A Wrist Worn SpO_2 Monitor with Custom Finger Probe for Motion Artifact Removal

Preejith SP, Akshay S Ravindran, Rohan Hajare, Jayaraj Joseph and Mohanasankar Sivaprakasam

Abstract— **Continuous monitoring of blood oxygen saturation (SpO_2) level and heart rate is critical in surgery, ICUs and patients suffering from Chronic Obstructive Pulmonary Diseases. Pulse oximeters which compute SpO_2 using transmittance photoplethysmography (PPG), is widely accepted for continuous monitoring. Presence of motion artifacts in PPG signals is a major obstacle in the extraction of reliable cardiovascular parameters, in real time and continuous monitoring applications. In this paper, a wrist worn device with a custom finger probe with an integrated accelerometer to remove motion artifacts is presented. An algorithm which can run on low power systems with processing constraints is implemented on the device. The device does continuous acquisition of PPG and accelerometer waveforms and computes SpO_2 using the proposed light weight algorithm. The measurement results are continuously synced with an Android tablet, which acts as a gateway and is pushed on to the cloud for further analysis. The accuracy in SpO_2 measured by the device was validated using Fluke ProSim 8 SpO_2 simulator and the efficiency in accurately computing SpO_2 in the presence of motion was validated over 40 healthy volunteers in a controlled setting.**

I. Introduction

From patients undergoing surgery to those in critical care units and for subjects afflicted with pulmonary disorders, pulse oximetry gives a moment by moment reading on patient stability. Continuous and non-invasive pulse oximetry is a standard and a must in critical care. Photoplethysmogram (PPG) is the most commonly and widely accepted technique as an indicator of cardiovascular status, sympathetic tone and respiration [1],[4]. Pulse oximetry is a non-invasive method which measures blood oxygen saturation and pulse rate of a human being. SpO_2 also known as blood oxygen saturation is considered as the fifth vital sign in medical community. Oxygen plays a pivotal role in the functioning of various cells in human body. Cells will be damaged if they are deprived of oxygen for a prolonged period [2].

With caregiver-patient ratio ranging from 1:4 to 1:10 monitoring high acuity patients on the med-surgical unit is a challenging task [3]. Pulse oximetry, helps in providing the big picture of a patient status and facilitates early intervention for patients with mismatched oxygen demand and supply, inside and outside critical care units. Absence of calibration, minimal operator training, and absence of warm up site preparation makes pulse oximetry the preferred choice for continuous monitoring of vitals. Society of Critical Care Medicine (SCCM) and the consortium on respiratory monitoring on the general care floor recommends continuous pulse oximetry monitoring for patients suffering from unstable airway, lung dysfunction, obstructive sleep apnea and cardiopulmonary diseases. SCCM also recommends intermittent pulse oximetry monitoring for patients on supplemental oxygen and long term mechanical ventilation for Chronic Obstructive Pulmonary Disease (COPD) [3].

In medical terminology oxygen saturation refers to the fraction of oxygen saturated hemoglobin with respect to the total hemoglobin, comprising both saturated and unsaturated hemoglobin in blood. If concentration in arterial blood of hemoglobin without oxygen (reduced hemoglobin, Hb) is N_{Hb} and that of the oxygenated hemoglobin (oxyhemoglobin, HbO) is N_{HbO}, then blood oxygen saturation level is computed as shown in (1) [2].

$$\%SpO_2 = \frac{N_{HbO}}{N_{HbO} + N_{Hb}} \times 100 \quad (1)$$

Accurate and reliable measurements of arterial blood oxygen saturation using photoplethysmography still remains an open area of research and researchers among the world face issues due to motion artifacts caused by seizures, tremors, incorrect sensor placement, presence of airgap between sensors and fingertip, incorrect probe size, dark skin pigmentation, cold hands, presence of nail polish, artificial nails and varying perfusion levels [2], [3]. Motion artifacts can drive the measurements far from their true physiological values, resulting in false evaluation about a subject's condition [4]. PPG signals fall within a frequency band of 0.5Hz to 5Hz and noise introduced by finger or hand movement and tremors fall within frequencies less than 5Hz [6]. Since the frequency spectrum of motion artifacts overlap with that of PPG signals, traditional band-pass filters are not capable of reducing the noise without causing significant signal distortion. Commercially available pulse oximeters are designed for the computation of average saturation level and pulse rate and do not employ explicit techniques to measure motion to reduce motion artifacts in PPG signals [1].

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In this paper, we present a novel method for motion artifact removal using a custom finger transmittance probe with an integrated 3 axis accelerometer. The probe is attached on to a wrist worn continuous SpO_2 monitor. Having accelerometer on the probe, at the site of measurement gives superior performance in the presence of motion thereby improving the accuracy of measurements. In the following sections, details of the wearable platform, hardware, software design, custom finger probe design, algorithm implemented for blood oxygen saturation level computation with motion artifact cancellation is presented along with results while validating the prototype under controlled environment.

II. Method and Design

A. Pulse Oximetry

Pulse oximetry uses a light emitter with red and infrared LEDs. Commonly used sites for measurements for an adult are finger, toe, ear lobe and pinna. For infants, measurements are usually taken at big toe, thumb, foot and palm of the hand. A photodetector is placed at the opposite end of the emitter to receive the light coming out of the measurement site. Pulse oximetry is based on the red and infrared absorption characteristics of oxygenated and deoxygenated hemoglobin. Oxygenated hemoglobin absorbs more infrared light and allows more red light to pass through. Deoxygenated hemoglobin absorbs more red light and allows more infrared light to pass through [5],[2].

B. System Architecture

The wrist based wearable device is capable of continuous monitoring of blood oxygen saturation level along with heart rate. The device uses transmittance photoplethysmography for computing arterial blood oxygen saturation level. It consists of a wrist worn element and a detachable custom finger probe, housing optical and motion sensors. 2 probes of different sizes are provided, to accommodate fingers of various sizes. SpO_2 and heart rate measurement algorithms run continuously on the device and the results obtained are updated on a smart phone/tablet which is wirelessly connected to the device. In addition, the results are also stored locally on the device. The wrist based wearable health monitor along with smart phone/tablet interface and custom probes is shown in Fig. 1.

C. Custom probe design

A cross sectional view of the custom probe used for computing blood oxygen saturation level is shown in Fig. 2. The probe is made of medical grade silicone rubber and was designed ensuring minimal air gap between the finger, LED and photodetector. A dual wavelength common anode LED with wavelengths around 660nm (red) and 910nm (infra-red) and a three axes accelerometer is placed on the top section of the probe such that the LED comes directly on top of the nail. A photodetector with an active area of $16mm^2$ and a spectral peak around 850nm is placed at the bottom section of the probe. The probe is terminated using a custom 10 pin connector and is attached on to the wrist piece of the wearable health monitor. Housing the accelerometer on the probe helps in capturing motion at the site of measurement.

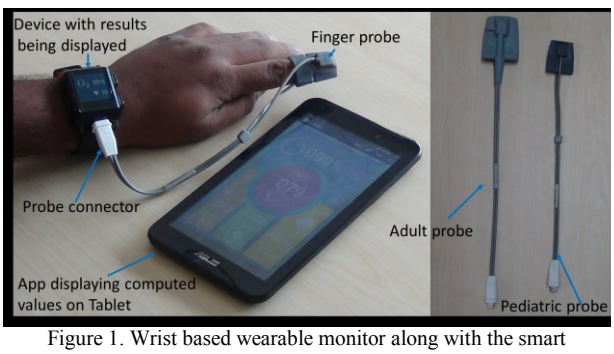

Figure 1. Wrist based wearable monitor along with the smart phone/tablet and custom probes

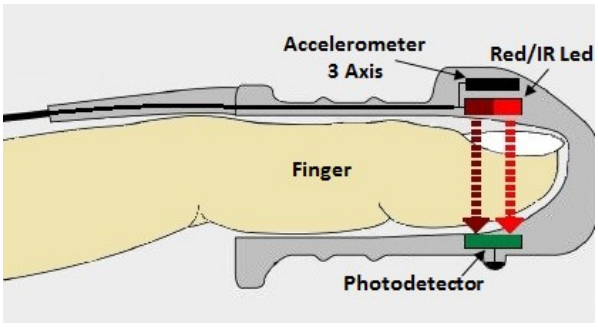

Figure 2. Custom probe design

D. Hardware Design

The system level block diagram of the wrist based wearable health monitor is shown in Fig. 3. A low power consuming 32-bit ARM cortex M4 microcontroller controls the overall functioning of the device. The wearable device is powered by a 200mAh Li-Po battery. The device communicates with external world using a custom android application running on the smart phone/tablet. The system architecture can be divided into two sections namely finger probe and processing unit. Finger probe contains the PPG sensor & LEDs and a three axes accelerometer for motion artifact removal. The processing unit comprises of the ARM core and analog front end. LED driver circuit switches between RED and IR LEDs to generate the PPG signals. Intensity of LEDs are adjusted with the help of a PID controller implemented in firmware. The amount of light reflected from the finger is sensed by the photodetector and the trans-impedance amplifier converts the reverse current generated by the photodetector to voltage. This voltage level is measured by the internal ADCs and blood oxygen saturation level is computed using the algorithm mentioned in the next section.

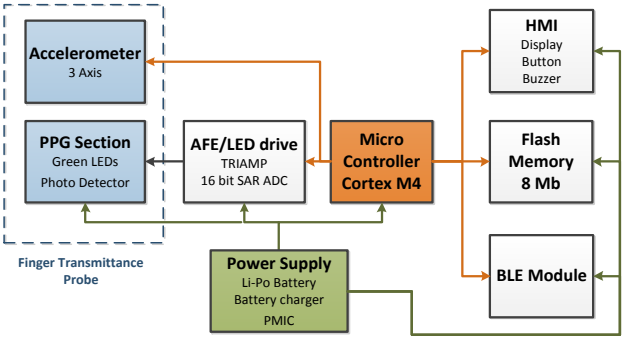

Figure 3. Hardware block diagram

E. Software Design

A custom Android application that runs on the gateway(tablet), controls the wrist based finger SpO_2 monitor, collects measurement results and pushes the data to the cloud. SpO_2 measurement is triggered by the user from the tablet interface or can be automated by programmatically setting the desired measurement frequency. In user initiated mode, the application sends a request to the device which triggers the measurement and the result is updated on the tablet.

F. Algorithm

The algorithm used for SpO_2 computation is depicted in Fig. 4. The algorithm can be subdivided into 8 major sections.

1) Sensor placement check

Proper placement of the finger probe is critical for an accurate arterial blood oxygen saturation level computation. The LEDs should be placed on top of the finger nail and there should be minimal airgap between the sensor and finger.

2) Setting intensity using PID controller

The intensity of LEDs is controlled with a PID controller implemented in firmware. PID based intensity adjustment helps in tuning AFE for any skin complexion.

3) DMA based signal acquisition

PPG and acceleration signals are acquired simultaneously with the help of DMA. PPG signals are acquired at a sampling rate of 125 samples per second (Sps) for both RED and IR. Accelerometer signals are captured at 12.5 sps per axis. Data is collected for a duration of 10 seconds.

4) Ambient light cancellation

Ambient light component from both RED and IR are removed and an anti-aliasing second order Butterworth low pass filter with 5 Hz cutoff is applied on to the raw waveforms.

5) Removal of baseline wandering

Baseline 'B' is computed by applying a moving average filter of window size 150 samples on the signal 'S'. Baseline wandering removal can be represented as (S-B + mean (B)).

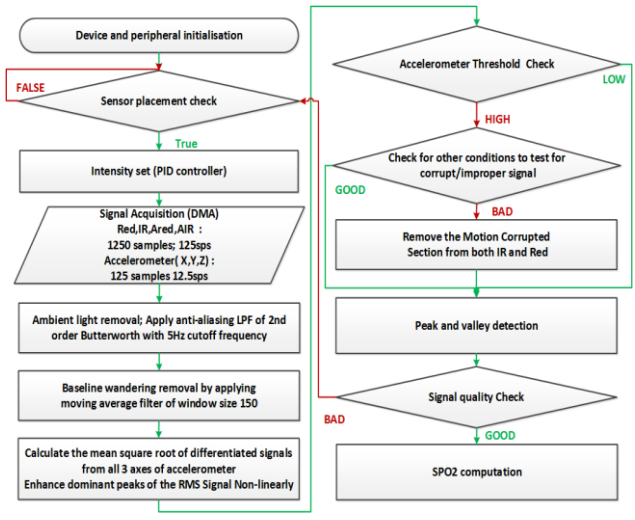

Figure 4. Algorithm Flowchart

6) Motion artifact removal

The accelerometer data from the three axes are differentiated and root mean square value is computed. The obtained signal is then squared to enhance dominant peaks non-linearly. The acquired signal is compared with respect to a pre-defined threshold, to identify and remove motion corrupted sections.

7) Signal quality check

The respective peak and valley points of the motion artifact free PPG waveforms are identified. The signal is segmented into different cardiac cycles and different parameters like (a) Relative position of peak in the cardiac cycle; (b) Relative position of IR and red valleys with respect to each other; (c) Valley to peak height and (d) Relative peak and valley position are computed. Signal quality is estimated from these parameters using a proprietary algorithm.

8) Blood oxygen saturation level computation

R is computed from DC (non-pulsatile) and AC(pulsatile) values for both IR and RED signals as shown in (2) [6].

$$R = \frac{\text{ACr} \times DCir}{\text{DCr} \times ACir} \tag{2}$$

SpO_2 is computed from R using (3). The constants K_1, K_2 and K_3 were computed from the R curve obtained from Fluke ProSim 8 SpO2 simulator.

$$SpO_2 = K_1R^2 + K_2R + K_3 \tag{3}$$

where, $K_1 = -10.09$, $K_2 = -19.52$, $K_3 = 111.4$

III. Tests and Results

The efficiency of the proposed algorithm in accurately measuring SpO_2 values ranging from 80-100, was analyzed using IR and red PPG waveforms generated using Fluke ProSim 8 SpO_2 simulator. The experimental setup used is shown in Fig. 5. Data was collected for 10 seconds for each increment in SpO_2 value from 80 to 100. Data was collected for heart rates of 50bpm, 100 bpm and 150 bpm to validate the fact that accuracy of computed SpO_2 is independent of heart rate. SpO_2 was computed over the data collected using the proposed algorithm and the results obtained are represented in Fig. 7.

Figure 5. Test Setup

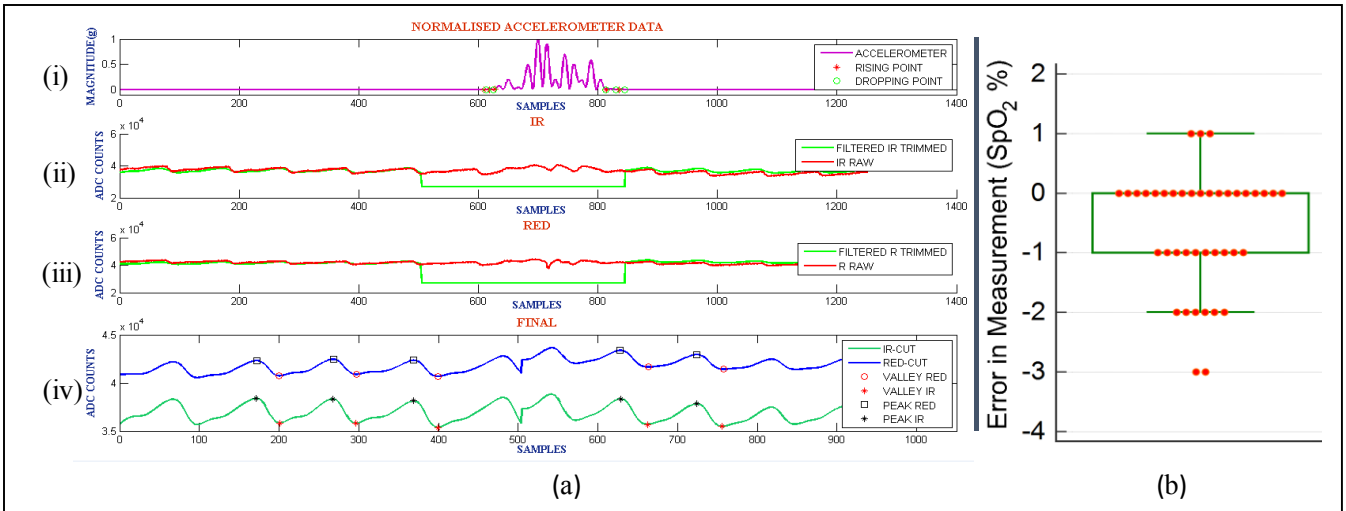

Fig. 6(a). (i) Accelerometer final waveform with onset and offset threshold points marked (ii) Raw and filtered Red waveform with trimmed section (iii)Raw and filtered IR waveform with trimmed section (iv)Final waveforms-peaks and valleys of the sections used for SpO_2 computation are marked. 6(b). Box and whisker plot representing error in mean SpO_2 from the device value when compared to the reference measurement

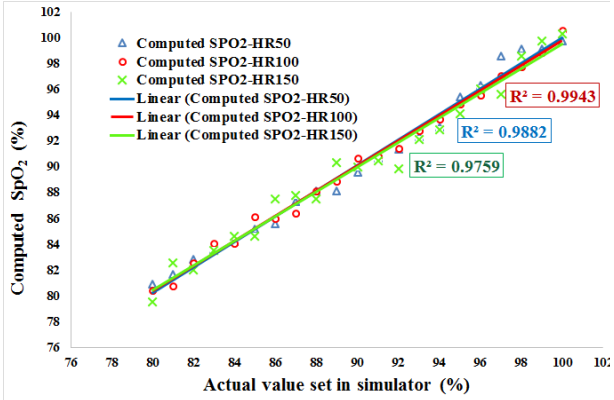

Fig.7. Validation of SpO_2 values obtained over different heart rates

To validate the efficiency of the proposed modality in the presence of motion, an experiment was carried out in a controlled setting. 40 volunteers including 23 men in mid-20s were asked to wear the device for 5 minutes and were instructed to carry out different aperiodic & periodic motions using hand, wrist and finger. Volunteers were instructed to avoid vigorous movements. A sample segment in the data collected and the operation of the algorithm is represented in Fig. 6(a). The mean and standard deviation of all the SpO_2 values generated per volunteer over the 5-minute duration was computed. A reference SpO_2 measurement was taken for each volunteer using Masimo Radical 7 Pulse oximeter, in the absence of motion. Fig. 6(b) represents the data obtained from the experiment using a box and whisker plot and shows the error in mean SpO_2 value when compared to the reference measurement, for each volunteer. The top of the box represents the median and the upper quartile. The bottom of the box indicates the 25th percentile which represents the lower quartile. The ends of the whiskers represent the lowest datum still within 1.5 IQR (Interquartile Range) of the lower quartile, and the highest datum still within 1.5 IQR of the upper quartile.

IV. Conclusion

A novel method to address the problem of motion artifacts in wearable SpO_2 monitors is presented. A wrist worn device with a finger probe assembly which can continuously measure SpO_2 by eliminating motion artifacts using accelerometer data was developed. An Android application was developed to interact with the wearable device and sync the results on to a cloud server. The accuracy of the device in measuring SpO_2 values in the range 80-100 was validated using a Fluke ProSim 8 SpO_2 simulator. The efficiency in eliminating motion corrupted signals was also validated in a controlled setting on 40 healthy volunteers. A large scale clinical validation to assess the accuracy of the device in measuring SpO_2 values from 80-100 in critically ill patients with low SpO_2 levels is being planned in an ICU setting.

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