Non-contact wearable single forearm cardiac biopotential acquisition device

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Abstract. In this work the authors propose a novel approach to obtain the electrocardiogram in the forearm using non-contact sensing. This new solution should be at same time portable, ergonomic and robust, enabling its use in different set of applications. A system of four electrodes was used in an adjustable sleeve to be wrapped in the forearm. No additional electrode references were used in other body parts. In order to increase the sensitivity of the system, an harmonium like approach was used in the design of the electrodes. The prototype was then compared with a similar system with a flat conformation. The developed prototype enabled the acquisition of an ECG signal in the forearm and the inclusion of the harmonium like electrode conformation resulted in a considerable increase of the sensitivity of the system. The acquired signal did not enable the identification of all characteristic cardiac waves. However, it was possible to identify clearly a signal pattern, characteristic of the QRS complex. The properties of the acquired signal restrict their use in rigorous electrocardiographic studies, allowing, however, its application in heart rate variability monitoring and biometric identification without the disadvantages usually associated with conventional electrodes. This makes it specially useful for man-machine interfaces and automated identification.

1. Introduction
Devices to acquire ECGs are certainly not new. To do it without contact, making use of capacitive electrodes is also not new [1, 2]. Interesting enough the acquisition on a single arm, specifically the left arm, is also not new [3,4]. What the authors claim to be new is the approach and localization. The paper in [3] and application notes found on this topic [4] show that near ECG signals can only be acquired from the arm, being the forearm and wrist locations with too weak signal to noise ratio, even using normal Ag-AgCl wet electrodes. In our approach we were able to acquire near ECG type signals on the forearm while avoiding any contact whatsoever with skin on any other part of the body. This makes this an extremely convenient approach for acquiring ECG signals, comfortable to wear for long periods of time. Furthermore we were able to use it over long-sleeved shirts and pullovers. Our goal with the development of such a device was to increase the viability of applications like biometric user validation, sports physical effort monotorization, game-play control system, prosthesis control and fatigue and drowsiness detection for drivers.

2. Biomedical considerations
The biosignals in the human body are a resultant of electric potential propagation caused by variations in the distribution of ions. The skin is composed by different layers, which present different electrical properties. The stratum corneum, external layer of the epidermis (dead cells), presents some
semipermeability to the body ions and consequently acts as an insulator. Its capacitance is not well characterized, since its value is dependent of the skin properties, especially the thickness and humidity of this layer [5]. Taheri et al. estimated that the stratum corneum capacitance can have minimum values of 100nF.cm\(^{-2}\). On the other hand, Rosell et al. obtained values for skin bioimpedance that varied from 10 k\(\Omega\).cm\(^{-2}\) till 100 M\(\Omega\).cm\(^{-2}\) at 1 Hz, 220 \(\Omega\).cm\(^{-2}\) at 100 kHz and 120 \(\Omega\).cm\(^{-2}\) at 1MHz, which implies amplifier circuits with a very high input impedance in order to avoid the voltage conversion from the common-mode to differential-mode [6]. The skin-clothing-electrode interface can be approximated by a conductive layer (dermis), which for the usual cases acts as a pure resistor, in series with parallel RC elements (stratum corneum, clothing layers, etc.) and in series with the electrode equivalent circuit. In the case of capacitive electrodes, this circuit can be approximated by a capacitor. On the other hand, the usual ECG electrodes are well described by a half-cell potential, in series with two parallel RC elements (electrolytic paste and stratum corneum) and in series with a conductive layer (dermis) [10].

In this way, when the conventional electrodes are used, a better signal can be obtained if the values of the stratum corneum resistance, capacitance and half-cell potential are reduced. A usual technique to decrease these values is to rub the areas under the electrodes. However, the regeneration capability of this layer is high, which results in variations of these values in time and consequently in the measured signal.

3. Methodology

While the main goal is the assessment of an ECG, we wanted the setup to easily permit determination of bioimpedance. This would allow arterial plethysmography information to be assessed simultaneously. As such the electrode configuration we designed has this dual capability but the focus in this paper will be on the biopotential recording.

The system consists in an armband with four capacitive electrodes positioned according to the schematic shown in figure 3.1.

![Figure 3.1 – Schematic representation of the developed electrodes: a) Body location; b) lateral view – cloth support (blue), ground layer (orange), dielectric - paper (violet) guard layer (black), silicone sheet (pink), conductor electrodes/guards (red) and silicone gel (green); c) top view – guard electrodes (black), injection electrodes (red), measurement electrodes (blue) and Velcro (purple)](image)

The first and fourth electrodes are responsible for creating an ion current in the body, which will be used to measure the plethysmographic impedance. The remaining electrodes will alternately measure both ECG biopotential and bioimpedance. The use of different electrodes for current injection and signal acquisition is preferable, since this configuration results in a more uniform current density, avoiding problems related with higher density currents in the areas near the injection electrodes and problems in the discrimination of the impedance of the skin-electrode interface and the area of interest. In order to guarantee the decoupling of both reading and injecting electrodes, three guard electrodes are displaced between these as presented in Figure 3.1 c). In addition two guard electrodes, which are
connected to the circuit ground, are displaced in the extremities of the system, ensuring the shielding of the measured signal from the external noise sources.

Two more conductive layers are added to the system. An external layer, which is connected to the ground, allows the shielding of signals from parasite noise sources, such as power lines sources and biosignals originating from other body parts. A medial conductive layer connected to the guard common was also used. The inclusion of this layer resulted from some experiments that showed that the addition of it led to a better signal-noise ratio (SNR). Thin sheets of dielectric material separate all these layers.

4. Electrode design

The proper design of the circuit implies the previous study of the properties of the electrodes. The interaction electrode-skin can be approximated by a capacitor in which the subject arm and the electrode are the conductors separated by a dielectric (clothing and other insulators). Furthermore, since it was intended that the system wraps the entire arm, the interaction skin-electrode can be approximated by a cylindrical capacitor. The capacitance of a cylindrical capacitor can be estimated using both the definition of the capacitance (4.1) and the calculus of the electric field (E) to an infinite cylinder by using the Gauss’s Law (4.2):

\[ C = \frac{Q}{V} = \frac{\lambda L}{\Delta V} \quad (4.1) \]
\[ E = \frac{\lambda}{2\pi \varepsilon_0 r} \quad (4.2) \]

in which C is the capacitance, Q represents the ratio of charges between the conductors to the voltage V, L is the cylinder length, \( \lambda \) and \( \varepsilon_0 \) represents respectively the charge per unit of length in the conductor and the vacuum permittivity and r is the radial distance to the center of the conductor. The voltage difference between the conductors can be computed by integrating E along a radial line:

\[ \Delta V = \int_{r_1}^{r_2} \frac{\lambda}{2\pi \varepsilon_0 r} \, dr = \frac{\lambda}{2\pi \varepsilon_0} \log \left( \frac{r_2}{r_1} \right) \quad (4.3) \]

where \( r_1 \) represents the internal conductor radius and \( r_2 \) is the radial distance between the medial side of the external conductor and the center of the internal conductor. Substituting equation (4.3) in equation (4.1) and considering a dielectric with the dielectric constant \( \varepsilon_r \), the capacitance for a cylindrical capacitor is derived:

\[ C \approx \frac{2\pi \varepsilon_r \varepsilon_0 L}{\log \left( \frac{r_2}{r_1} \right)} \]

The developed system should be as robust as possible, enabling its use over a non-determined set of clothing layers. Thus, in order to enhance the signal acquisition it is important to consider the different parameters that can affect it.

A schematic representation of the relation between the impedance of the electrodes (Zelec), the impedance of the body part in measurement (Zbio) and the acquired signal (Vout) is presented in Figure 4.1. Simplifying, this relation can be approached by a voltage divider referenced to the ground between both impedances.

\[ V_{\text{out}} = \frac{Z_{\text{bio}}}{Z_{\text{bio}} + Z_{\text{elec}}} V_{\text{in}} = \frac{Z_{\text{bio}}}{Z_{\text{bio}} + 1/j \omega C_{\text{elec}}} \quad (4.4) \]

Figure 4.1 – Schematic representation of the relation between the impedance of the electrodes (Zelec), the impedance of the body part in measurement (Zbio) and the acquired signal (Vout)

Therefore, the value of Zelec should be minimized as much as possible in order to achieve high values of Vout. Considering the relation between the impedance and capacitance of a capacitor (\( Z = 1/j \omega C \)), the minimization of the value of Zelec implies the maximization of the value of electrode capacitance (Celec). Bearing in mind these issues and considering the equation 4.4, two main parameters can be
varied to guarantee high values of Celec – Electric area and electric permittivity. We improved both through appropriate design. To increase the area the electrodes were wrapped like a harmonium, effectively doubling the electric surface. To optimize the permittivity we used high permittivity materials like silicone.

5. Results and discussion
We have performed an extensive set of tests with the purpose of evaluating the performance of the design according to different parameters. These tests include sensitivity analysis, frequency response, lift-off performance and electromyographic interference.

5.1 Sensitivity analysis
Being this essentially a capacitive system, both electrode configurations should be able to detect electric field variations caused by the subject movements. It is expected that the different geometry of the electrodes lead to different sensitivities. These can be determined simply through the amplitude of signals obtained by a simple hovering hand movement at a given distance from the electrodes. This distance was kept the same. Since everything was kept the same except for the electrode geometry, amplitude differences can be attributed to geometry. Figure 5.1 shows the difference of sensibility between both systems, when the user’s hand is passed over them, approximately at 6 cm. As expected the corrugated system presented a high sensitivity to hand passages. In fact, this system presented a high sensitivity to a large number of motions, detecting some movements at distances higher than 50 cm.

In particular in figure 5.4.1 can be seen the actual ECG that was obtained by the final device previously described.
While this biopotential cannot be considered an ECG, and thus cannot be used for clinical evaluation of the heart condition, it can be used for heart rate variability assessment, physical strain and biometric identification.

5.2 Frequency response and lift-off performance
A frequency analysis was performed to understand the differences between sensitivities of both systems to different frequencies. A cupper band (2.5 cm x 15 cm) connected to a function generator was placed 4 mm above the open prototype in the middle position. Different frequencies (0.1 Hz - 100Hz) with the same amplitude (3 Vpp) were tested. Figure 5.2 shows the amplitude response of both systems for different frequencies. The corrugated system presented a higher sensitivity, especially to high frequencies. This fact is a direct result of the capacitance increase of the corrugated electrodes. A similar experimental setting was used to study the effect of the distance in both prototypes. However, in this case, the frequency was maintained constant (5 Hz), varying the distance between the copper band and source. No significant differences were observed between prototypes (see Figure 5.2). It would be expected to observe a higher sensitivity in the corrugated prototype. There is a general trend for the corrogated design to exhibit higher amplitude but the difference was lower than
we had anticipated. However, in practice we did observe much better results from the corrugated design than with the flat design as depicted in figure 5.4.2.

5.3 Electromyographic interference

One of the issues to consider in this type of systems is the interference of the electromyographic signals (EMG) from the forearm and fingers muscles. The amplitude order of these biopotentials is substantially higher, overlapping the ECG signal. For instance, for a gain of 100 and ±12V supply voltage, the amplifier went into saturation for some of the performed movements. Therefore, a methodology to subtract these signals should be considered in the next developed prototypes. Figure 5.2 c) shows the influence of the flexion and extension of the fingers in the measured signal. In this figure, it is possible to observe differences in the signals according to the type of movement performed – flexion and extension of the fingers. The system enables also to detect movements of the hand and of each finger. However, further studies have to be performed in order to understand signal patterns for each type of movement (hand and motion of each finger), enabling the application of this type of prototypes in EMG controlled systems with high potential for man-machine interfaces (MMI).

5.4 Electrocardiogram

The ECG experimental results were obtained in a static sitting position, with the sleeve wrapping the left forearm. A first prototype, without the third layer connected to the ground, was tested. In this case the system became very vulnerable to undesired body noise sources. A clean signal was obtained when the arm was deviated from the body, however when the arm is placed near the body, the QRS complex was more or less visible, presenting the same amplitude of the noise. The introduction of the third layer enabled to route the electric field lines from noise sources to ground, which enabled to acquire ECG signals with the arm near the body. In Figures 5.4.1 and 5.4.2, the ECG reading of a 24 year old male subject with no history of cardiac disorders is shown. Inspection of the graph enables clearly to identify the QRS complex. The obtained results are quite interesting, since besides the fact that these had been acquired from the forearm, no other electrode references were used. The obtained results do not allow identification of other characteristic waves, such as the P wave and T wave. This fact restricts the application of this type of systems in the rigorous study of the electric activity of the heart. However, this type of systems could be used as an ECG monitoring system both in clinic and in ambient assisted living scenarios. Moreover, it could also be applied in the analysis of biometric parameters, without the disadvantages of the usual AgCl/Ag electrodes. Once more, significant differences could be observed between both prototypes. Despite being possible to identify also the QRS complex in the flat conformation, the peaks are not so well defined.

6. Conclusions and future work

One of the main objectives was the development of an efficient yet unobtrusive system to acquire ECG biopotentials in the forearm using capacitive sensing. In order to increase the sensitivity of the
system, a new design using corrugated harmonium-like electrodes was proposed. The prototype enabled the measurement of ECG signals, resulting in a higher SNR, when compared with a similar prototype with flat electrodes. The obtained signals did not enable their application in rigorous studies of the electric activity of the heart; however, this can be applied in ECG monitoring and biometric systems without the disadvantages of the usual ECG electrodes (Ag/AgCl) or even dry electrode approaches, and without requiring wires to cross the body or to get undressed. One interesting particularity we observed while making tests to the system was the capability to isolate EMG activity from each finger. This could be used for man-machine interface systems namely the control of prosthesis, robotic arms or game play control. More work will be devoted to increase the electrical surface to physical surface ratio.

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**7. References**

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