Wireless System for Noninvasive and Continous Monitoring of Arterial Blood Pressure

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Abstract. *This work presents the development of a wireless system for noninvasive and continuous monitoring of arterial blood pressure applied to diagnosis support and personal use. The system performs the measurement of heart rate, blood oxygen saturation (SpO2) and estimates the blood pressure. It comprises two plethysmographic sensors and a device for signal conditioning, acquisition, data processing and transmission via Bluetooth technology to a Smartphone. The received data is presented to the user by means of an Android application. System's test benches were performed and the parameters were measured for healthy volunteers. The results indicate the relationship between pulse wave velocity (PWV) and blood pressure. Based on these findings, it is discussed the pros and cons of continuous monitoring for each measured parameters.*

1. Introduction

Cardiovascular diseases (CVDs) are the major cause of death, causing about 17.5 million deaths over the world. Of these, complications of hypertension account for 9.4 million deaths worldwide every year [World-Health-Organization 2013]. Therefore, systems to monitor health stats in real time are a subject of interest.

Nowadays, all techniques to measure blood pressure (BP) can be classified according to two main factors: invasiveness and periodicity. The actual gold standard system to measure BP is the sphygmomanometer, which is a device capable of providing measurements in a discrete period, during his inflation/deflation, in a noninvasive way. Despite to accurate devices that are emerging on the market, they have not been designed for hospital use yet [O'Brien 2001], where invasive and continuous methods still predominate.

Several noninvasive techniques have been proposed to solve the problem of a wearable arterial blood pressure monitoring device. They have been presented since 1970s, when J. Penaz described a technique to measure BP directly from fingers [Boehmer 1987]. A prototype was created using the theory, known as Vascular Unload Method, linking the blood volume in the digital artery, measured using a light sensor, and the blood pressure. However, the blood volume has a nonlinear relationship with the vascular wall, which is greater in smaller arteries. This effect can be minimized by accessing a bigger artery, like the radial on the wrist. Many works were developed for the automatic noninvasive palpation using a tonometric sensor [Salo et al. 2004].

The noninvasive method for blood pressure measurement proposed in this paper is based on the correlation between the blood velocity in a peripheral artery and the arterial pressure. Measuring the pulse wave velocity (PWV) or the pulse transit time (PTT) is an issue covered by various authors, since Moens and Korteweg that proved its relation to the arterial blood pressure (ABP) [Asmar 1999]. Estimation of ABP using calibrated pulse transit time measurements derived from an ECG and peripheral PPG sensor have been built since 1996 [Franchi et al. 1996] [Chen et al. 2000] [Poon and Zhang 2005], until 2006 when a MIT research group presented a PWV measurement system based on two in-line PPG sensors [McCombie et al. 2006], as shown in Figure 1.

Figura 1. Arrangement of the PPG sensors to measure PTT.

The purpose of this paper is to describe the development of a cheap and low power system to measure PTT, according the technique shown by [McCombie et al. 2006], and experimentally demonstrate its relationship with ABP. At the same time, the chosen method allows the measurement of the SpO2 and the heart rate. The measurements are transmitted to an Android application in a smartphone. Additionally, a framework to detect local peaks from the PPG signals will be presented.

2. Materials and Methods

Sensors – Measurement of the PTT will be performed using two plethysmographic sensors, arranged above the radial artery at the wrist joint and above the digital artery of the index finger. The finger sensor shall be responsible for the oximetry and heart rate measure too.

To make it possible, the finger PPG sensor was built to have the same structure of an oximeter. This structure consists of two LEDs (infrared and red waves) and a photodiode, arranged to measure the light transmission through the finger. The difference between the amount of light that reaches the photodiode, from these two wavelengths, show the oxygen saturation in the peripheral artery. This technique was adopted by the International Standards Organization (ISO) and the European Committee for Standardization [Shang et al. 2007].

The pulse PPG sensor purpose is to trigger the measure of the PTT and hence this component only consists of one infrared LED and a photodiode. Considering the circumference of the wrist, the sensor was built to measure the light reflection from the artery. Figure 2 shows the sensing components developed in this work.

The selected components for the development of this work were the red LED VLMD31M2P1-GS08 (λ = 648nm) and the infrared LED VSML371-GS08 (λ = 940nm)

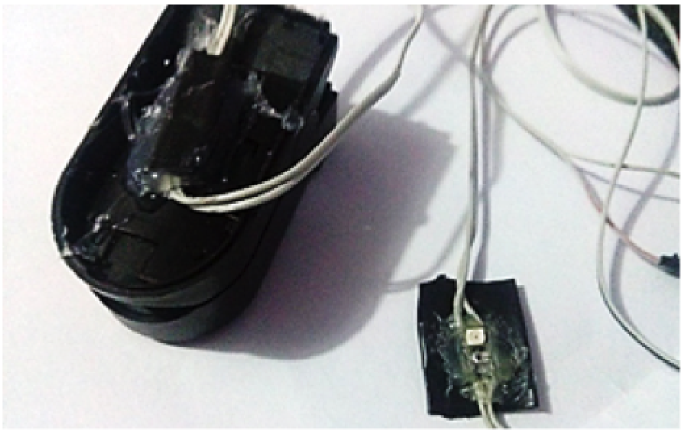

Figura 2. Finger (a) and wrist (b) sensors prototypes.

from Vishay Semicondutors and the photodiode SFH-2400 from OSRAM Opto Semiconductors. Sensors signals have been conditioned through an analog preprocessing circuit, responsible for protect them from external noise and to adjust the range for the acquisition module. This step consists of a transimpedance amplifier, bandpass filter and gain module.

The peak detector is a self-corrective algorithm developed to ignore local peaks without digital filtering. When each LED is activated, the analog circuit takes time to converge. Once the signal reaches steady state, the algorithm search for a threshold value automatically, based on the range of the signal. This value is actualized every period. Thereafter, a moving average value is compared with the previous value to determine if the signal is rising or falling. When a rising state is detected and the moving average value pass by the threshold it marks the time as a peak origin, until the signal starts to fall below the threshold.

Processing Unit – For signal acquisition and processing we choose the ultra-low power mixed signal microcontroller MSP430G2553, from Texas Instruments®, with a built-in 10-bit SAR A/D converter and 16-bit timers. The module was developed with three control clocks. The first one at 8 MHz to control the main flow of the system, the secondary clock at 4 MHz used to control the peripherals and a precision clock at 32768 Hz to time stamp.

Each measurement step was taken separately because each one have an exclusive sequence for the LEDs controlling. The system's main flow can be summarized in the following steps:

1. Measure heart rate by reading the time difference between two global peaks from the PPG signal. Only the infrared LED of the finger sensor is used in this step, given the higher signal-to-noise ratio (SNR) and range in the acquisition.
2. Read the amplitude of the PPG signals by activating first the infrared LED and then the red LED in the finger sensor.
3. Monitor a global peak in the wrist sensor signal to start the measurement of the PTT. It triggers the timer, which stops when the same peak is noticed in the finger sensor signal.

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Once the measurements were made, the processing unit packages the data and sends it through an UART interface to a Bluetooth module, which transmits data to a smartphone. An application was developed to calculate and explain the data to the user.

User Interface – The application was developed to home-users and is responsible for the system control. Users can start or stop a measurement anytime and when data are ready, the software calculates and shows the results on the screen.

By sending raw data, we save processing on the microcontroller and optimize the measurement. The post-processing can be made by the mobile devices, which has more processing power than the PU.

3. Results and Discussion

Circuit tests – Each step of the development was isolated to test and validate. Figure 3 shows the output signals from the analog conditioning circuit when the finger sensor (yellow) and the wrist sensor (blue) are active, with infrared LEDs emitting across the artery. Despite the fact of the signals are showing equal amplitudes, two different gain circuits conditioned them. It occurs because each sensing component has different transmissivity principles.

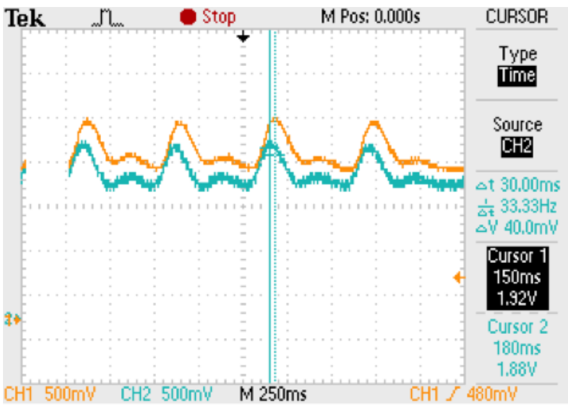

Figura 3. Output signal from finger and wrist sensors.

The amplitude of the signals depends on different physiological property like the blood density, skin color, the thickness of the skin and fat, and with the sensor position. Therefore, each time the sensor is placed on each different user, a different gain value must be set to make measurements.

Figure 4 shows the difference in the signals amplitude when the infrared and red LEDs are active with same filter and gain circuits. The light absorption at different wavelengths significantly changes in oxyhemoglobin and its deoxygenated form, allowing the determination of level concentration from the absorption ratio.

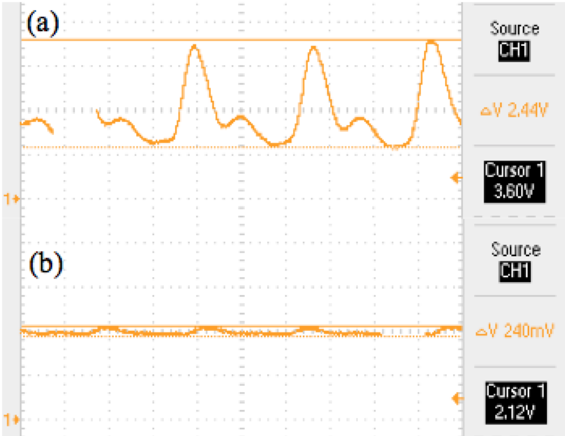

Figura 4. Signals from finger with infrared (above) and red LED (bellow).

Lastly, Figure 5 shows the peak detection response. It starts the PTT measurement when a peak is found on the wrist signal (a) and finishes the measurement when a peak is found on the finger signal (b).

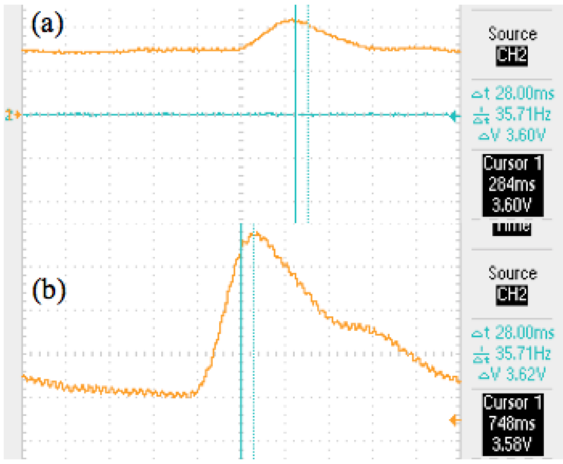

Figura 5. E-mail Peak on the wrist signal triggers the timer (above), while a peak on the finger signal stops the timer (bellow).

System evaluation – The system was tested with the author of this work. PPG waveform data was collected with the lower arm, wrist, and hand parallel to the horizontal plane resting on a rigid platform. In order to compare and calibrate, the blood pressure of the test subject was measured automatically at the same time with a Satellite JA-6002 oscillometric device. Measurements were performed with the subject relaxed and when subjected to physical exercises in order to vary the heart rate.

The relationship between the PWV and BP signals obtained during systole and diastole was calculated over a logarithm curve (Equation 1), based on [McCombie et al. 2006]:

$$k_2 = P - k_1.ln(c^2) \quad (1)$$

where c is the blood velocity and P the blood pressure. Each calibration step produces k constants, which allow the estimation during certain time.

Furthermore, the major number of references indicate that mathematical estimation method must be constantly calibrated. Moreover, the estimation is much more accurate when carried out separately for each person, since each individual has different physical and biological characteristics.

The measurement results are displayed on the developed application screen, as shown in Figure Figure 6.

Figura 6. Android application screen.

4. Conclusion

In this paper we have developed a device to measure continuously and noninvasively the heart rate, SpO2 and blood pressure. The method was based on [McCombie et al. 2006] and it uses two PPG sensors to measures peripheral pulse wave velocity to estimate BP. The finger sensor was modified to measure SpO2 by oximetry. We have shown experimentally the relation between PTT/PWV with BP. A framework for peak detection has been presented and the system components were explained.

”An experimental procedure was conducted to measure the blood pressure of the author of this work using a commercial sphygmomanometer and the proposed system. From a calibration procedure, the results obtained with the system were satisfactory. It is estimated that the cost of the implemented system is significantly lower than a commercial sphygmomanometer because it does not require a cuff, an inflation system and a pressure sensor.”

As future work, we intend to implement an automatic technique to perform automatic adjustment of the gain values in the analog circuit. ”The calibration procedure needs to be evaluated with different individuals to certify its effectiveness”. Besides, other methods to correlate the PTT with BP will be studied to exclude the calibration necessity. In addition, the developed system needs to be tested in experimental subjects with blood pressure variability in order to evaluate the accuracy and precision of the measurements.

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