New Displacement Current Sensor for Remote Recording of Human Biopotentials

Lorenzo Faggion, Abdulhussain E Mahdi

Department of Electronic and Computer Engineering
University of Limerick, Limerick
email: lorenzo.faggion@ul.ie, hussain.mahdi@ul.ie

Abstract— **We describe the recording of human heart and movement related biopotentials remotely from a subject in an open space. A new low-cost, low-noise, displacement current based sensor has been developed and used to record heart related biopotentials at distances up to 40 cm from the surface of the body, and movement related biopotentials at distances up to 10 m from the body. The sensor is built around a simple transimpedance amplifier circuit which utilises a resistive feedback T-network to eliminate the need for ultra high values resistors normally needed in amplifiers for this type of measurements. The sensor provides an operational bandwidth of 0.5 – 250 Hz, and a noise level of 7.8μV/√Hz at 1 Hz down to 30nV/√Hz at 1 kHz. Reported results, which were all obtained in normal unshielded environments, demonstrate the sensor's remarkable capability in remotely recording a wide range of human body electrical signals.**

Keywords – **Displacement current sensors, non-contact biopotentail sensors, ECG/EMG.**

I INTRODUCTION

There is keen interest in technologies which enable the remote detection of human presence and body through walls, rubbles and similar conditions. Over the last decode, numerous systems/techniques have been developed to facilitate effective means fro the remote detection of humans in relation to various defence, law-enforcement and humanitarian applications. Currently, the most commonly used technologies for remote human detection are those based on surface penetrating radars/radar vision, radio waves transmitters/receivers, and carbon dioxide and other human waste characteristics based detectors [1-5]. Despite being effective, most available systems are relatively expensive, require prior installation and/or can not easily be moved around. They also suffer from a number of practical problems that could give rise to false reading, making them prone to evasion [1, 2].

An ideal human presence detection system for above applications should be: a) non-invasive/safe; b) capable of non-contact sensing through solid walls and similar conditions; c) operating on sensing human-related phenomena that are not easy to control by the subjects to be detected; and d) portable or easy to install/operate. One potential means for meeting these requirements is via sensing human biopotentials associated with the activities of human organs, especially the heart and muscles. For instance, the heart produces a signal called an electrocardiogram (ECG), the brain produces a signal called an electroencephalogram (EEG), and the activity of muscles, such as contraction and relaxation, produces an electromyogram (EMG) [6]. Table 1 list typical specifications of above mentioned biopotentials [6]. As illustrated in this table, due to their amplitudes and bandwidths, both the ECG and the EMG are relatively easier to measure compared to other biopotentials and, hence, can potentially provide an important way for detection of human presence. However, recording of these signals still relies primarily on galvanic contact of electrode sensors with the skin using Ag/AgCl electrodes in with and without electrolytes [6]. These limitations have long been recognised, and considerable efforts have been made to develop alternative systems and approaches. One particular approach that has received a great deal of attention is the use of SQUID magnetometer based systems in remote human sensing. SQUID magnetometers offer superior sensitivity and can be used for non-contact off body sensing of biopotentials [7]. However, sensor cooling requirements at cryogenic temperatures and associated high set up costs limit the usability of SQUID based sensors. As an alternative to galvanic contact electrodes, capacitive electrodes that do not require direct contact with the body have been demonstrated to record biopotentials, often through several layers of clothes [8, 9]. Reported work on developed/available capacitive sensor based systems demonstrates various non-contact, off body detection capabilities of ECG and EEG signals [10-13]. However, despite being able to detect human biopotentials without any electric connection to the subject's body, generally most of these sensors have to be either placed in very close proximity to the body/skin, or few centimetres away from the body.

Table 1. Main specifications of the ECG, EMG & 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

Capacitive biopotential sensors effectively rely on measuring the displacement current that is proportional to the rate of change of the electric field associated with the ECG/EMG signals. This is achieved by coupling the input of the sensor's amplifier to the signal through a capacitance formed by the sensor's metal electrode and the body surface. For the low frequency measurements associated with ECG for example, this weak coupling crucially requires the sensor's input impedance to be in excess of $10^{12}\Omega$, since any finite input resistance would attenuate the signal itself. For most recently reported capacitive sensors, these and the high gain requirements have been optimally met by using an ultra high input bias resistor, to effectively dump the displacement current. For example, in the case of the electrical potential probes demonstrated in [10], this as well as improved noise performance has been achieved through the use of an input-bias-stabilisation network employing an ultra high resistor of glass-encapsulated carbon-film type. However, the addition of such high resistance significantly increases the time constant of the amplifier resulting in a very slow response. It also introduces an extra noise source due to thermal effects, degrading the sensor noise performance. Plus, resistors with resistances in the range of 10^{12} Ω with small tolerances, high stability and low thermal noise are very expensive and not readily available.

In this paper we present a new low-cost, low-noise, high sensitivity non-contact sensor for remote detection of human presence via sensing body biopotentials, such as those related to the ECG and EMG. The sensor uses a simple, inexpensive transimpedance amplifier which employs a resistive T-network in its feedback path to achieve high current-to-voltage sensitivity [14]. It operates by feeding the displacement current directly into the summing point of the transimpedance amplifier, eliminating the need for an ultra high input bias resistance.

II SYSTEM DESIGN, CONSTRUCTION AND CHARACTERISATION

An outline of the new displacement current sensor is shown in Figure 1. The system consists primarily of an electrode forming the sensor head or antenna, an amplification stage, a filtering stage and a guard. Our prime target from this work is to develop a relatively low-cost, small and portable system for remote detection of human subjects. As such, additional consideration was given to issues related to size, power consumption and type of electronic components/materials to be used in designing the system. The electrode in our current prototype is basically a 0.5 mm thick aluminium disc with a diameter of 5cm. A 1cm thick lightly charged (statically) dielectric (polyetilene-diyl) layer is added to the front of the electrode, as shown in Figure 1, to enhance the sensitivity of the sensor. The amplification stage consists of a transimpedance amplifier followed by a standard voltage follower. This is followed by a bandpass filter formed by cascading an active 1st order low-pass filter, an active 50 Hz notch filter and a simple RC high-pass filter, giving an effective bandwidth of 0.5Hz – 250Hz. The circuitry forming the amplifier and the filter has been built around four TL082 op-amps from National Semiconductors, and other readily available components. TL082 is a low-power, high input impedance ($10^{12}\Omega$) op-amp with extremely low input noise characteristics (0.01pA/√Hz, 16nV/√Hz). A 5cm×4cm multilayer PCB with an overall thickness of 1.6mm has been developed to mount the circuitry. The PCB design also facilitated the circuit guard shown in Figure 1. This, as well as a reduction of PCB parasitics, was achieved through a combination of an on-board ground ring encircling the circuitry, and a 4-layer power-ground sandwich mounting [15]. No metal case or any other integrated/non-integrated shielding means have been employed in our present prototype of the sensor.

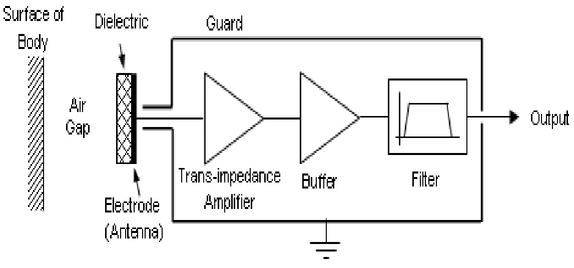

Figure 1: Block diagram of the developed sensor.

The amplification stage is formed mainly by a transimpedance amplifier (TIA), or current-to-voltage converter. TIAs are simple op-amp circuits well suited to applications where the current produced by the source is of importance [14, 16].

Figure 2 shows the circuit diagram of the actual TIA used in our system, as well that of the voltage follower and the filter.

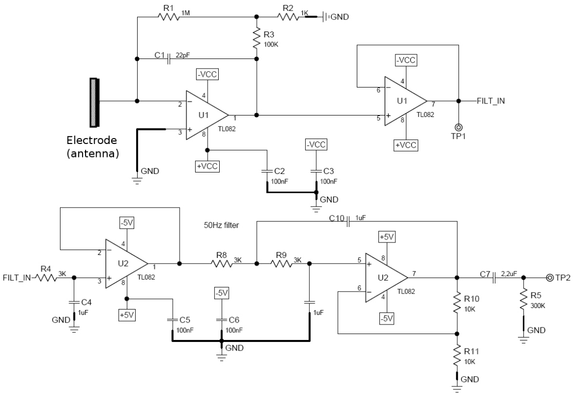

Figure 2: Circuit diagram of the developed sensor.

The gain/phase response of the sensor is shown in Figure 3(a). Figure 3(b) shows the sensor noise spectral density for non-contact off-body application over a frequency range of 10^{-2} – 10^{3} Hz. As can be seen, the sensor has a remarkable noise level of 7.8μV/√Hz at 1 Hz down to 30nV/√Hz at 1 10^{3} Hz. This gain/noise performance is clearly of great importance for a variety of conditions where remote detection of most human biopotentials is required. In particular, it demonstrates very promising potential to our prime target application which is related to detection of hidden subjects behind walls, insider containers and in rubble.

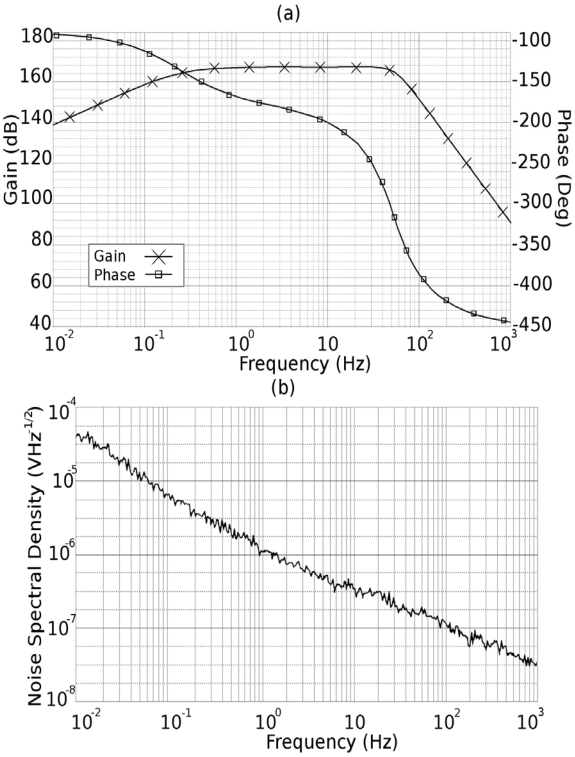

Figure 3: (a) Frequency and Phase response, (b) Noise spectral density of the sensor.

III SYSTEM PERFORMACE AND EXPERIMENTAL RESULTS

To demonstrate the performance of the developed sensor in remote off-body sensing of human biopotentials, we conducted two experimental tests both in a non-shielded environment. The first test is to demonstrate the capability of the sensor in detecting human presence based on sensing the subject biopotential signal generated by current flow in the heart. The set-up for this experiment is shown in Figure 4 which illustrates the relative positioning of the human subject and the sensor electrode. A single sensor is used to record body signals with electrode to body distance A. It must be stressed here that no electrical connections are made to the body, with the subject sitting down in front of the sensor wearing normal clothing layers and in a normal non-shielded laboratory room. Figure 5(b-d) show the waveforms of measured signals, recorded at the output of the sensor, when the electrode is at a distance A = 1, 10 and 40 cm, respectively. We would like to stress that signals shown are the raw output signal and no additional processing was applied. For comparison, we also show in Figure 5(a) the corresponding ECG detected using a standard 3-lead Ramesy-ECG1C electrocardiogram monitor. It is clear that all the waveforms in Figure 5(b-d) exhibit the shape of the distinctive periodic PQRST pattern of an ECG signal, displaying near perfect R and S peaks. The patterns displayed do not exactly mimic the conventional on-body ECG and exhibit some time delay with respect to the ECG trace shown in Figure 5(a). This feature has also been reported in the measurement of other similar sensors, such as that in [10], and has been attributed to the multi-polar nature dynamic electric fields generated by the cardiac system.

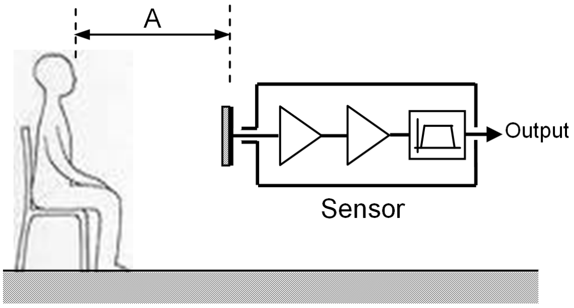

Figure 4: Remote ECG detection experimental setup.

The second experimental test is to demonstrate the sensor's capability in detecting human presence via sensing the subject movement and muscle related biopotentials. The set-up for this test is shown in Figure 6, which illustrates the positioning of the sensor's electrode relative to a human subject walking/passing in front of the sensor. Again we would like to emphasis that there were no electrical connections to the body, the subject was wearing normal layers of clothing, and the measurements were recorded in a non-shielded environment. Figure 7(a) shows the waveform of measured raw signal at the output of the sensor when the normal distance between the body of the subject and the parallel plane at the position of the sensor's electrode, denoted A in figure 6, is 10 m. Figure 7(b) on the other hand shows the waveform of the sensor output when a concrete wall separates the subject form the sensor, with the distances B and C shown in figure 6 being 4 m and 1 m, respectively. For both cases, it is clear that the measured waveforms display the typical shape of an EMG signal normally associated with the leg and biceps movements.

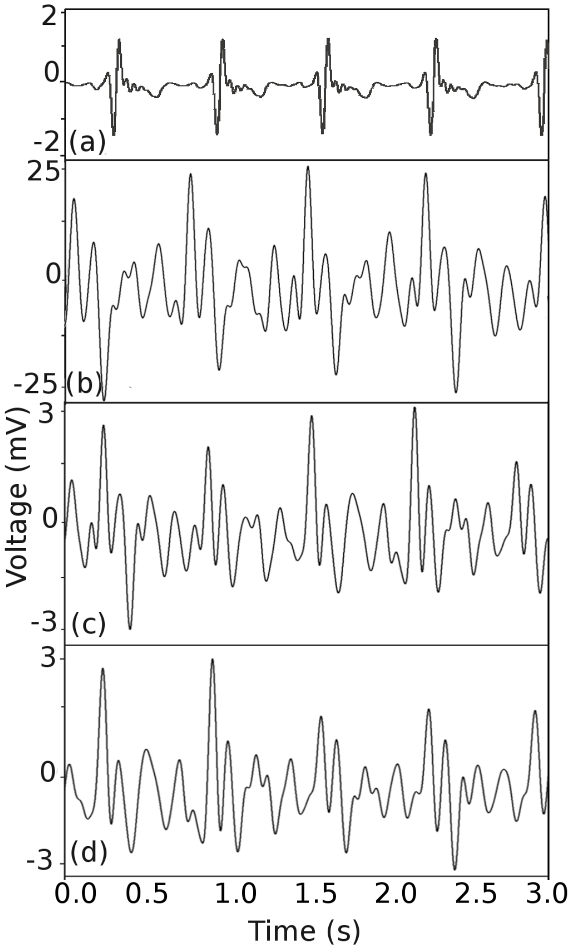

Figure 5: Results for the first experimental test (see text in Section III).

IV CONCLUSIONS

In this paper we have described the design and construction of a contact-less sensor for the remote recording of human biopotentials. Presented experimental results illustrated the remarkable performance of our new low-cost displacement current based sensing system, and demonstrated its suitability for the remote detection of the human body/presence via sensing the subject's heart and muscle related bio-signals. The sensor has been built using readily available, inexpensive components, and uses a simple but improvised transimpedance amplifier that employs a T-network utilising relatively low values resistors. Despite of its relative simplicity, the system offers very low noise characteristics, as highlighted by the reported results. In terms of capability in remotely sensing biopotential signals generated by human heart and muscle activities, the performance of the sensor is very comparable to recently reported similar sensors which have been developed using modern microelectronics, fabrication and shielding techniques. Currently, we are working on further develop and optimise the noise and sensitivity performance of the system, as well as on transforming it into a portable human scanning system suitable for remote detections of human behind walls, inside containers, or under rubble.

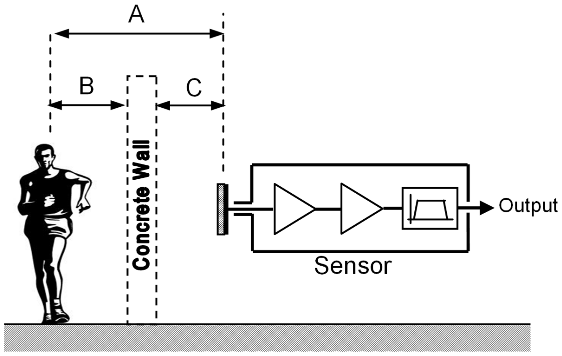

Figure 6: Remote human movement detection experimental setup.

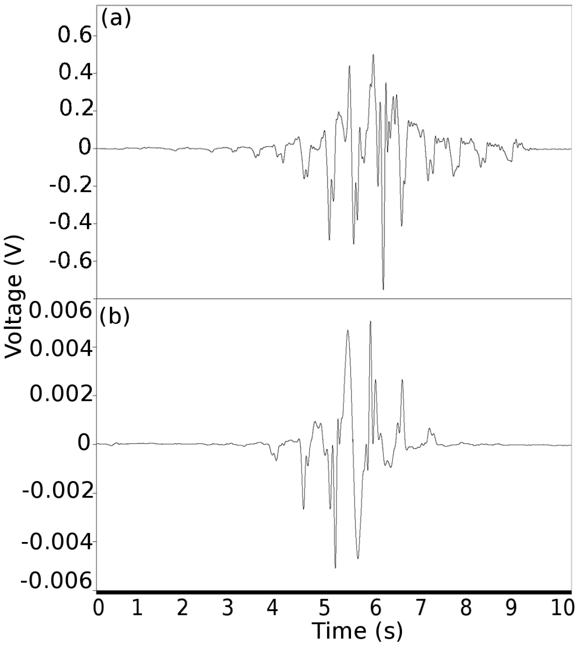

Figure 7: Results for the second experimental test (see text in Section III).

ACKNOWLEDGMENT

This work is funded by the Joint Research Centre of the European Commission, Ispra – Italy, where Lorenzo Faggion is currently conducting the bulk of his PhD research work.

REFERENCES

[1] T. Dogaru, L. Nguyen and C. Le, “Computer models of the human body signature for sensing through the wall radar applications” *Public Report ARL-TR-4290, Army Research Laboratory*, Adelphi, MD, 2007.

[2] A. K. Brenda, “Selected systems for the detection of human stowaways in air cargo containers”, in *IEEE Carnahan Conf. Sec. Technol.*, Lexington, KY, 16-19 Oct 2006, pp 26-29.

[3] M. Nishi, S. Takahashi and T. Yoshida, 2006, “Indoor human detection systems using VHF-FM and UHF-TV broadcasting waves”, in *IEEE Intl. Symp. Personal, Indoor and Mobile Radio Communications*, Helsinki, Finland, 11-14 Dec. 2006, pp 1-5.

[4] W. Chi-Wei and H. Zi-Yu, “Using the phase change of a reflected microwave to detect a human subject behind a barrier”, *IEEE Trans. Biomed. Eng.*, vol. 55, no. 1, 2008, pp 267-272.

[5] D.A. Brown, “Human occupancy detection”, in *IEEE 29th Int. Carnahan Conf. on Security Technology*, Surrey, UK, 18-20 Oct 1995, pp 166-174.

[6] N.V. Thakor, “Biopotentials and electrophysiology measurement”, in *The Measurement, Instrumentation, and Sensors Handbook*, J G Webster (ed.), CRC Press, Boca Raton, FL, 1999.

[7] A.E. Mahdi, L. Panina and D. Mapps, “Some new horizons in magnetic sensing: high-Tc SQUIDs, GMR and GMI materials”, *Sensors & Actuators A: Phys*, vol. 105, no. 3, 2003, pp 271-285.

[8] A. Lopez and P.C. Richardson, “Capacitive electrocardiographic and bioelectric electrodes”, *IEEE Trans. Biomed. Eng.*, vol. BME-16, no. 1, 1969, p 99.

[9] Y.G. Lim, K. Kim and K.S. Park, “ECG measurement on a chair without conductive contact”, *IEEE Trans. Biomed. Eng.*, vol.53, no.5, 2006, pp 956–959.

[10] R. J. Prance, S. T. Beardsmore, P. Watson, C.J. Harland and H. Prance, “Remote detection of human electrophysiological signals using electric potential sensors”, *Appl. Phys. Lett.*, vol. 93 , no. 3, 2008, pp 033906 - 033906-3 (DOI: 10.1063/1.2964185).

[11] R. Matthews, N.J. McDonald, I. Fridman, P. Hervieux and T. Nielsen, “The invisible electrode – zero prep time, ultra low capacitive sensing”, in *Int. Conf. on Human Computer Interaction*, Las Vegas, NV, 22-27 July 2005, pp 22–27.

[12] C.J. Harland, T.D. Clark and R.J. Prance, “High resolution ambulatory electrocardiographic monitoring using wrist-mounted electric potential sensors”, *Meas. Sci. Technol.*, vol. 14, 2003, pp 923-928.

[13] M. Oehler, V. Ling, K. Melhorn and M. Schilling, “A multichannel portable ECG system with capacitive sensors”, *Physiol. Meas.*, vol. 29, 2008, pp 783-793.

[14] G. Clayton and S. Winder, “*Operational Amplifiers*”, 5th ed., Newnes, Oxford, Boston, 2003.

[15] Semtech, “*RF design Guidelines: PCB layout and circuit optimization*”, Appl. Note AN 1200.04, Semtech, 2006 (www.semtech.com).

[16] Microchip, “*Analog sensor conditioning circuits – an overview*” Appl. Note AN990, Microchip Technology Inc., 2005 (www.mirocchip. com).