Design of a Low-power, Low-cost ECG & EMG Sensor for Wearable Biometric and Medical Application

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***Abstract*—With the advent of IoT and growing health awareness, the applications of wearable ECG & EMG sensors have grown manifold. These applications demand the sensors to be low-cost, low-power and highly portable. These requirements put several limitations on the wearable ECG & EMG sensors design and development. This paper presents a new ECG & EMG sensor which had power consumption less than 1.65 mW (I<500 µA @ 3.3 V) and cost less than USD 10. The paper also discusses the implementation details and various testing results.**

***Keywords*— Electromyography (EMG), Electrocardiography (ECG), Wearable sensor, Wearable device, Sensor based medical application, Low power ECG, Low power EMG, Pre-gelled Electrodes, Instrumentation amplifier.**

I. Introduction

Development of wearable devices has grown so phenomenally during the last decade that it has got a new name, *Wearable Technology*. Besides its fashion quotient, it has serious healthcare applications, particularly for old age people and health freaks. The sensors used in such devices have several constraints over design and development their parameters which include wearability, portability, size, weight, longevity, ergonomics and power consumption [1]. Only after meeting these design parameters such sensors can be successfully used for continuous health monitoring in daily life [2].

Numerous ECG & EMG sensors are already available in the market. However, such sensors are either expensive or not portable. Moreover, majority of them are not based on open-source platform which is desirable to encourage their development and usability for diverse biometric and medical applications.

Over the years, various researches have been made towards the design and application of the ECG & EMG sensors. However, most of them do not satisfy criteria such as, size, operating voltage and power ratings, which are critical for wearable and battery operated applications. Further, these sensors are wire-based which are neither safe nor reliable for the wearable and portable systems [3].

This paper presents a novel approach towards the design of an analog frontend for the wearable ECG & EMG applications. [2, 4-5]. It is a single board design which uses inexpensive and readily available discrete components. The sensor captures the ECG/EMG signals non-invasively and it can send it to the ADC of a microcontroller for post-processing and analysis. This makes it a multipurpose sensor which can be used in several applications including eye blink, muscle movements and for controlling prosthesis instruments, in a cost-effective manner.

Section II presents the specifications used for designing the sensor. The details and functionality of various components used in the sensor are presented in Section III. Section IV discusses the design implementation and results of some of the experiments.

II. Sensor Specifications

The desired specifications of ECG & EMG sensor based on the requirements of various wearable applications, viz., heartbeat, eye blink, muscle movements etc. are given in Table I.

TABLE I. SENSOR SPECIFICATIONS

Parameters	Values/Range
Supply Voltage	+1.8V to +3.3V
Current Consumption	300 to 500 µA
Common Mode Rejection Ratio (CMRR)	≥ 100 dB
Gain	100-15000
Low-Frequency Cutoff	0.15 Hz
High-Frequency Cutoff	400 Hz
Weight	≤ 10g
Price	≤ USD 10

III. Sensor Description

The block diagram of the designed ECG & EMG sensor is shown in the Fig. 1.

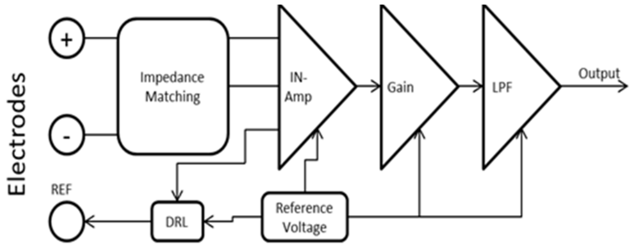

Fig. 1. Sensor Block Diagram

A. Electrodes

The ECG & EMG sensor uses electrodes to acquire the signals non-invasively. The proposed sensor uses conventional snap on pre-gelled Ag-AgCl electrodes. This sticks on the target body and provides good stability to the system while in motion. This ensures portability of the wearable device. A pre-gelled electrode also offers high SNR as it reduces the skin impedance [9].

B. Impedance Matching

An input-stage impedance matching is required to ensure maximum transfer of power from the electrodes to next stage. The proposed design uses two basic single ended passive filters for matching and to resist the flow of any bias current. It also removes the dc-offset which enables the design to achieve high CMRR. This setup also helps in setting a high gain at the instrumentation amplifier stage [1].

C. Instrumentation Amplifier

The sensor uses three op-amp instrumentation amplifiers as it offers various performance benefits compared to other configurations. This further improves our system CMRR and gain [10]. Further, to remove the common mode signal and EMI noise at 50/60 Hz from the sensor output one can also apply a fix [7] or self-tuned notch filter [2] after the output of the amplifier stage. But it also removes critical information from the signal [11]. Instead, a Right Leg Driver Circuit or DRL has been used to remove the EMI noise.

D. Driven Right Leg (DRL) Circuit

The human body can act as an active antenna capable of picking up EMI, especially 50/60Hz noise. To eliminate this noise the sensor has been designed with Right Leg Driver Circuit [12]. The DRL is the circuit [13] implemented to reduce the common mode noise staying on the skin. It also matches the body's reference potential to that of the circuit. As shown in the Fig. 1, the DRL stage receives the signal from the node of Instrumentation Amplifier's (IN-Amp) gain resistors. It can also be obtained from either the gain resistor input pins or from the input pins of the amplifier [14]. Thus the effective electrode resistance gets reduced by several orders of magnitude. This allows only a safe amount of current flow through the third electrode.

E. Gain and Low Pass Filter Stage

According to the Friis's formula for noise factor [15], noise figure increases with each cascaded amplifier stage. Therefore, two separate amplifiers, one for improving the gain and next as a low pass filter (LPF), as shown in Fig. 1 It resulted in achieving higher gain (> 100) in the initial stage only. It allowed us to keep the LPF at unity gain, thereby the linearity and performance of the LPF were maintained throughout the bandwidth. The gain stage was a simple non-inverting amplifier followed by a 2[nd] order inverting multiple feedback amplifier. We chose 400 Hz as the low pass cutoff for making the sensor system suitable for multiple applications. Fig. 2 shows the transfer function of the LPF.

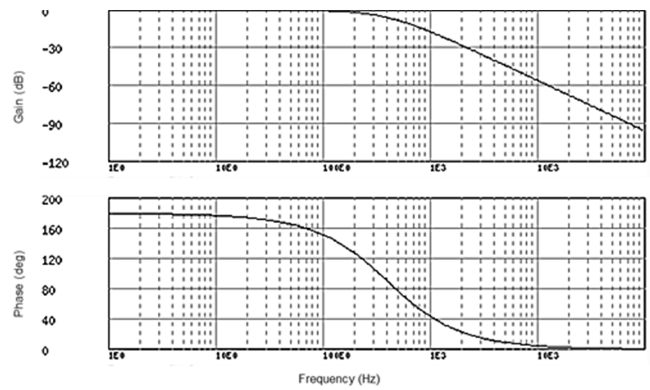

Fig. 2. Transfer Function of the LPF

In last we added a passive anti-aliasing filter just before the output of the sensor. We used total five op-amps in the entire front end, of them two were for the gain amplifier, two were for LPF and one op-amp for reference generation.

IV. Sensor Fabrication and Testing

To implement the readout circuit for the sensor, a two layer PCB was designed and fabricated. As the sensor is designed for wearable application, the size of the PCB was an important parameter. The dimension of the PCB was 59x15 mm^2. It can be reduced further by using professional tools and very small size SMD components. Fig. 3 shows the image of the PCB layout. The cost for each sensor is calculated approximately to USD 10.

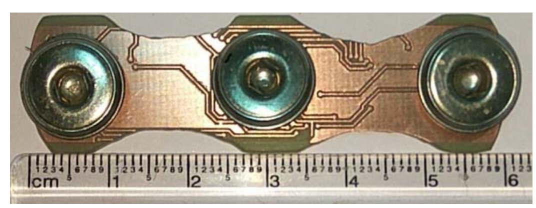

Fig. 3. Sensor Layout

In order to test the sensor and analyze its output, a test-bench was setup using the Analog Discovery 100MSPS USB Oscilloscope & Logic Analyzer of Digilent Inc. make. As per the specification mentioned in the Table I, the gain of the readout circuit was set to 11400.

Further, a basic skin preparation was done before placing the electrodes. It is a standard process to remove dead cells from the skin and to ensure a better connection between the sensor and the body.

Case 1 Sensor is not connected to the body

Fig. 4 shows the output waveform of the sensor when it was not placed on the body. The output signal was biased at the reference voltage of 1.65 V. The measured noise was 1.68 $mV_{p\text{-}p}$.

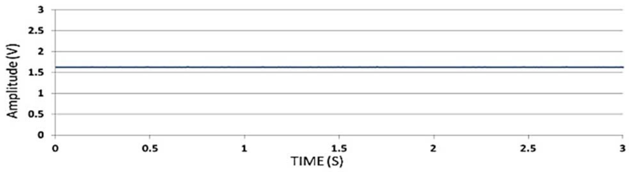

Fig. 4. Sensor's Output for unconnected leads

Case 2 ECG : Sensor placed in the middle of the chest

Fig. 5 shows the acquired ECG signal when the sensor was placed in the middle of the chest. Its amplitude is 2.30 $V_{p\text{-}p}$ biased with the reference voltage. The output clearly shows all the 6 components of the ECG, i.e., P, Q, R, S, T, U.

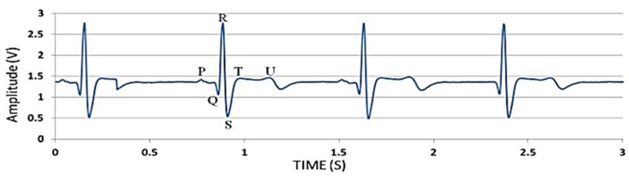

Fig. 5. Sensor's output from the chest

Case 3 EMG: Sensor placed in the middle of left forearm

Fig. 6 shows the output waveform when the sensor was placed in the middle of the left forearm. The EMG signals were acquired while moving the wrist up and down in continuous motion. The upper peaks show the event when the wrist was moved in the upward direction, while the lower peaks indicate the downward wrist movement. The EMG signals had a peak-to-peak voltage of 2.66 V biased with the reference voltage.

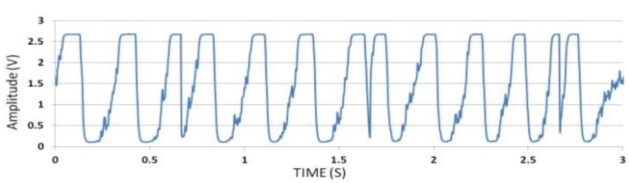

Fig. 6. Sensor's output for wrist movement when placed on forearm

V. CONCLUSION

This paper presentd a low-cost, low-power ECG & EMG sensor which could be used for numerous wearable biometric and medical applications. The dimensions of the handmade PCB for the sensor readout were 59x15 mm^2. The size of the PCB can further be reduced to 20x20 mm^2 by using small size SMD components and professional tools for fabrication. The prototyping cost of each sensor is USD 10. With a gain of 11400, the noise of the sensor was measured to be 1.68 $mV_{p\text{-}p}$. During the experimentation the sensor showed very high sensitivity, capturing and identifying even a small muscle movement quite distinctly. The estimated power consumption of the sensor, based on the components datasheet, is 350 μA. This is significantly lower as compared to the existing competing devices such as 2 channels EMG Sensor Module with EMG & EMG Envelope Output [16] or Muscle Signal Sensor EMG Module [17]. This enables the sensor to work on 3.3 V coin-cell battery for approximately 700 hours. Since the market of wearable biometric and medical applications is currently in a very nascent stage, we hope that the ECG & EMG sensor presented in this paper can open up many new opportunities for the market.

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