Non-contact biopotential sensor for remote human detection

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Abstract. This paper describes a new low-cost, low-noise displacement current sensor developed for non-contact measurements of human biopotentials and well suited for detection of human presence applications. The sensor employs a simple, improvised transimpedance amplifier that eliminates the need for ultra high values resistors normally needed in current amplifiers required 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 experimental results demonstrate the sensor’s capability in measuring heart related biopotentials within 0.5m off-body distance, and muscle related biopotentials within 10m no obstacles off-body distance, and 5m off-body distance with a concrete wall in between.

1. Introduction
The field of human presence and body remote sensing though walls, rubble or similar obstacles, has received a great deal of interest during the last few years from defence, law 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 [1-5]. Despite being effective, most available systems are relatively expensive, require prior installation or not easy to move around. They also suffer from a number of practical problems that cause 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) operates on sensing human-related phenomena that are difficult 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 many human organs, such as the heart, the brain and the muscles. For example, 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]. Owing to their amplitudes and bandwidths, the ECG and the EMG (typical amplitudes/bandwidth of ECG: 0.1-5mV/0.5-100Hz; EMG: 1-10mV/20-500Hz) are relatively easier to measure compared to other biopotentials and, hence, can potentially provide an important means 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 combination with electrolytes [6]. To eliminate the need for direct skin contact, considerable amount of work has been devoted, for example, to using SQIUD magnetometer based
systems, which offer superior sensitivity for sensing biopotentials in a non-contact mode up to few centimetres off the body [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]. Advances in modern microelectronics and fabrication techniques have revived interest in this type of capacitive sensing with successful efforts resulting in improving sensor performance and manufacturability. Prance and co-workers [10], for example, developed feedback enhanced and stabilised electrometer based amplifiers that operates on displacement current, have ultra high input impedance and yield very-low noise floor at the operating frequencies of most biopotentials. Further advances in non-contact ECG sensors were reported by Matthews et al [11].

Displacement current is a phenomenon analogous to an ordinary electric current, posited by J.C. Maxwell to explain magnetic fields produced by electric fields around a capacitor. Referring to figure 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 the ECG/EMG signal, $V_S$. This is effectively achieved by coupling the sensor’s amplifier to $V_S$ through a capacitance, $C_S$, formed by the sensor’s metal electrode and the body surface, which typically corresponds to 0.1-10pF. 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 $V_S$. In 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, $I_D$. 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 value resistors significantly increases the time constant of the amplifier resulting in a very slow response. It also introduces an extra noise source, due to thermal effect, degrading the sensor noise performance. Plus, resistors with resistances in the range of $10^{12} \Omega$ 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 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 [12]. It operates by feeding the displacement current, $I_D$, directly into the summing point of the transimpedance amplifier, eliminating the need for an ultra high input bias resistor.

2. System design, construction and characterisation
An outline of the new displacement current sensor is shown in figure 2. The system consists primarily of an electrode forming the sensor head or antenna, an amplification stage, and a filtering stage. Our
prime target in this work is to develop a relatively low-cost, portable system for remote detection of human presence. As such, additional consideration was given to issues related to size, power consumption and type of components/materials to be used in developing the system. The electrode in our current prototype is basically an aluminium disc of 5cm in diameter and 0.5mm in thickness. A 1cm thick lightly charged (statically) dielectric (polystyrene) layer is added to the front of the electrode, as shown, 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\(^{12}\)Ω) 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 also facilitates the circuit guard shown in figure 2. This, as well as a reduction of PCB parasitics, were achieved through a combination of an on-board ground ring encircling the circuitry, and a 4-layer power-ground sandwich layout [13]. No metal case or any other integrated/non-integrated shielding means have been employed in our present prototype of the system.

![Figure 2. Block diagram of the new displacement current sensor.](image)

Transimpedance amplifiers (TIAs), or current-to-voltage converters, are simple op-amp circuits that are well suited to applications where the current produced by the source is of importance [12, 14]. Figure 3(a) shows the basic configuration of a TIA. As the op-amp tends to maintain its inverting input terminal at ground potential, it forces the input current to flow through the feedback resistor, \(R_F\). Thus, \(I_{IN} = I_F\) and \(V_O = -I_{IN} R_F\). This results in a current scaling, or signal gain \(A_{SIG} = V_O / I_{IN} = R_F (V/A)\). TIAs are usually operated at very high gain and, hence, there is a possibility of closed loop instability. This problem can be eliminated by adding a small capacitor, \(C_F\), in the feedback loop as shown in figure 3(a). In very small current measurements, as the case in our application, the high values required for \(R_F\) pose a problem because stable high value resistors are not freely available. In the developed system, this has been avoided by using a resistive T-network, as shown in figure 3(b), whereby the voltage divider formed by \(R_1\) and \(R_2\) increases the effective value of the feedback resistance, and hence \(A_{SIG}\), to \(R_F (1+R_2 / R_1) [12]\). This allows high gain to be achieved using relatively small value resistors. In our current prototype, we achieved a sensitivity of \(-10^8\) V/A (equivalent to \(-160\) dB) by setting \(R_F = 1\,\text{M}\Omega, R_1 = 1\,\text{k}\Omega\) and \(R_2 = 100\,\text{k}\Omega\). Figure 3(c) shows the circuit diagram of the actual TIA used in our system, as well as that of the voltage follower and the filter.

The frequency response of the sensor, illustrating its sensitivity/gain, is shown in figure 4(a). Figure 4(b) shows the sensor noise spectral density for non-contact off-body application over a frequency range of 0.01Hz-1kHz. As can be seen, the sensor has a remarkable noise level of 7.8μV/√Hz at 1 Hz down to 30nV/√Hz at 1 kHz. 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 for our target application which is related to detection of hidden subjects behind walls, inside containers and under rubble.
3. System performance and experimental results
To demonstrate the performance of 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 a 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 5(a) 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(c-f) show the waveforms of measured signals recorded at the output of the sensor, when the electrode is at a distance $A = 1, 10, 40$ and $50$ cm, respectively. We would like to stress that signals shown correspond to the raw sensor output and no additional processing was applied. For comparison, we also show in figure 5(b) the corresponding ECG detected using a standard 3-lead Ramesy ECG1C.
electrocardiogram monitor. It is clear that all the waveforms in figure 5(c-f) 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 has some time delay with respect to the ECG trace shown in figure 5(b). This feature has also been reported in the measurement of other similar sensors [10], and has been attributed to the multi-polar nature of the dynamic electric fields generated by the cardiac system.

The second experimental test is to demonstrate the sensor’s capability in detecting human presence via sensing the subject movement/muscle related biopotentials. The set-up for this test is shown in figure 6(a), 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 6(b) shows the waveform of measured raw signal at the output of the sensor when the normal distance between the subject and the vertical plane marking the position of the sensor’s electrode, denoted A in figure 6(a), is 10 m. Figure 6(c) on the other hand shows the waveform of the sensor output when a concrete wall separates the subject from the sensor, with the distances marked B and C in figure 6(a) 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 activities of the leg and biceps muscles.

Figure 5. Set-up and measurement results for first experimental test (see text in Section 3).

4. Conclusions
We have described the design, construction and performance of a new low-cost displacement current based sensor for remote detection of human body/presence through sensing heart and muscles related biopotentials. 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. Presented data showed that the system offer remarkable noise characteristics. In terms of capability in remotely sensing the biopotentials generated by the 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, our system is undergoing further developments with regards to optimising its noise and sensing performances, as well as integration into a portable scanning system suitable for remote detection of humans hidden behind walls, inside containers, or under rubble.
Figure 6. Set-up and measurement results for the second experimental test (see text in Section 3).

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