Multimodal physiological sensor for motion artefact rejection

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Abstract— **This work introduces a novel physiological sensor, which combines electrical and mechanical modalities in a co-located arrangement, to reject motion-induced artefacts. The mechanically sensitive element consists of an electret condenser microphone containing a light diaphragm, allowing it to detect local mechanical displacements and disregard large-scale whole body movements. The electrically sensitive element comprises a highly flexible membrane, conductive on one side and insulating on the other. It covers the sound hole of the microphone, thereby forming an isolated pocket of air between the membrane and the diaphragm. The co-located arrangement of the modalities allows the microphone to sense mechanical disturbances directly through the electrode, thus providing an accurate proxy to artefacts caused by relative motion between the skin and the electrode. This proxy is used to reject such artefacts in the electrical physiological signals, enabling enhanced recording quality in wearable health applications.**

I. INTRODUCTION

Out-of-clinic monitoring and diagnosis is gaining attention in many developed countries as a means of reducing hospitalisation costs. In particular, ways are being explored of obtaining robust physiological readings from experiments set outside the lab and hospital environments, where subjects can be monitored in an unobtrusive fashion without restricting their quality of life. Brain computer interface (BCI) systems are making progress with the introduction of general consumer systems, e.g. Emotiv and Mindo, enabling next generation gaming and new communication pathways for the physically disabled. Despite all of the recent advances in signal processing and rapid miniaturisation of electronics, many of the above applications are still hampered by electrodes which are inadequate for wearable scenarios. Several obstacles must be overcome for wearable health to become a reality. In particular, there is significant scope for improvements in the area of electrode and sensor technology to allow high quality continuous physiological recordings in natural environments.

Current electrodes are relatively unsophisticated and are typically developed to obtain low electrical impedance between the instrumentation equipment and the body. In practice, one of the biggest challenges associated with physiological recordings are the motion artefacts induced by relative movements between the electrode and the skin, which affect the electro-chemical electrode-skin interface, thus causing interference. Although, there has been a significant effort to develop mechanically stable electrode-skin interfaces, current electrodes are still prone to motion artefacts as well as other skin-related effects [1], [2] (e.g. skin stretch). Research in electrode technology has primarily focused on enabling physiological recordings without the conductive gel; while this provides greater user comfort, it typically increases the level of signal degradation due to motion artefacts. Even in controlled environments where movements of a subject are constrained, modern electrodes provide suboptimal signal quality when dealing with vulnerable populations [3] such as the elderly and those suffering from neurodegenerative diseases (e.g. Parkinson's).

Over the past few decades a variety of solutions has been explored in order to reduce the motion-induced artefacts particularly in electrocardiograms (ECG). Early work by Hamilton *et al.* [2], [4] investigated ways to augment standard electrodes in recording ECG with stretch and optical sensors which measure movement nearby the electrodes. Then, estimates of the artefacts were computed using signal processing and subtracted from corrupted ECG to obtain the clean signal. Similarly, Devlin *et al.* [5] and more recently Kim *et al.* [6] have used electrode-skin impedance measurements as a means of motion artefact detection and estimation; others have experimented with magneto-resistive sensors [7], accelerometers [8], pressure sensors [9] and combinations of these [10] as well as electrode-skin half-cell potential monitoring [11].

Far less research has been conducted in the area of multimodal artefact removal for electroencephalography (EEG), yet the EEG potentials are extremely weak (only a few tens of micro Volts) and are often much smaller than the motion-induced potentials. A partial solution has been proposed recently [3], where head movements were detected with an accelerometer placed on the electrode cap. This approach provided visual reduction in motion artefacts due to involuntary head movement in people suffering from cerebral palsy.

Ideally, for artefact rejection, only *local* electrode movements with respect to the skin should be used as noise estimates, i.e. the artefact measuring sensor must have the body of the subject as a frame of reference. This is clearly not the case with e.g. an accelerometer, which picks up whole body movements, thus its output contains many additional components not related to the specific electrode's displacements, making artefact estimation less accurate. Another important aspect is the placement of the motion measuring device relative to the electrode. To produce accurate estimates of the artefact the sensor should ideally be *co-located* with the electrode – a subject of this work.

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II. MULTIMODAL SENSOR

We propose to combine an electrode with a mechanical modality in the form of a highly sensitive electret condenser microphone (ECM) to obtain a robust and reliable multi-modal signal acquisition unit. The mechanical transducer is mounted directly on top of the electrode, so that both elements are co-located and integrated inside a single miniature package.

A. Sensor construction

The current prototype uses a 9723 GX microphone from Sonion primarily used in hearing aids applications. It has a low frequency cut-off at 20 Hz, high baseline sensitivity of -33 dBV/Pa at 1 kHz and a very low current consumption of only 35 µA. The high accuracy of the motion artefact estimate is achieved by mounting a flexible electrode directly on top of the sound hole on the front face of the microphone (see Figure 1), allowing the ECM to sense local displacements through the electrode.

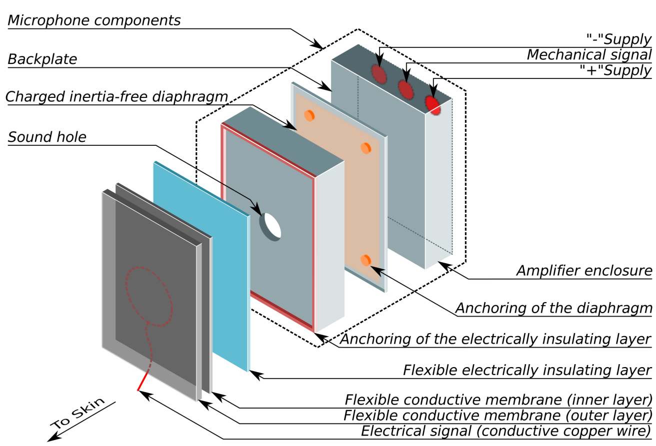

Fig. 1. Detailed construction diagram of the multimodal sensor.

The microphone within the proposed sensor is an active electret condenser type and comprises two capacitor plates. One of the plates is formed by a thin and light (low inertia) diaphragm with charge deposited on it during manufacturing. The backplate consists of a rigid piece of metal connected to the microphone casing. Compression waves pass through the hole on the front face of the casing, while the geometry of the hole determines in part the frequency response of the microphone. The waves impinging on the diaphragm cause its movement, leading to changes in distance between the capacitor plates. Such changes in capacitance produce changes in the potential difference between the plates which is then preamplified, hence three connections on the microphone: positive supply, negative supply and signal. The negative supply contact is connected to the casing of the microphone which, in turn, is connected to the backplate of the capacitor.

The electrical modality of the sensor is obtained by first sealing the microphone with several layers of thin flexible insulating material, while ensuring that there is a pocket of air formed above the sound hole. Subsequently, a layer of flexible conductive material is applied, followed by an attachment of a thin wire. In the last step, several more layers of flexible conductive material are deposited on top of the wire providing sturdy connection.

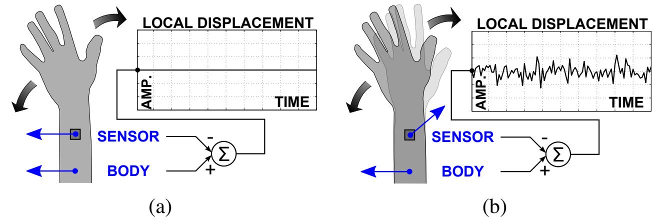

Fig. 2. Principle of the multimodal sensor. (a) The diaphragm inside the mechanical transducer has very small mass, thus body movements which do not cause displacements of the electrode with respect to skin are not detected. (b) Abrupt movements leading to displacements of the sensor with respect to the skin are detected by the mechanical transducer directly through the surface; such a mechanical signal can be used to denoise the electrical signal.

The flexibility of the electrode ensures that the compression waves caused by skin movement propagate freely into the sound hole. Since the diaphragm of the microphone has very small mass the ECM is sensitive only to the local mechanical activity and is largely immune to the whole-body or global movements, as depicted in Figure 2.

B. Sensor characteristics

The electrically sensitive part of the proposed device was found to have similar impedance characteristics to that of the standard electrodes used for biosignal acquisition. It has shown good resistance to wear and tear as well as negligible impedance degradation after a month of regular usage (several times a week).

The mechanical part of the sensor was characterised through a number of tests to investigate its linearity across frequency. The device was placed on a vibration plate (VP) to obtain an estimate of its frequency response in a scenario comparable to motion-induced displacements along the sensor/skin interface. The electrically conductive face of the sensor that is attached to the skin (see Figure 1) was fixed to the VP with a strong double-sided tape and also covered with several layers of medical tape. Such an arrangement models the sensor being placed over a pulsating region on the human body, e.g. at the radial artery site. The displacement of the plate was set to 1 mm and the frequency was varied over a 2 – 50 Hz range, a common range of interest in ECG and EEG recordings.

Figure 3 demonstrates the transfer function based on the mechanical output of the sensor. Notice that for the considered frequency range the mechanical response of the sensor remained within a 3 dB window, confirming sensor linearity. Such behaviour was somewhat unexpected since, based on low frequency characterisation information provided by Sonion, all the ECMs exhibited roll-off characteristic below 20 Hz.

The likely reason for the observed linearity in Figure 3 is that the response of the microphone has been modified by sealing its front face with a flexible membrane (acting as an acoustic filter), thereby creating an isolated pocket of air between the electrode and the diaphragm inside the device. As a consequence, any movement of the conductive membrane, that has a component perpendicular to the skin, leads to changes in pressure inside that pocket of air, which in turn causes a corresponding movement in the diaphragm. Motion of the diaphragm is coupled to the motion of the membrane, thus enabling the key feature of the proposed device – its high sensitivity to mechanical movements of the flexible electrode.

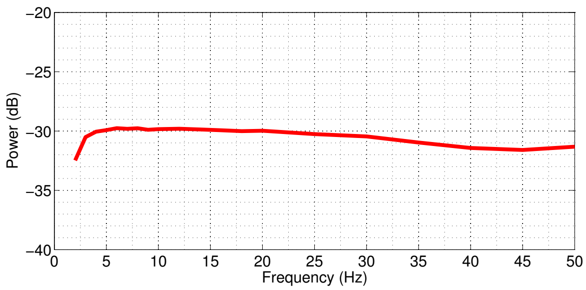

Fig. 3. Frequency response of the mechanical part of the multimodal sensor. The sensor was firmly attached to the vibration plate oscillating at a 1 mm displacement amplitude and the frequency was varied over a 2 – 50 Hz range.

III. MOTION ARTEFACT REJECTION

The conventional way of dealing with motion-induced artefacts is to detect their onset and subsequently discard the contaminated part of the recording. This approach reduces the size of the datasets and introduces discontinuities, leading to loss of information. In scenarios where the motion artefacts do not have large amplitudes, it can be difficult to distinguish the underlying EEG, which leads to incorrect analysis. A number of algorithms for artefact rejection in EEG exist [12], [13], [14], however, such algorithms primarily cater for scenarios where a large number of electrodes are placed at different locations across the scalp, so that there are sufficient data statistics available to identify and discard the artefact. Instead, the proposed sensor is designed to cater even for the most complicated recording scenarios based on only a single or reduced number of electrodes (common in wearable applications [15]).

To evaluate the ability of the proposed sensor in acquiring the motion-induced artefacts in EEG recordings, the multimodal sensor was attached to the middle of a subject's forehead. Motion artefacts were simulated by lightly pressing and rubbing the sensor, monotonically as well as abruptly, in different directions. Four standard electrodes were placed at a distance of 3 cm from the sensor and equidistant from each other. Taking the average of the signals from these electrodes established the ground truth, i.e. the clean/desired EEG signal. All of the five electrical signals were measured with respect to the standard reference electrode placed on the right earlobe. The mechanical component of the sensor was powered by a Duracell CR2032 coin cell. The g.tec

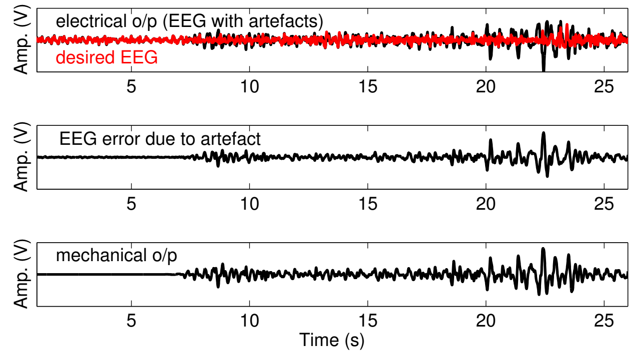

Fig. 4. Motion artefact detection. Top panel: the EEG signal corrupted with motion artefact together with the clean EEG obtained by averaging the signals from four standard electrodes. Middle panel: the difference between the noisy and clean EEG signal. Lower panel: the mechanical output of the multimodal sensor.

g.USBamp unit was used for data acquisition of all the signals (five electrical and one mechanical) at a sampling frequency of 256 Hz. All electrodes, including the electrical component of the multimodal sensor, were gelled with a standard EEG electrolyte and the skin on the forehead was abraded.

Figure 4 shows a recording of 25 s duration with the setup described above; the top panel plots the electrical output of the proposed sensor as well as the clean/desired EEG signal obtained from the surrounding electrodes. Artefacts were induced in the recording after 7 s. This is further illustrated in the middle panel of Figure 4 which shows the error from the proposed sensor – the difference between the electrical output and the clean/desired signal. The mechanical output of the sensor is shown in the lower panel of Figure 4, observe a high degree of correlation with the error signal. This all indicates that the mechanical output represents a good estimate of the motion-induced artefact and can therefore be used to denoise the electrical output.

An artefact rejection scheme for the proposed sensor was introduced in [16] based on multivariate extensions of empirical mode decomposition (MEMD) [17]. We shall denote by $\mathbf{y}$ the EEG signal (electrical modality) obtained from the multimodal sensor which may be compromised by artefacts, by $\mathbf{d}$ the unknown desired/clean EEG signal, and by $\mathbf{x}$ the mechanical output which is assumed to approximate the electrical error up to a scaling factor α. The components $\mathbf{y}$, $\mathbf{x}$ and $\mathbf{d}$ are all $L \times 1$ column vectors. Let $\mathbf{Y}$ and $\mathbf{X}$ denote the $L \times M$ intrinsic mode function (IMF) matrices for $\mathbf{y}$ and $\mathbf{x}$ obtained via MEMD or noise assisted-MEMD [18]. The artefact-free signal $\mathbf{d}$ can then be estimated by [16]

$$\widehat{\mathbf{d}} = \mathbf{Y}\mathbf{w} \tag{1}$$

where $\mathbf{w} = [w_1, \ldots, w_M]^T$ denotes a $M \times 1$ weight vector with each of the weights defined by

$$w_i = \min\left[\frac{\max\left[(\mathbf{Y}_i^T\mathbf{Y}_i) - \alpha(\mathbf{Y}_i^T\mathbf{X}_i), 0\right]}{(\mathbf{Y}_i^T\mathbf{Y}_i)}, 1\right] \tag{2}$$

where $\mathbf{Y}_i$ and $\mathbf{X}_i$ denote, respectively, the i^{th} IMFs – the i^{th}

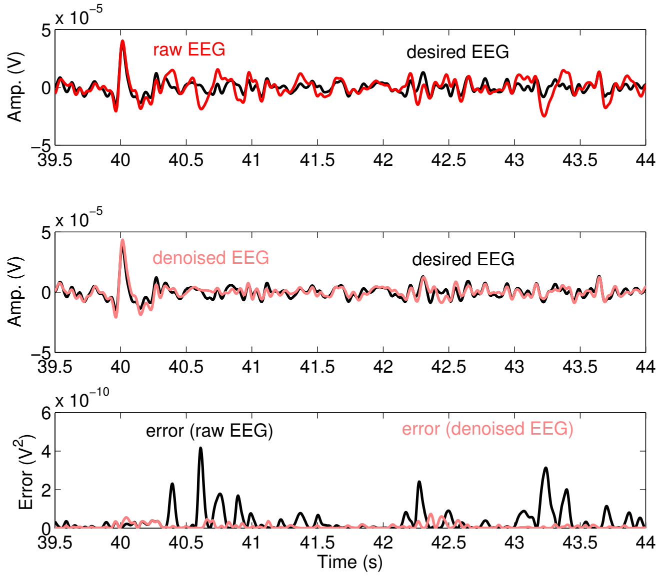

Fig. 5. Motion artefact removal. Top panel: clean/desired and corrupted EEG signals. Middle panel: desired and denoised EEG signals. Lower panel: the squared error prior to and after denoising.

columns of the IMF matrices – for $\mathbf{Y}$ and $\mathbf{X}$.[1] The approach is suitable for nonstationary data and is robust to any additional mechanical components (noise) that are not generated by sensor-skin movements, see [16] for more details. Figure 5 shows 4.5 s of data prior to (top panel) and after the artefact removal (middle panel), together with a panel comparing the squared error before and after denoising (lower panel). The significant reduction in error shown in Figure 5 (lower panel) clearly illustrates that the proposed sensor promises high quality continuous EEG recordings in natural environments. Note that the considered scenario is particularly challenging, because the motion-induced artefact produces disturbances of approximately the same amplitude as the EEG signal itself, proving that the microphone can detect even the slightest displacements of the electrode.

IV. CONCLUSION

A novel multimodal physiological sensor has been introduced. It consists of a flexible electrode and a mechanical transducer in the form of an electret condenser microphone. The sensor has been constructed such that the local mechanical disturbances at the sensor-skin interface can be measured directly through the electrode with high accuracy and sensitivity. Owing to the co-located arrangement the mechanical sensor is capable of acquiring motion-induced artefacts, so that its output can subsequently be used to denoise the electrical modality. This has been demonstrated experimentally, whereby the quality of an EEG signal was enhanced with the aid of a recently developed multimodal denoising technique. This all indicates that the proposed sensor promises improved recording quality of physiological signals in wearable health applications.

[1]The weights were calculated within overlapping widow segments across the IMFs.

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