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Techniques of Recording Photoplethysmographic Signals

Abstract: The photoplethysmography optically measures blood volume changes within micro vascular tissue. Furthermore, photoplethysmographic signals are used within pulse oximeters in order to calculate the oxygen saturation of the blood. This standard measurement technique is performed as a non-invasive spot check method for human health conditions in hospitals or other health care facilities. Usually at least two light sources are used alternating in order to measure photoplethysmograms at different wavelengths. In this paper we will investigate different methods of optically recording photoplethysmographic signals.

Keywords: photoplethysmography, pulse oximeter, hardware controlled photoplethysmography, constant current, constant intensity, amplitude modulation

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1 Introduction

The pulse wave of a human can be monitored optically [1]. The heart pumps blood through the cardiovascular system. This pulse wave causes a volume change within the measurement area, e.g. the finger, wrist, ear or toe. With every heartbeat new, oxygenated blood is arriving at the measurement area, e.g. at the finger. The absorption coefficients of the oxygenated and the deoxygenated blood differ and depend on the wavelength. This is the fundamental principle the pulse oximetry is based on. These two effects (volume change and absorption coefficient change) enable to optically measure cardiovascular cycles. As shown in fig. 1 (simplified) a light source, such as an LED, illuminates the human tissue at the

measurement area. A photodiode detects the transmitted light. The output signal of the photodiode represents the photoplethysmography. In fig. 1 a setup with two LEDs (red and infrared (ir)) and a single wideband photodiode can be seen. The light source intensity must not be high in order to protect the tissue from (over-) heating [2] and at the same time it needs to be high enough to produce evaluable signals.

Therefore, the intensity of the light source needs to be monitored and readjusted regularly, as described in section 2. In order to use the photoplethysmographic signals in a pulse oximeter the ambient light needs to be omitted, which is described in section 3. Measuring the oxygen saturation requires at least two photoplethysmograms to be recorded simultaneously at the same location, which is introduced in section 4.

Figure 1: Schematic of two LEDs transmitting light through a finger, which is then captured by the photodiode

2 Light source readjustment

Conventionally, the light source (LED) will be constant within one or multiple cardiac cycles and readjusted periodically (section 2.1). Alternatively, it is possible to regulate the light source in a way that the output of the photodiode remains constant (Constant light incidence, section 2.2).

2.1 Constant light emission

Recording a photoplethysmographic signal is conventionally done by using a light source of constant brightness, as

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Figure 2: On the left (fig. 2a) a simple voltage regulated current source is shown which drives an LED for constant light emission. On the right (fig. 2b) a current source with a feedback loop from an transimpedance amplifier is shown, which is able to regulate the LED current that the light incidence at the photodiode remains constant.

shown in fig. 2a: A voltage controlled (V_{in}) current source formed by *OPA1* and *T1* regulates the LED-current $I_C \cong V_{in}/R_E$ [3]. The photoplethysmographic signal is captured at the photodiode, as shown in fig. 1. The output current of the photodiode can be converted to a voltage using a standard transimpedance amplifier in order to amplify and digitise the PPG signal. The brightness of the light source remains constant until it is adjusted in order to accommodate for patient related variations. As the regulation only takes places once in a while (e.g. after some/each cardiac cycle) the regulation can be calculated with a software (e.g. on a microcontroller).

2.2 Constant light incidence

Figure 3: Blue: PPG signal: $V_{shunt}(t) \sim I_C$ recorded with constant light incidence method ($V_{in} = \text{constant}$), amplified with a negative-feedback-amplifier (gain=100); Orange: hypothetical LED current I_C in constant light emission method

An alternative approach to section 2.1 is to regulate the brightness of the light source such that the light incidence at the photodiode (see fig. 1) remains constant. In this concept the photoplethysmographic signal is represented by the light source intensity. Referring to fig. 2b, the LED brightness is proportional to the LED current I_C . Therefore, the PPG signal

can be measured with the shunt resistance R_{shunt} . A PPG represented by V_{shunt} can be seen in fig. 3 (blue). The regulator of the LED needs to be very fast and can be realised with hardware components directly on the circuit board, as shown in fig. 2b: An operational amplifier *OPA2* is used to control the LED-current I_C through a transistor *T2*. The LED emits light through tissue (as shown in fig. 1) and the photodiode captures the transmitted light. The photodiode output current I_{PD} is converted to the voltage V_{TIA_out} . The operational amplifier *OPA2* acts as PI-controller: It controls the current $I_B \sim I_C$ in such a way that $V_{in} = V_{TIA_out} = \text{constant}$. The resistors R_{r1} , R_{r2} and capacitance C_r are used to adjust the behaviour of the PI (proportional-integral) regulator by dimensioning the controller gain K_p and integral time constant K_i :

$$K_p = \frac{R_{r2}}{R_{r1}} \quad K_i = \frac{1}{R_{r1} \cdot C_r} \quad (1)$$

2.3 Comparison

The methods presented in sections 2.1 and 2.2 are both able to optically measure a PPG. The main difference lays in the way the LED is driven: either a constant current is used or a variable current depending on the light incidence at the photodiode is used. This may reduce the total light emitted into the human tissue: In fig. 3 the orange graph represents the simulated intensity of the LED when using the constant light emission method of section 2.1: The luminosity of the LED is controlled in such a way that the minimum light incidence at the photodiode is always above the minimum detectable quantity. This reduces the light absorption (and heating) of the

tissue to a minimum. The light absorption varies within each cardiac cycle. Using the constant light incidence method, it is possible to reduce the total light incidence further. This can be seen in fig. 3: The blue LED current remains (almost always) smaller than the orange LED current, while the light incidence at the photodiode remains always above a minimum detectable quantity in both scenarios. Hence, the constant light incidence method can reduce the application of energy into the tissue.

Disadvantages of the constant light incidence method are its increased complexity and reduced robustness when compared to the conventional method with constant current. In addition, it is not possible to directly measure the ambient light incidence, which disqualifies this method to be used for pulse oximetry without further optimisation.

3 Ambient light suppression

An important task is to suppress the influence of ambient light onto the PPG signal in order to use it for gas saturation measurements like the pulse oximetry. Different ambient light suppression techniques are presented and compared against each other in the following subsections 3.1 to 3.4.

3.1 Passive light blocking in the sensor

A straight forward approach is a passive light blocking attempt. As shown in fig. 1 a finger could be wrapped into a silicone sock, which is a common technique in modern pulse oximeter sensors. This is a simple and effective way of reducing the influence of ambient light but cannot be applied everywhere and only reduces the influence of ambient light but does not completely eliminate it.

3.2 Measure and subtract ambient light

If the constant light measurement technique (section 2.1) is used, a convenient way of directly measuring the influence of the ambient light is to measure the ambient light with the LED turned off. Directly before/after that one PPG signal sample is measured with the LED turned on. Now the ambient light measurement is subtracted from the PPG signal measurement in order to remove the offset of the ambient light. It is important to note that this approach assumes that the ambient light is constant for the whole time the two measurements take place. Therefore, the measurements need to be as short as possible to fulfil this requirement. This might be a problem, e.g. if the measurement happens in an environment which is illuminated with pulse modulated light.

3.3 Amplitude modulation

In the following an approach is proposed, which overcomes the problems of the ambient light subtraction method by modifying the voltage V_{in} in fig. 2 to

$$V_{in}(t) = A \cdot \sin(f_c \cdot t) + o \quad (2)$$

Where A is the amplitude, f_c the carrier frequency and $o > A/2$ the offset of the sine wave. This results in a voltage V_{in} which is always greater than zero. Therefore, the measured PPG signal $V_{PPG} = V_{PD}$ (fig. 2a, where V_{PD} is the transamplified output current of a photodiode) or $V_{PPG} = V_{shunt}$ (fig. 2b) results in eq. 4 and 5 respectively.

$$V_{PD}(t) = PPG(f_{HR} \cdot t) \cdot \{A \cdot \sin(f_c \cdot t) + o\} + o_a(t) \quad (3)$$

$$V_{shunt}(t) = \frac{1}{PPG(f_{HR} \cdot t)} \cdot \{A \cdot \sin(f_c \cdot t) + o\} + o_a(t) \quad (4)$$

The PPG signal ($0 < PPG(f_{HR} \cdot t) < 1$) is a periodic signal, its frequency depends on the heartrate (f_{HR}). It is modulated onto the carrier signal $A \cdot \sin(f_c \cdot t)$ with a constant offset $o > A/2$. The ambient light adds a varying offset $o_a \geq 0$. In fig. 2a the blood and tissue directly reduce the maximum possible transmitted amplitude of the emitted light reducing the light incidence at the photodiode, as shown in eq. 3. In fig. 2b the irradiated light at the photodiode remains constant. Therefore, a reduction in transmittance (due to the PPG signal in the tissue) leads to an increased LED brightness. As seen in eq. 4, a complete light blocking ($PPG(f_{HR} \cdot t) = 0$) would lead to the maximum possible brightness of the LED and V_{shunt} .

In order to extract the PPG signal from V_{PPG} , a notch filter (with a centre frequency f_c) is applied and after that a (quadrature) demodulation takes place. The amplitude modulated signal consist of three components: the modulation signal, the upper- and the lower sideband. The ambient light offset o_a is added to all three components separately. Therefore, the PPG signal can be derived from the difference of the upper- (US) and the lower sideband (LS). A quadrature demodulation of eq. 3 or 4 leads to eq. 5, which shows the two sidebands, where $P(f_{HR} \cdot t)$ is the PPG signal of eq. 3 or 4 with $P(f_{HR} \cdot t) = PPG(f_{HR} \cdot t)$ or $P(f_{HR} \cdot t) = 1/PPG(f_{HR} \cdot t)$ respectively. The ambient light influence o_a cancels out in the subtraction of the US and LS in eq. 6. This leads to a PPG

Figure 4: PPG signal: $V_{shunt}(t)$ recorded with constant light incidence method and amplitude modulation, demodulation (DM) with hardware circuitry

signal as shown in fig. 4, where the demodulation took place in hardware and while using the constant light incidence technique (section 2.2) with the modulation frequency $f_c = 10\text{kHz}$.

$$V_{US;LS}(t) = P(f_{HR} \cdot t) \cdot \{A \cdot (\pm 1) + o\} + o_a(t) \quad (5)$$

$$V_{US}(t) - V_{LS}(t) = 2 \cdot P(f_{HR} \cdot t) \cdot A \quad (6)$$

3.4 Comparison

The passive light blocking approach should be used wherever possible and in combination with other signal processing light omission techniques.

The measure and subtract approach is great as it is simple to implement and understand. It works best if the ambient light is constant during the measurement. Measurements are taken serially and not parallel.

The amplitude modulation approach can overcome the limitations: The signal and the ambient light are separated in the demodulation process. The signal processing is more complex and the photodiode (and transimpedance amplifier) need to be fast in order to capture the modulation frequency.

4 Simultaneous measurement

The principle of pulse oximetry is to use the different wavelengths and monitor their absorption inside the tissue in order to conclude the gas saturation out of the different absorption rates. Two LEDs with different wavelengths can be used for light emission as an example but these approaches can be adopted for more light sources and wavelengths. [4]

It is possible to use two LEDs combined with two wavelength-specific photodiodes. The transmitted/reflected light is filtered optically before being measured by the photodiode. Therefore, each photodiode only reacts to one LED. As both LED and photodiode pairs operate independently, a simultaneous measurement is possible. This approach is not common, as the setup is not a low-cost design due to the necessary optical filters.

Using one wideband photodiode together with multiple LEDs (as shown in fig. 1) is a common approach, most commercial standard pulse oximeter sensors are built like this. It is crucial to differentiate the single output signal of the photodiode resulting from multiple input signals with different wavelengths.

One possibility to differentiate between multiple input signals is to activate the LEDs alternating in a predefined, fixed pattern, similar to section 3.2. This ensures, that the photodiode only measures the corresponding transmitted light.

The switching needs to be of high frequency in order to treat two consecutive measurements of two LEDs as (pseudo) simultaneous measurements.

Another possibility for differentiating can be achieved by using an amplitude modulated signal V_{in} (fig. 2), as described in section 3.3. If different modulation frequencies f are used for each LED/wavelength, it is possible to demodulate each signal independently. Each wavelength would be extracted with a notch filter which omits all other modulation frequency components of the other LEDs. This approach works best with the constant light emission (section 2.1).

5 Conclusion/Summary

We presented and compared methods to measure PPG signals and omit the influence of ambient light. A proposed method based on amplitude modulation enables to simultaneously capture multiple PPG signals with different wavelengths. A proposed hardware based capturing method is faster than the widely used standard and reduces the light absorption and heating of the human tissue.

Author Statement

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