Photometry based Blood Oxygen Estimation through Smartphone Cameras

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ABSTRACT

We introduce a lightweight, cost-effective, and portable solution for real-time peripheral oxygen saturation (SpO_2) measurement using photometric sensing through a smartphone's camera. Specifically, we design a hardware plug-in module that snaps onto the smartphone's flashlight and estimates the blood oxygen content from the light intensity reflected off the user's finger and registered on camera images. The oxygen levels are mapped to equivalent photoplethysmography (PPG) signals used for the SpO_2 estimation using a machine learning based one-time calibration. With the knowledge that blood oxygen largely responds to Infrared (IR) and Red wavelengths, state-of-the-art pulse oximetry techniques use IR and RED light emitting diodes and photodetectors to sense each channel. We further develop a novel solution that exploits the IR leakage of the LED white light of the smartphone. The system is incorporated with a hardware of IR and RED filters that are spatially separated such that the respective signals are registered on independent areas of the image sensor. We present the preliminary results and analyse possible challenges for further improvement.

1 INTRODUCTION

Human life relies on the oxygen level in the blood. Normally, a small fraction of molecular oxygen transported by hemoglobin is dissolved in healthy people's blood. Hence, assessing oxygen saturation (SpO_2) – the fraction of oxygen-saturated hemoglobin relative to total hemoglobin – is critical to indicate the health status of human brain, heart, and respiratory system. Referred to as peripheral oxygen saturation (SpO_2), pulse oximetry is a common physiological measurement of SpO_2 in both in-hospital environment and at in-home healthcare. Such the SpO_2 monitor is done using a non-invasive pulse oximeter by emitting light at specific wavelengths into an area of the body (e.g. finger, toe, earlobe, etc.). While FDA-approved pulse oximeters provide a reliable SpO_2 level, they have a number of short comings including (1) high price, (2) large probe, (3) ill-fitting finger, and (4) external device carry requirement.

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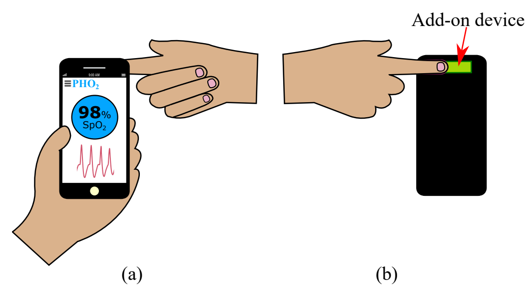

Figure 1: System in use viewed from (a) the front and (b) the back

Recently, mobile applications for SpO_2 estimation have been widely deployed and address those problem in different ways. Existing work commonly made use of build-in flashlight and camera on smart phones to predict the oxygen level. Particularly, users touch their finger on the camera surface to capture the reflected lights coming from a particular light source. On the other hand, users can simply carry their smart phone installed with the MoveSense app while walking. By analysing their walking gait, this app can passively predict their SpO_2 level. However, all of them provide a low accurate SpO_2 level that is absolutely not intended for use with medical quality.

This work proposes a novel practical oxygen saturation sensing system, shown in Figure 1, which has the potential to accurately provide the SpO_2 level. In details, the system includes an add-on containing multiple filters and clapped to the smart phone as simply as using a phone case. By leveraging the advancement of 3D printing technology, the add-on is really low-cost and lightweight. Due to limitations of camera hardware, the reflected light captured by the device needs to be further processed to obtain usable PPG signals.

[1] MoveSense app: https://goo.gl/ePmr1c.

Thus, our system takes the recorded frames and processes to acquire a clear PPG signal. The high-quality signal is finally input into a non-linear calibrated model to obtain the SpO_2 level.

Challenges. The system design addresses the following challenges.

- In existing apps, color channels have been used to substitute for the use of LED Red and Infrared lights in commercial pulse oximeters. Even though such applications bring a simple design to the hardware, their accuracy is not high due to a short distance among visible wavelengths. This phenomena can be reasonably explained using a relational graph between the SpO_2 and the choice of light sources [1]. Accordingly, our main goal aims at keeping one in the range of Red and pushing the other closely to Near-Infrared. Thought that the problem can be solved by adding multiple LEDs to the front or back of the smartphone [4],it, however, seems to be displeasing where it will cost an amount spent for extra components.
- The second problem arises when people sometimes place their finger outside the camera region. As a result, the average intensity includes non-pulsatile pixels that possibly increases the prediction error. In addition, mobile devices nowadays come with various designs for the camera and technical implementation for its lens integrated in the image sensor and the flashlight.
- Recall that the absorption ratio is calculated following the change of oxygen hemoglobin in the circulation corresponding to the minimum and maximum extrema in the PPG signal. Diacrotic notch, on the other hand, is a certain stage in the circulation system that can cause a sudden closure of aortic valve to produce an almost flat region in the middle of cycle. Despite of the short period of this phase, it still accumulates to the prediction error. Therefore, it should be profoundly removed also with other possible noise and distortion.

We make the following contributions in this work:

(1) Designing and printing the pre-form of a 3D prototype that can easily snap to the phone's back as an add-on device.
(2) Deriving and implementing a number of algorithms to accurately estimate the SpO_2 level. In this model, we integrate an adaptive control over the camera, a flexible computation of PPG signal, and a dual calibration of SpO_2 estimation model.
(3) Conducting a preliminary evaluation of proposed system regarding its performance and the capability to integrate to existing device.

2 SOLUTION AND SYSTEM OVERVIEW

Our system design, which aims to extract the Red and IR from a white light using a 3D add-on, is efficient in term of time alignment and wavelength specification.

Spatial modulation: Light rays from flash-light bounce off our finger and penetrate through the filters set in front of camera lenses. The goal of our mounted camera add-on is to (1) assist the reflected lights toward the camera lenses (2) extract explicitly the IR and Red at the same time stamps. The add-on component not only limits the range of wavelengths but also assists the lights not to be off the camera lenses region, which is the main cause in the reflectance mode.

Raw PPG acquisition based adaptive ROIs: Under our specific screen division, trivial adaptive regions selection such as intensity based [3] or taking the image centres are inadequate. Therefore, we are motivated to use a spatial sliding window which satisfies (1) spatial stability and (2) strong temporal variation. While spatial stability represented by the variance of intensities, the second condition estimates the variance of average intensities in one specific amount of time. Shifting a window by one to another pixel and estimate these statistical parameters would not be computationally efficient due to the overlapping patches. Therefore, to avoid this kind of recalculation issue, we approach to use the Integral Image with a suitable modification of the mean and variance calculation. The output PPG undergoes a linear phase filter that helps to remove unwanted frequencies except heart rates . A window size is chosen as 6 seconds as sufficient to gain enough number of peaks and troughs for estimating values R. In each window, a dicrotic removal refines the location of local extrema by cleaning all the parts of dicrotic. Those problems coming from light scattering, image intensity versus real-intensity can be handle through a calibration at training.

Non-linear calibration: In our opinion, the SpO_2 should follow the Beer-lambert equation. The values of absorption parameters are predicted through a non-linear regression model.

In general, our system consists of 4 main stages that processes the raw signal, camera frame, to predict oxygen level.

(1) Extracted PPG signals from Red and IR filter are denoted as s_r and s_{ir}. Each point t in PPG signal is calculated by the mean value at frame t of specific channel.
$$s_r(t) = \mu(InpVid\{U_r^t, t\})$$
$$s_{ir}(t) = \mu(InpVid\{U_{ir}^t, t\})$$
with $t = \overline{1, T}$ and U denotes for the region of interests in specific time.
(2) A bandpass filter is utilized to remove components that are not related to the pulsatile signals. We define the signal frequencies are from 40 bpm to 230 bpm following the range of human heart beat.
(3) Dicrotic notch is the natural factor that appears in the shape of PPG signal. Absorbtivity ratio is an estimation between the local peak and trough, which the dents along signal can distract our measurement. According to the nature property of dicrotic which has the length or dircortic parts them-self compares to the true local maxima and minima. Obviously, the distance of two successive max and min in dicrotic component is much smaller than that of the real local extremes. Therefore, by sorting all the distance between two consecutive peaks and troughs and looking for the points where the abnormal change occurs, we can remove all the local extremes from the beginning up to this point as considered to be dicrotic parts.
At this stage a sliding window is used to segment the signal into small chunks and predict the oxygen saturation in each of them.
(4) AC (I_p) and DC(I_b) component of each channel (wavelength) is obtained using the corresponding standard deviation or

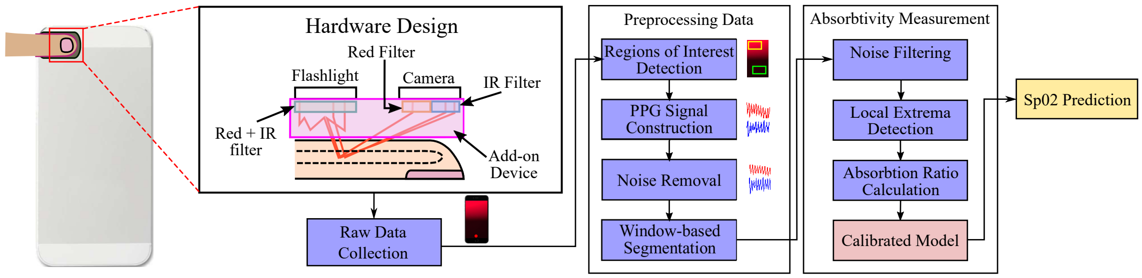

Figure 2: Overall system design and architecture of measuring Sp02 with dual filters.

(difference of max and min value) and mean of each ppg signal. After that, we can receive the absorptivity ratio using

$$R = \frac{AC(s_r)/DC(s_r)}{AC(s_{ir})/DC(s_{ir})}$$

(5) The intensity of light can be referred to the number of photon perceived per a unit area. Theoretically, it should be dependent on wavelength, but, due to the Quantumn Efficiency which defines the percentage of photons can be successfully converted. Specifically, lights penetrates differently on the depletion layer of Charges Couple Device (CCD) or Complementary Metal Oxide Semiconductor (CMOS) according to their wavelength. Therefore, a calibration procedure is needed to compensate the degradation. In practice, the coefficients are non-linear calibrated with ground truth data to suit with different camera models.

3 IMPLEMENTATION AND RESULTS

We build a 3D printed add-on with specific features that are suitable for most of the common models. Solid Work is applicable to persuade our work for different pre-sketched phone models. We then manipulate the form of our device so that it can capture a clean pulsatile waveform by introducing a light-guiding component to improve the beam focus and reduce scattering. Secondly, user-targeting ease of usage and diversity is another issue that our design should take care off. Basically, the thickness of that add-on should be qualified enough to leave space for lights to bound off from our finger and lands on the camera lenses but still be pocketable. 3D printers now become popular in terms of giving a quick overview of actual model and detailing small items such as our add-on module. With that benefits, our first prototype is produced and is illustrated in Figure 3 for evaluation.

Three types of filters are utilized into our design for different purposes. The red component from the white light is extracted by the dark color red film filter. On the other side, the negative film is integrated to cancel out all the visible components and only let the IR go through [2]. The third component is an optical glass filter to gather the light from only a certain range of wavelength (less than 1200 nm). We perform the evaluation of our device using Matlab version 2013 equipped with Image and Signal Processing toolbox.

Subject for evaluation is assisted to deliver a set of recording sequences using four Samsung Galaxy S4. The time stamp between the ground truth obtained from qualified pulse oximeter and our devices is monitored and matched according to the information

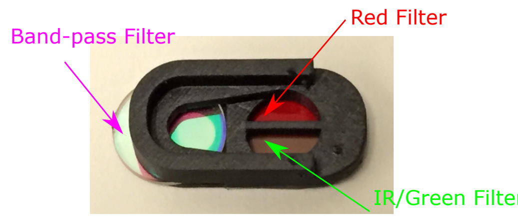

Figure 3: A 3D print add-on for Samsung Galaxy S4.

from a hand-held digital camera. In specific, ground truths are collected from the Accumed pulse oximeter - NELLCOR PM10N at the same time of recording mobile devices. We maximize the exposure level to obtain the information of IR channel. The subject need hold their breath to reduce the oxygen level while recording. Figure 4 demonstrates our system performance by predicting the

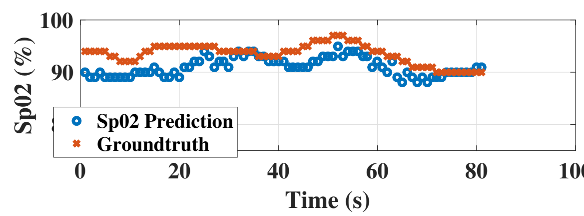

Figure 4: Prediction of oxygen level comparing with the ground truth.

level of oxygen with the mean of error rate is 4%.

4 APPLICATIONS AND DISCUSSION

Motivated by the limitation of current system regarding wavelength selections and light guiding, we introduce a spatial divider as an add-on. We present end-to-end system structure with a preliminary result. We are working on deploying the system on smart phone for real-time processing instead of using Matlab.

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