylamide (BIS) 98% as cross-linker, N,N,N',N' tertramethylethylenediamine 99% (TEMED), ammonium persulfate 98% (APS) and aniline purum 99% was used. All chemicals were purchased from Aldrich and used as received without any further purification. Deionized water was used for all the dilutions, the polymerization reactions, as well as for the gel swelling. PAAM is synthesized by the standard free radical polymerization method using 1ml Acrylamide (30%), 60ìl APS (25%), 20ìl Temed with no crosslinker under vacuum. After complete polymerization the resulting gel was diluted in 4ml of deionized water and 5ml Acrylamide (30%), 250ìl BIS (2%), 10ìl APS (25%) and 4ìl Temed was added to form the precursor solution.

After its preparation, the gel was placed between two metallic plates and an external voltage was applied. The gel was 1 cm thickness and the voltage applied was of 2 V. Fig. 8 shows the gel before the experiment (fig. 8.a)) and the effect of the applied voltage in the gel characteristics, more specifically its deformation (fig. 8.b)).



a) b)

Figure 8. PAAM hydrogel before (a) and after (b) the application of 2V.

We can see that the hydrogel shows a vast deformation of about its thickness (1cm) in response to an external applied voltage of 2V. Since we are able to detect deformations at a nano scale, and assuming a linear relationship between the voltage applied and the PAAM thickness alteration, we can estimate a minimum electric field detected. Therefore, assuming this linear relationship, we have:

$$y = mx + b, \qquad (2)$$

where the voltage applied is y and the deformation corresponds to x. Assuming the inexistence of offset, i.e. for no voltage applied, there is no hydrogel deformation (b equals 0), (2) can be re-written into:

$$V = 2x. \qquad (3)$$

By (3) we can obtain the voltage needed for a deformation, for instance of 1 nm:

$$V = 2 \times 1 = 2nV. \qquad (4)$$

We can now calculate the correspondent electric field using (1). Since we have a distance of 1cm (hydrogel thickness) and a voltage of 2nV:

$$E = -\frac{2}{1} = 2nV/cm. \qquad (5)$$

Given this order of magnitude and since the electric field resultant from brain activity has magnitudes of around µV/cm, PAAM hydrogel is an eligible electroactive material to use as a brain activity sensing element. However, further measurements will be required to characterize the PAAM frequency response, as well as the interaction between the electric field and hydrogel deformation, mainly the mechanism leading to the gel deformation.

IV. CONCLUSION

A new generation of wearable and contactless electrodes for brain potential measurement, based on an innovative fabrication technique, was proposed. Our sensor design presents the uniqueness of requiring no electrical contact between their surface and the subject skin, avoiding time consuming and uncomfortable attachment procedures. This contactless sensor is a fiber-based device which basis of operation relies on the electro-active principle. We tested the use of an electroactive hydrogel as a candidate for the sensing/modulator component– PAAM. This polymeric material showed a 1cm deformation, when submitted to an external voltage of 2V. Since we're able of detecting deformations at a nano scale, we can estimate that the minimum electric field detected is in the order of nV/cm. As a final remark, our flexible Brain Cap is an attractive solution for BCI applications, since it overcomes some of the limitations of the existent brain cap systems, mainly the wearable issue, as well as the disadvantages regarding the dry or wet electrodes.

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