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New displacement current sensor for contactless detection of bio-activity related signals

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ABSTRACT

This article describes a newly developed low-cost displacement current sensor for non-contact, non-invasive sensing of human bio-activity related signals, well suited for applications requiring remote and portable means for detection of human presence. The sensor, which consists of an input electrode forming the sensor head or antenna, an amplification stage, and a filtering stage, operates by detecting the displacement current between the human body and the sensor's antenna. The antenna comprises a thin 5 cm in diameter circular aluminium disc with a 1 cm thick lightly charged dielectric layer attached to its front surface to enhance the sensor's sensitivity. The sensor employs a simple, improvised transimpedance amplifier which uses a resistive feedback T-network to eliminate the need for ultra-high values resistors normally needed in current amplifiers required for this type of measurements. It provides an operational bandwidth of 0.5–250 Hz, and a noise level of 7.8 μV/$\sqrt{}$Hz at 1 Hz down to 30nV/$\sqrt{}$Hz at 1 kHz. Reported results, obtained in normal unshielded environment, demonstrate the sensor's remarkable capability in measuring human heart's bio-activity related signals resembling ECG at off-body distance up to 0.4 m, and skeletal muscle's movement related signals resembling EMG within 10 m off-body distance with no obstacle in between, and 5 m off-body distance with a brick wall in between.

1. Introduction

The field of human presence and body remote sensing though walls, rubble and similar obstacles, has received a great deal of interest from defence, law enforcement and humanitarian agencies around the world. Over the last decade, numerous systems and technologies for remote human detection have been made available. Currently, commonly used technologies include surface penetrating radars/radar vision, radio waves transmitters/receivers, and carbon dioxide and other human waste characteristics based detectors [1–10]. Despite being effective, most available systems are relatively expensive, require prior installation and/or not easy to move around. They also suffer from a number of practical problems that cause false readings making them prone to evasion [6,7].

Ideally, a successful human presence detection system for above applications should have the following characteristics: (a) the system should use a safe and non-invasive sensing approach that does not expose detected subjects or users to any danger or cause any adverse effects; (b) the system should be capable of remote, non-contact detection of human targets obscured by walls and barriers; (c) the system should operate by sensing readily-available human-related bio-signals and/or phenomena that are difficult to control by the subjects to be detected and, hence, difficult to be fooled, deceived or debilitated; (d) the system should be easy to install and operate for a variety of human presence detection applications, particularly those that require portable usage. A potential means for human presence detection that satisfies these needs is via sensing the electrophysiological and other bio-related signals associated with the biological functions of human organs, commonly known as human biopotentials. Physiological events associated with the biological functions of many human organs, such as the heart, the brain and the muscles, produce electric fields commonly referred to as biopotentials, as well as magnetic fields [11]. For example, the human heart produces a signal called the electrocardiogram (ECG), the brain produces a signal called an electroencephalogram (EEG), and the activity of the skeletal muscles, such as contraction and relaxation, produces an electromyogram (EMG). Table I lists the typical specifications of above mentioned biopotentials [11]. Owing to its typical signal amplitude and bandwidth, the ECG is relatively easier to measure compared to other biopotentials and, hence, can potentially provide an important means for detection of human presence.

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Table I
Main specifications of the ECG, EMG and EEG.

Source	Amplitude measured on skin surface (mV)	Useful bandwidth (Hz)
ECG	0.1–5	0.5–100
EMG	1–10	20–500
EEG	0.001–0.01	0.5–40

Current techniques for recording electrophysiological signals rely primarily on galvanic (resistive) contact with the skin, using either wet Ag/AgCl transducing electrodes with conducting gel, or dry conducting electrodes that require no gel or paste [12–14]. However, as the fidelity of the signal relies on a good resistive contact with the skin, both wet and dry electrodes suffer variably from changes in contact resistance, noise, movement signal artefacts and charge sensitivity [12–15]. They also have known disadvantages related to the necessity for skin preparation and consequent skin irritation and discomfort, and possible shorting between adjacent electrodes [12,15].

To address the limitations of galvanic contact based sensors, a considerable amount of work has been devoted over the last couple of decades to advancing contact-less recording techniques of human biopotentials. One particular approach that has received a great deal of attention is the monitoring of human physiological activities via the detection of the rather weak magnetic fields associated with these events using, for example, SQIUD magnetometers [16,17]. However, sensor cooling requirements at cryogenic temperatures and associated high set-up costs limit the usability of SQUID based sensors [16,17]. A different and more user-friendly approach to biopotentials measurements is to get rid of the resistive coupling to the skin and instead couple to the surface potential capacitively, as proposed first by Lopez and Richardson in 1969 [18]. The use of capacitive electrodes for non-contact detection of biopotentials at up to few centimetres off-body distances, often through several layers of clothing, has been successfully demonstrated [19–21]. However, as the case with dry resistive electrodes, capacitive electrodes can also suffer from noise, movement artefact and charge sensitivity, which are mainly caused by the mismatch between the high source impedance and the following electronics. This is overcome by the use of active insulated electrodes which comprise an impedance buffer integrated into the electrode structure [14,22]. Active electrodes, however, can be bulky, require power supply and not easily miniaturised for good spatial resolution [22]. The performance of active, insulated electrode sensors was significantly improved over the last decade thanks to advances in modern microelectronics and fabrication techniques. A major development in this context is the Electric Potential Sensor (EPS) developed by Prance and co-workers [22,23]. The EPS is a feedback enhanced and stabilised electrometer-based amplifier that operates on displacement current and utilises an ultra-high input impedance to yield very-low noise floor at the operating frequencies of most human biopotentials.

Displacement current is a phenomenon analogous to an ordinary electric current posited by J.C. Maxwell in 1861 to maintain continuity of the magnetic field produced by electric fields around a capacitor. Capacitive sensors therefore can be used to sense the displacement currents induced by the time-varying electric fields associated with various human biopotentials. Referring to Fig. 1, capacitive biopotential sensors effectively rely on detecting the displacement current, i_d, that is proportional to the rate of change of the electric field associated with monitored biopotential, v_s. This is achieved by coupling the sensor's amplifier to v_s through a capacitance, C_e, formed by the sensor's metal electrode and the skin, which typically corresponds to ~0.1–10 pF. For the low frequency measurements associated with the ECG for example (0.1–100 Hz), this weak non-contact coupling crucially requires the

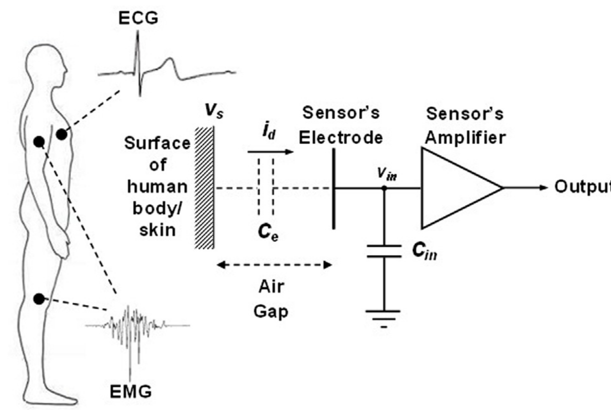

Fig. 1. Illustration of the operational concept of a capacitive biopotential sensor.

input impedance of the sensor to be in excess of 10^{12} Ω since any finite input resistance would form a high-pass filter with C_e and, thus, shunting the signal v_s. In addition, it is also crucial to minimise any parasitic capacitance, C_{in}, at the amplifier's input since it further attenuates the body signal v_s, due to the voltage divider formed by C_e and C_{in} which can effectively be described by:

$$v_{in} = \frac{C_e v_s}{(C_e + C_{in})} \quad (1)$$

For most recently reported capacitive biopotential sensors, these requirements as well as the required high gain have been optimally met via the use of an ultra-high input bias resistor, which is effectively used to dump the displacement current, i_d. For example, in the case of the above mentioned EPS, the above requirements and hence the improved noise performance have been achieved through the use of an input-bias-stabilisation network employing a special ultra-high resistor of glass-encapsulated carbon-film type. However, the addition of such high resistance to the sensor's circuit significantly increases the time constant of the amplifier resulting in a very slow response. Moreover, highly stable resistors in the range of 10^{12} Ω with small tolerance and low thermal noise are very expensive to design and fabricate.

In this paper we present a new low-noise, high sensitivity non-contact displacement current sensor for remote detection of human presence via sensing two bio-activity related signals which closely resemble the commonly known ECG and EMG recordings. Two main features characterise our sensor. Firstly, it employs a safe passive signalling approach by monitoring readily available bio-activity and movement related electrical signals produced by the human subject to be detected. This is in contrast to other reported active signalling techniques, such as the use of microwave doppler radar [34,35] and optical vibrocardiography [36,37], which involve exposing the subject to either microwave or laser radiation. Secondly, it is a new low-cost system involving the use of readily available, off-the-shelve components and design techniques to achieve sensitivity and performance on par with other similar sensors, such as the EPS [22,23] which uses more elaborate and relatively expensive design and fabrication techniques. The sensor, which consists of an input electrode forming the sensor head or antenna, an amplification stage, and a filtering stage, uses a simple, inexpensive transimpedance amplifier which employs a resistive T-network in its feedback path to achieve high current-to-voltage gain and sensitivity. It operates by feeding the displacement current, i_d, directly into the summing point of the transimpedance amplifier, eliminating the need for ultra-high input bias resistance. The sensor's head is formed using a thin aluminium disc with a lightly charged dielectric layer attached to its front surface to enhance sensor's sensitivity.