Remote Camera-based Pulse Oximetry

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***Abstract*—The oxygen concentration in the blood is a very important physiological parameter. This variable is ordinarily monitored using a pulse oximeter, a device that measures the proportion of Hemoglobin that carries oxygen. Although noninvasive, this device needs constant contact with the patient's skin. The possibility of performing the same measurement without contact using a color camera and ambient light is investigated in this work. Particularly, the presence of signals necessary to oximetry measurement on recorded videos is evaluated. It was found that photo-plethysmographic signals are present at two color channels simultaneously, depending on the analyzed region of the videos. Thus, remote camera-based oximetry is possible in principle. Such a device could find numerous applications for patient monitoring, either at the hospital or at home.**

Keywords-pulse oximetry; contactless; camera; SpO2.

I. INTRODUCTION

Among the physiological parameters of interest for patient monitoring, blood gases' concentration is of particular importance. Patient's oxygenation status is a key factor and should be followed closely by the physician in several cases. This parameter is ordinarily measured by a *pulse oximeter* [1]. This device is a low-cost, noninvasive instrument that measures the peripheral oxygen saturation (S_pO_2) and provides an approximation to the arterial oxygen saturation. The later is the ratio between the amount of oxygen-carrying hemoglobin (oxyhemoglobin, HbO_2) and the total hemoglobin content, which includes HbO_2 and oxygen-free hemoglobin (deoxyhemoglobin, Hb), in the arterial blood. Although reliable and small, the pulse oximeter needs constant contact with the patient's skin, usually on the finger tip or the ear lobe, and is prone to movement artifacts [1].

One interesting alternative method to perform pulse oximetry, if possible, would be the use of a simple camera remotely filming the patient. Such a method would greatly simplify the monitoring of S_pO_2 at the hospital, and could be used to reduce patient discomfort due to the use of sensors in applications that require data acquisition during sleep, such as screening for Sleep Apnea Syndrome [2] and automatic sleep staging [3].

Recent literature provides some insight on whether such approach is possible. First, some results show that the acquisition of photo-plethysmography, one of the key ingredients of pulse oximetry, is possible via simple cameras. In [4], consumer level digital cameras were used to record facial-area videos of human subjects trying to maintain static positions under ambient light. A signal with a strong component corresponding to the subject's heart rate was reliably recovered by using spatial averaging over selected regions of interest (ROIs), usually on the green channel. The authors conclude that this signal is mostly due to a variation in volume of sub-cutaneous blood vessels and thus a real photo-plethysmography (PPG). Similar results were found in [5]. In [6], automatic face tracking was used to provide a ROI on each video frame to take care of subject movement. To further improve the response to movement artifacts, the authors used a technique of blind source separation to extract a heart related signal.

Another type of result regarding the second necessary ingredient to pulse oximetry — multi-wavelength measurement — has also been reported. In [7], a camera was used in a special illumination setup where all ambient light was blocked and the subject's arm was illuminated with monochromatic light. Up to three different wavelengths were used, however not simultaneously, and videos were recorded. Oscillations at the heart rate were observed at all tested wavelengths. Simultaneous PPG measurement in two wavelengths was obtained in [8], although with a controlled light source synchronized with the camera. In [9], a mobile phone camera was used to actually estimate S_pO_2, but the camera needed to stay in contact with the subject's skin.

For the oximetry camera to be possible, two conditions must be attained at the same time: remote PPG measurement *and* multiple wavelength measurement, both under normal ambient light. The aim of present study is to verify whether these are possible. This work in progress, once completed will, hopefully, construct a pulse oximetry camera or show its feasibility.

This contribution is organized as follows. Section II summarizes the theory behind pulse oximetry and shows how a camera could be used to acquire the necessary data. Section III describes the experimental setup used and the first results obtained. Finally, Section IV discusses the results and presents some perspectives.

II. PULSE OXIMETRY

A good review of the theory of pulse oximetry is provided in [1]. The interested reader is referred to that work, and references therein, should he or she desire a more detailed explanation. Here a short summary is included for sake of completeness.

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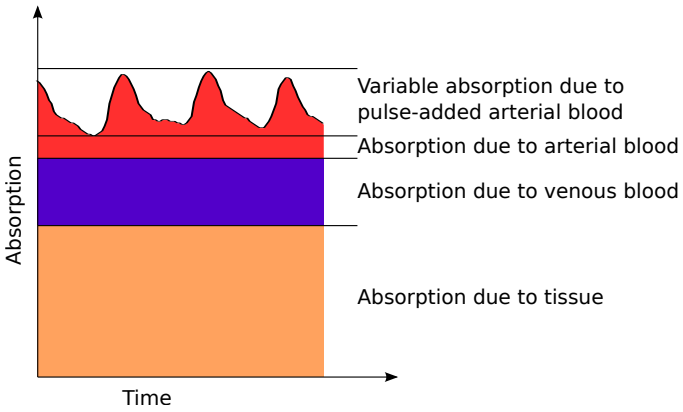

Figure 1. Light absorption in living tissue. Adapted from [1].

The physical principle used in oximetry is the different optical absorption spectra of Hb and HbO_2. This is responsible for the difference in color between oxygenated and deoxygenated blood. The absorption of light passing by a solution at a specific wavelength depends on the path length of the light, the concentration of the solute and a characteristic of the later called *molar absorptivity*. Under a few assumptions, the proportion of the concentration of one solute with respect to another in a two-solute solution can be determined by absorption measurements in two wavelengths. The wavelengths usually used correspond the red and infrared lights. However, any two wavelengths for which HB and HbO_2 have different absorptivity can in principle be used. This method can be used to measure the oxygen saturation of a blood sample. However, when such method is applied to measure oxygen saturation noninvasively in a patient, for instance by shining light through some part of the patient's body and measuring the transmitted or the reflected light, the unknown optical characteristics of the patient's tissues make the calibration of the instrument very difficult.

An interesting approach was proposed by [10] and [11]. The light traveling through live human tissue have a time-varying component in its absorbance signal. This time-varying signal is called photo-plethysmography (PPG) and is caused by the change of volume of the blood vessels related to the cardiac contraction. The higher pressure during cardiac systole corresponds to a larger volume of the arteries and, hence, to a greater absorption due to the increased volume of blood. The situation is reversed during diastole. This is depicted in Figure 1.

The optical characteristics of tissue are represented by the lower part of the graphic. Albeit unknown, the tissue's absorption can be considered constant during short periods. The same is valid for the venous blood's absorption. The variable part of the signal is due mostly to the change in volume of arterial blood. If the absorption is considered additive, one can use the variable signal to perform a normalization and take into account only the contribution of the arterial blood. This provides two advantages. First, only arterial blood saturation is measured, which is the physiological parameter of interest. Second, calibration is easier since only the blood's optical characteristics impact the measure, instead of the subject's tissue.

The normalization is usually performed by dividing the pulsating part of the PPG signal (commonly referred as the *AC* part) by the non pulsating part (the *DC* part). The normalization is performed for each wavelength, yielding two normalized measurement signals, one for the red light and one for the infrared. The ratio between these signals is then used to compute the oxygen saturation. In this later step, an empirical calibration table is used in order to compute the actual saturation.

The pulse oximetry requires, therefore, two "ingredients". First, at least two distinct wavelengths have to be used where Hb and HbO_2 have different absorptivities. Second, an oscillatory signal corresponding to the change in volume of the arteries must be present at both wavelengths.

A. *Camera-based pulse oximetry*

Color cameras, even simple webcams, are devices capable of acquiring a large amount of data. For instance, an webcam with a resolution of 640x480 pixels recording at 30 frames per second will measure light at 307200 different locations (each pixel) at 3 different wavelengths (red, green and blue) 30 times each second.

A camera-based pulse oximeter would use a camera to measure the light that comes from the subject in a similar manner that a regular pulse oximeter uses discrete phototransistors or photodiodes as photodetectors. A camera pointed at a subject from some distance away in a place where enough normal ambient light is present is comparable to a reflectance pulse oximeter. The hardware of the later consists of at least two light emitting diodes (LEDs), one for red and one for infrared, and one or more photodetectors. Both LEDs and photodetectors are packed together in a way that their active sides point at the same direction. When the device is placed in contact with the subject, the LEDs illuminate the subject's skin and the photodetectors measure the reflected light. The camera's pixels play the role of the photodetectors and the broad-spectrum ambient light combined with the color filters in the camera provide the measurement at different wavelengths.

In order for such a camera-based oximeter to be feasible, it remains to be verified that both "ingredients" for pulse oximetry are present. Multi-wavelength measurement is already a feature of color cameras. What remains to be verified is that a reasonably clear PPG signal can be acquired in at least two color channels simultaneously. That is the objective of this work.

III. Experimental setup and initial results

The experimental setup carried out was as simple as possible. Videos of human adult subjects were recorded, one subject per video. During recording, the subject was in a sitting position facing the camera, while trying to remain static. The camera imaged the frontal part of the subject's face from about 40cm away. The illumination was composed of natural daylight and the regular fluorescent ceiling lamps already present at the office. The camera used was an of-the-shelf consumer webcam (HD Webcam Citrine WC064, Sweex Europe B.V., Netherlands). It can record color videos at 640x480 pixels resolution and at 30 frames per second.

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This setup mimics what would be a possible arrangement for a future camera-based pulse oximeter. For instance, a patient would be lying on a hospital bed in a illuminated room. The camera of the pulse oximeter would be pointed to the patient's face, as this part is likely to present uncovered skin. The oximeter would be at some distance away from the patient, possibly at the ceiling, and would measure the S_pO_2 without encumbering the patient with a contact sensor. The actual distance from the camera to the patient should not be critical provided adequate optics are used, as a longer distance from the camera to the patient can be compensated with a longer focal length. What is important is that a sufficiently large part of patient's skin is visible from the camera's point of view.

Several videos of about one minute in length were recorded. In order to avoid any disturbance, each video was stored in raw format (YUV422)[12] in an AVI[13] container file. This is important because most video compression techniques lose information. Since the PPG signal is not usually seen with the naked eye, a video compression algorithm could, in theory, cause an important damage to the acquired PPG signal while maintaining the perceived quality of the compressed video. The drawback of recording raw video is the large size of the video file. An one-minute raw video file has a size of about 1.2 GiB. However, this difficulty is particular of the experimental protocol used and is should not be present in the final device since the later should process the video signal in real time and will have no need to record the video.

Video recording was done with MPlayer[14] in a PC running GNU/Linux.

Video processing was made in Python[15] using the OpenCV library[16] and custom made code. The Python language was chosen due to its simplicity that allowed a fast application development. As in [4], spatial averaging was used to improve the signal-to-noise ratio (SNR). Each color of each pixel has a relatively low amplitude resolution of 8 bits, which leads to a poor SNR. This can be partially overcome by averaging together neighboring pixels in a region of a frame. In this work, each frame was divided in 20x20 pixel regions that where averaged together in each color channel. This provided a single value per region, per channel and per frame. The channel time series of the regions were later analyzed looking for the presence of PPG signals.

A. Results

Figure 2 shows parts of two videos. These images where created by averaging the green channel over the entire video for illustration purposes. The subject on the left shows considerable movement while the one on the right was able to keep a more static position. Superimposed on the images are the grids formed by the 20x20-pixel regions.

Three regions in Figure 2 are indicated by letters, two on the left image and one on the right image. The time series corresponding to the region "A" are shown in Figure 3. All time series show an increasing trend, probably related to the subject's movement during the recording. On the green channel, two oscillatory components are visible, one with a low frequency and one with a relatively higher frequency. The low frequency component is possibly related with the subject's

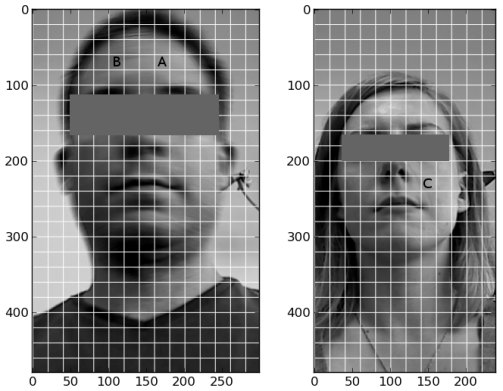

Figure 2. Images formed by averaging the green channel of all frames together. Overlaid are grids of 20x20 pixels. Units shown are in pixels.

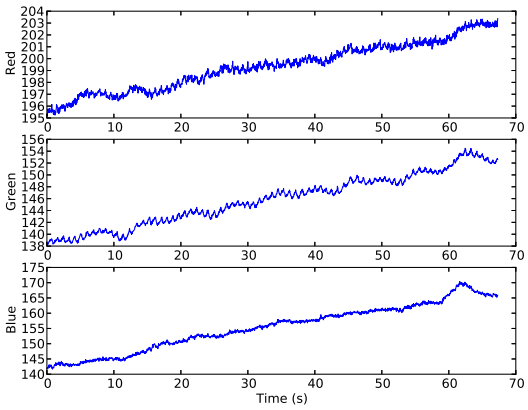

Figure 3. Time series corresponding to the region "A" in Figure 2.

respiration. The high frequency component is the PPG signal. Its presence on the green channel is in according to what was found in [4]. The red channel, on the other hand, shows what appears to be a PPG signal, although with a lower SNR. The blue channel does not seem to have a PPG signal.

In order to better evaluate the possible presence of the PPG signal, the time series were band-pass filtered with a FIR filter with cut-off frequencies at 0.7 Hz and 2.5 Hz. The filtered signals are shown in Figure 4. The PPG signal is easily seen on the green channel. Even a slight amplitude modulation is present, also possibly related with respiration. On the red channel, the PPG signal can also be seen, particularly between 15 s and 40 s and around the 60 s mark. The signal quality is, nevertheless, worse.

The presence of a PPG signal in multiple channels is very dependent on the particular region chosen. As an example, the band-pass filtered time series of region "B" are shown in Figure 5. Although clearly seen on the green channel, the PPG signal is absent from the other channels.

Finally, different subjects may have different "optimal" face regions where the presence of PPG is concerned. The filtered time-series of region "C" on the second subject are

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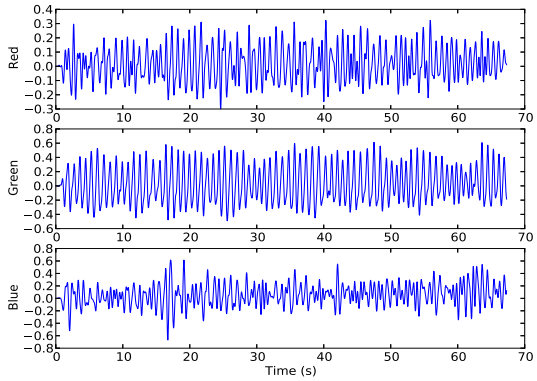

Figure 4. Band-pass filtered time series of region “A”.

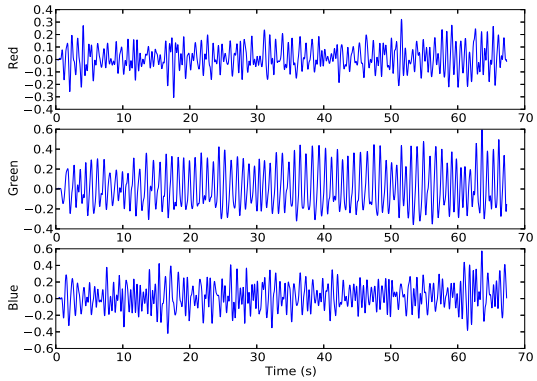

Figure 5. Band-pass filtered time series of region “B”.

shown in Figure 6. A strong PPG signal is present on both red and green channels.

IV. Discussion and Conclusion

The possibility of remote oximetry measurement via color camera and ambient light was investigated in this work. It was found that a necessary condition for pulse oximetry, namely the acquisition of PPG signals simultaneously in more than one wavelength, was present in the recorded videos with at least two different human subjects. The simultaneous presence of PPG signals in multiple wavelengths was not verified in previous publications under the conditions of this work (non-contact camera, ambient light). This positive result means that remote, camera-based pulse oximetry is in principle possible.

However, a lot of work remains to be done before such a device is constructed. First, systematic measurement of the recovered PPG amplitude for all face regions must be made. This will help with the development of the next necessary step that is an automatic and reliable way to detect and extract the PPG signals. To this end, tools from the computer vision domain may prove invaluable. After such extraction tool is devised, a further step would be to create an experimental protocol where different subjects are recorded while using standard pulse oximeters and breathing at different oxygen concentrations to provide a data base that would allow for

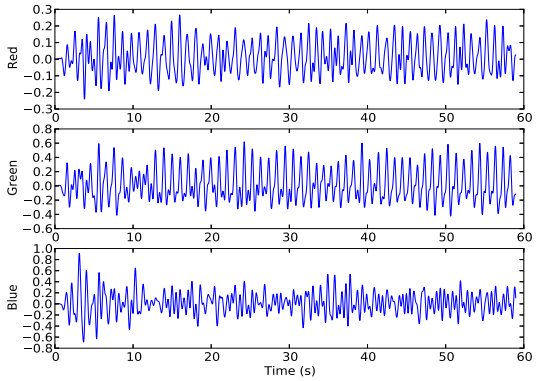

Figure 6. Band-pass filtered time series of region “C”.

calibration of the camera oximetry.

The possible applications of camera-based remote pulse oximetry are numerous. At one end, long-term hospital and home monitoring could replace contact oximeters in order to decrease patient discomfort. On the other end, novel and disruptive applications may become possible. For instance, a simple software application could transform a smartphone into a medical device capable to measure an important physiological parameter without any hardware modification and allow for screening or monitoring of several diseases at home.

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