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Detection of the Optimal Region of Interest for Camera Oximetry

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Abstract— **The estimation of heart rate and blood oxygen saturation with an imaging array on a mobile phone (camera oximetry) has great potential for mobile health applications as no additional hardware other than a camera and LED flash enabled phone are required. However, this approach is challenging as the configuration of the camera can negatively influence the estimation quality. Further, the number of photons recorded with the photo detector is largely dependent on the optical path length, resulting in a non-homogeneous image. In this paper we describe a novel method to automatically detect the optimal region of interest (ROI) for the captured image to extract a pulse waveform. We also present a study to select the optimal camera settings, notably the white balance. The experiments show that the incandescent white balance mode is the preferable setting for camera oximetry applications on the tested mobile phone (Samsung Galaxy Ace). Also, the ROI algorithm successfully identifies the frame regions which provide waveforms with the largest amplitudes.**

I. INTRODUCTION

Photoplethysmographic imaging is the recording of a pulse wave using an imaging array. It has recently gained attention within the mobile health research community as it allows the recording of heart rate with a mobile phone [1], [2]. Instead of connecting peripheral sensors to the mobile phone [3], photoplethysmographic imaging has the advantage that no additional hardware other than a camera and LED flash enabled mobile phone is required for the measurements (Fig. 1). Two different approaches for photoplethysmographic imaging have been suggested. In the contact approach the tissue is placed on the camera lens and LED [1], [4], [5]. The second approach requires no skin contact and is solely based on measurements of skin color changes [6]–[8]. In this manuscript, we will focus only on the contact approach when applied to camera oximetry. Camera oximetry is the estimation of the blood oxygen saturation (SpO_2), an additional vital sign, with the photoplethysmographic imaging technique.

The underlying measurement principle of photoplethysmographic imaging and camera oximetry is similar to the one in the well-established pulse oximetry: A light source illuminates blood perfused tissues with a known spectrum and a photo detector records the photons that passed through the tissue and were not absorbed or scattered away from the sensor. Beer-Lambert's law stipulates that absorption of a photon in a given medium is based on the wavelength of the photon, tissue composition and distance traveled. Since the optical path of the photons and consequently the total absorption changes with each heart beat due to an increase in blood volume, the number of photons hitting the sensor also changes. The recorded variation of light intensity is the photoplethysmogram (PPG) which allows accurate estimation of the heart rate. For the estimation of SpO_2 a second PPG is necessary. This is made possible by illuminating the tissue with two distinct wavelengths alternately. The wavelengths (typically in the red and infra-red (IR) spectrum) are chosen in a way that the absorptive properties of O_2-saturated hemoglobin (HbO) are the inverse of non-saturated hemoglobin (Hb). This produces two distinctive PPGs, one for each wavelength. The pulsatile (AC) and constant (DC) components of the two PPGs are compared and the ratio R of the AC/DC ratios are calculated as

$$R = \frac{AC_{\lambda 1}/DC_{\lambda 1}}{AC_{\lambda 2}/DC_{\lambda 2}}, \quad (1)$$

where $\lambda 1$ and $\lambda 2$ are the wavelengths of the light sources [9]. R can be calibrated against invasively measured arterial saturations and a lookup table or function provides the SpO_2 reading for any given R. This same principle has also been applied to mobile phone cameras and other complementary metal-oxide-semiconductor (CMOS) cameras in theory [2], [6] and practice [5]. The red and blue color channels of the captured video are extracted and used to calculate two PPGs. These PPGs are then used to calculate the ratio R as described in (1). Using the blue instead of the IR channel is possible because the absorptive properties of Hb and HbO in the blue are similar to that in the IR spectral range [2].

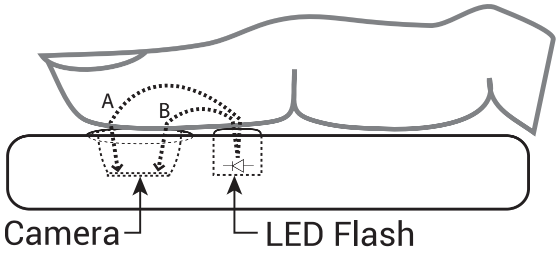

Fig. 1. Typical setup for contact Photoplethysmographic imaging. A finger is placed on the mobile phone camera and continously illuminated using the integrated LED flash. Photons with longer optical path lengths (A) will be more attenuated than photons with shorter path lengths (B).

We have previously described the challenges that emerge from integrating pulse oximetry on a mobile phone camera [2]. For example, the configuration of the camera can negatively influence the calibration settings. Another disadvantage

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is that blue photons travel less in human tissue than red photons. The light source for the illumination of the finger is on the same plane as the sensor (often referred to as reflectance pulse oximetry). The result is unequal path lengths traveled by the photons hitting the sensor (Fig. 1). Since the number of photons decreases with traveled distance, the camera pixels are illuminated non-homogeneously. Consequently, not all pixels are equally well suited for generating a PPG. This effect is stronger for blue photons that are absorbed more by tissues and travel on average less distance. As a result, pixels that require longer optical paths will record less photons and blue photons will be more rare than red. For pulse oximetry applications, it is important to have a strong signal for both wavelengths, as reliable estimation of SpO_2 at high signal-to-noise ratio is desirable. This is generally achieved with high amplitude signals.

The best signal-to-noise ratio can be obtained when the AC to DC ratio of the PPG is large. This ratio tends to be larger with larger AC, as the DC component is dependent on tissues and can be considered constant. A higher AC is achieved with increased perfusion of the finger and the selection of an optimal light path length. Perfusion of the subject cannot be influenced and other parameters such as the region of interest (ROI) need to be modified to get a large AC component. In addition to the selection of the optimal ROI, correct configuration of the camera is necessary to avoid attenuating the already weak blue color channel. With mobile phones, the configuration possibilities for the camera are limited and therefore, the selection of the white balance setting is an essential option for pulse oximetry applications.

In this paper we describe a novel method to automatically detect the optimal ROI of the captured image. We also present a study for choosing the optimal camera settings, notably the white balance. The experiments presented are necessary to achieve the best possible signals for subsequent SpO_2 estimation. The white balance and ROI selection are developed and validated using video recordings obtained from experiments specifically designed for this purpose.

II. METHODS

A. Data Collection

Two minute videos of right index fingers of 6 healthy subjects were recorded using a Samsung Galaxy Ace phone camera. The distance between the integrated LED flash and the center of the camera was 8.8 mm. The LED flash was a standard InGaN-based LED with the emission spectrum shown in Fig. 2. This phone model was running the Android 2.3.4 operating system which offered 8 different white balance settings: auto, incandescent, fluorescent, warm fluorescent, shade, twilight, daylight, and cloudy daylight. The videos were saved in 240x320 pixels resolution (QVGA) and the ”mp4” format to minimize processing load since the PPG application does not require a high resolution. The video sampling rate was 24 Hz.

The subjects' age ranged from 20-35 years and their skin color ranged from II to IV on the Fitzpatrick Sun-Reactive Skin Types scale [10]. The recording procedure was as follows: A custom developed software application called OxiCam was launched and the subject finger placed on the camera. Once the finger was reliably placed on the camera and the placement was correctly detected [11], the study operator pressed the recording button. The recording was automatically stopped after 2 min. This was then repeated with all white balance settings except auto. After 3 subjects, it became clear that the twilight, warm fluorescent, cloudy daylight, daylight, and shade white balance modes would not contribute to the PPG extraction in the blue and red channel together and were discontinued from further recording. The videos were imported to Matlab for algorithm development and the Red-Green-Blue (RGB) video formats were used for further processing.

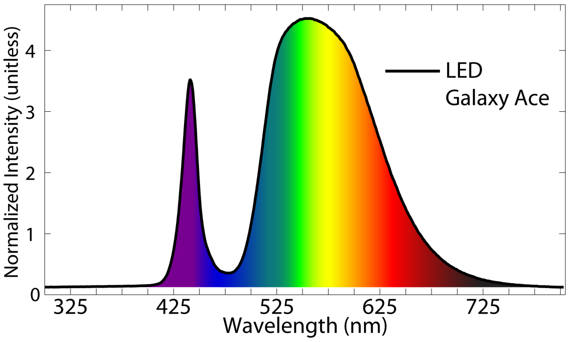


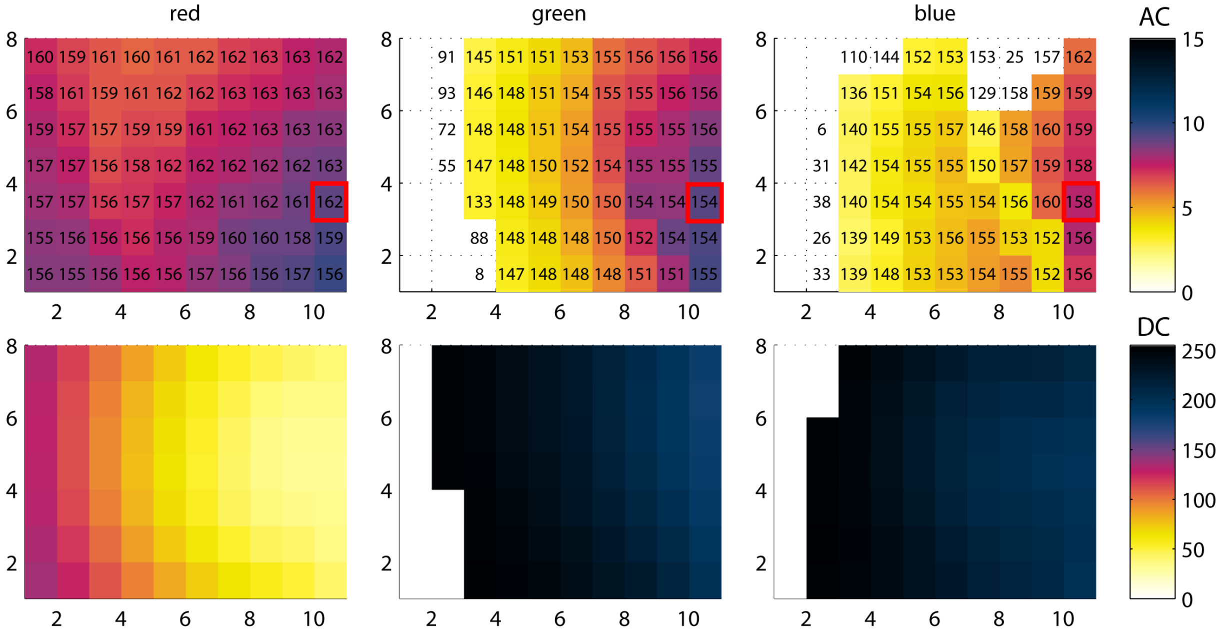
Fig. 2. Emission spectrum of the InGaN LED on the Samsung Galaxy Ace phone. Measured with an Ocean Optics USB2000+UV-VIS spectrometer.

B. Video Processing

Each video frame was split into the three color channels (RGB) and 30 x 29 pixels large ROI, resulting in 3 x 88 channels. The mean value of pixel intensity for each channel was then calculated. The mean intensities of each channel were summarized in a time series resulting in 3x88 independent PPG waveforms per recording. Each PPG was processed individually with the incremental-merge segmentation (IMS) algorithm that has been previously developed for the robust and efficient extraction of beats from the PPG [12]. The IMS algorithm segments the PPG into individual beats by combining small line segments with similar properties. The obtained segments constitute features that characterize a typical PPG pulse with systole and diastole. The principal segment, the upslope between diastole and systole provided the main features such as amplitude (AC) and baseline (DC) component of the pulse. The number of beats, the median AC and median DC for each channel were calculated. These statistics were calculated for the full 2-min recordings and for the first 5 pulses of each recording.

C. Analysis

To determine the best white balance setting, we compared the calculated median AC and the median DC for each ROI and color channel. The white balance mode offering the highest AC for blue and red as well the largest amount of active ROI was then selected. To determine the best ROI, the



red:

160	159	161	160	161	162	162	163	163	162
158	161	159	161	162	162	163	163	163	163
159	157	157	159	159	161	162	163	163	163
157	157	156	158	162	162	162	162	162	163
157	157	156	157	157	162	161	162	161	162
155	156	156	156	156	159	160	160	158	159
156	155	156	156	156	157	156	156	157	156

green:

	91	145	151	151	153	155	156	156	156
	93	146	148	151	154	155	155	156	156
	72	148	148	151	154	155	155	155	156
	55	147	148	150	152	154	155	155	155
		133	148	149	150	150	154	154	154
		88	148	148	148	150	152	154	154
		8	147	148	148	148	151	151	155

blue:

		110	144	152	153	153	25	157	162
		136	151	154	156	129	158	159	159
	6	140	155	155	157	146	158	160	159
	31	142	154	155	155	150	157	159	158
	38	140	154	154	155	154	156	160	158
	26	139	149	153	156	155	153	152	156
	33	139	148	153	153	154	155	152	156

Fig. 3. Distribution of median pulse amplitude (AC) and median pulse baseline (DC) over the frame for red, green and blue channel of a sample recording with incandescent white balance setting. The ROI size is 30 x 29 pixels. Numbers on ROIs in the first row indicate the number of pulses detected by the incremental-merge segmentation algorithm. The square indicate the selected ROI. The LED position was on the right of the frame.

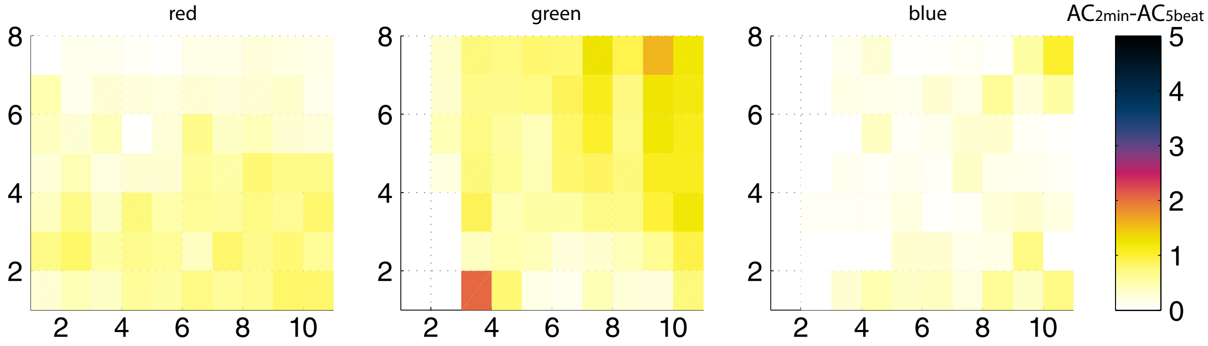


Fig. 4. Distribution and intensity of the difference between median pulse amplitude of the full video recording (AC_{2min}) and median pulse amplitude of the first 5 beats (AC_{5beat}).

TABLE I

AMPLITUDES FOR DIFFERENT COLOR CHANNELS AND WHITE BALANCES (MEDIAN (MIN - MAX) / MEAN NB. OF USEFUL ROIS PER FRAME)

White balance	nb. cases	Red	Green	Blue
incandescent	6	5.94 (2.98-10.03) / 88	5.01 (2.43-12.59) / 68	3.70 (2.35-8.49) / 44
fluorescent	6	5.17 (3.03-7.81) / 71	3.61 (2.66-5.86) / 8	2.91 (2.40-3.60) / 7
shade	3	4.21 (0.40-7.01) / 66	3.22 (0.63-7.24) / 7	N/A / 0
twilight	6	3.01 (2.03-10.34) / 67	4.14 (2.03-9.47) / 11	3.49 (0.09-6.33) / 10
daylight	3	2.85 (2.42-4.20) / 25	N/A / 0	N/A / 0
cloudy daylight	3	2.39 (2.34-2.64) / 9	N/A / 0	N/A / 0
warm fluorescent	3	2.93 (2.44-4.07) / 76	2.65 (2.38-2.97) / 12	N/A / 0

AC amplitudes of the 88 blue channels were compared and the channel with the maximal AC was selected.

III. Results

Four of the 7 tested white balance modes (warm fluorescent, cloudy daylight, daylight, and shade) showed strong saturation of the red channel for most ROI and only very week amplitudes for the blue channel (<1 unit), which was insufficient to detect pulses. Consequently, only the incandescent, twilight and fluorescent modes were recorded from all subjects. Incandescent was found to be the only white balance setting with reliable detection of the blue waveform over a larger area of pixels (Table I, Fig. 3) and over all recordings. Fluorescent and twilight modes showed potential for recording blue PPGs, but the blue waveform was not consistent over all recordings and subjects (Table I).

The difference between median amplitude of the whole 2 minute recording and the first 5 beats was negligible (Fig. 4). It is therefore sufficient to determine the ROI at the beginning of the recording after the finger is placed on the sensor.

IV. DISCUSSION

We have developed a novel approach that allows the selection of ROI for camera oximetry where the selection of ROI has an impact on color sensitivity. Our experiments on 6 subjects with various skin colors have shown that the incandescent white balance mode is the preferable setting for camera oximetry applications that rely on the blue color channel and the Samsung Galaxy Ace phone model. Many of the available white balance settings did not sufficiently amplify the blue color channel. The blue channel was weakest because more blue light was absorbed by the tissue as compared to other colors. This was detectable as only the pixels closest to the LED showed activation. This finding is specific to the phone hardware as well as the operating system used and cannot be applied to other devices directly. However, our experiments have shown that the illumination of the sensor varies by area and it is important to select a ROI for subsequent processing. Previous studies have selected a fixed size ROI in the frame center [1], [5].

For photoplethysmographic imaging, where the primary focus is on pulse extraction, the red channel was shown to be adequate and with the highest amplitude over the largest sensor area. This is contrary to another study that used the green channel for HR estimation [5]. The discrepancy might originate from the fact that the authors in [5] are referring to their argumentation to non-contact photoplethysmographic imaging experiments [7] where ambient light is the light source and the majority of the optical path is in air which contains less water than tissue and does attenuate the wavelengths in question less, increasing the proportion of blue and red over red. Although in our case the red PPG was robust over a large pixel area, it still showed regions where the signal saturated and beats could not be extracted. These areas were concentrated around the edges closest to the LED (shortest optical path). For these situations our ROI method was useful.

For camera oximetry applications, where a high amplitude blue waveform was also required, the ROI algorithm was more important. Only regions close to the LED are suitable for processing. The decay of the blue photons was too large for the other optical paths.

The ROI selection is computationally expensive since a PPG has to be calculated for all ROIs in the frame. We have shown that it is sufficient to select the ROI at the beginning of the recording after a calibration phase of 5 beats. Further reduction of computational load is possible. For example the ROI can be restricted to an area of interest only by using a-priori knowledge. We have identified that the blue PPG amplitude is consistently higher on pixels closer to the LED. The size of the ROI could also be increased. This would reduce the number of ROI to be calculated. This comes with the drawback that with larger a ROI the PPG will be less precise in time and space. The resulting amplitude will be an average of all the pixels covered by the ROI. An iterative approach where the ROI is reduced from large to small over time might overcome this limitation. Another option is to replace the IMS algorithm used for the segmentation into pulses with another method that is less computationally expensive. For example, instead of extracting the pulses, simple statistics (mean, standard deviation, min, max) of the signal could be analyzed. All these options for improvement require further investigation.

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