Development of a Ring-Shaped Pulse Oximeter to Analyse Angle Dependency in SpO_2 Estimation

Lara J Reichelt[1], Idoia Badiola[1], Vladimir Blazek[1,2], Steffen Leonhardt[1], Markus Lüken[1]

[1]RWTH Aachen University, Aachen, Germany
[2]Czech Technical University, Prague, Czech Republic

Abstract

Photoplethysmography (PPG) is a non-invasive, opto-electric method widely used to estimate vital parameters such as heart rate and blood oxygen saturation (SpO_2). Typically, the determination of SpO_2 relies on a device-specific calibration curve, which correlates the ratio-of-modulation (R) with SpO_2 values and is commonly established using linear regression analysis. This work examines the dependency of SpO_2 estimation on the angle between light-emitting diodes (LED) and photodiodes (PD) using a ring-shaped PPG sensor. The developed sensor, including an opto-electric system, collected PPG signals from PDs at four angles (45°, 90°, 135°, 290°). A hypoxia study involving five healthy subjects was performed, collecting PPG data from the developed sensor and a reference pulse oximeter. Subsequently, the collected data was analysed to estimate the respective angles' R-value and to compare them to the reference values. The comparison showed high inter-individual signal quality variability. However, results from good-quality signals showed a clear angle dependency.

1. Introduction

Photoplethysmography (PPG) is a widely used non-invasive electro-optical technique for estimating blood peripheral arterial oxygen saturation (SpO_2), heart rate, respiratory rate, and other vital parameters. It is used in consumer devices like smartwatches and hospitals for vital sign monitoring [1]. Typically, the determination of SpO_2 relies on a device-specific calibration curve, which correlates the ratio-of-modulation (R) with SpO_2 values. The R-value is defined as the ratio of the quotients of pulsatile (AC) to non-pulsatile (DC) components of the PPG signals for red and infrared (IR) light, respectively [2]. This calibration curve is commonly established using linear regression analysis. However, some aspects of the transmissive and reflective PPG (tPPG and rPPG) remain unknown.

Min Gyu Joo et al. developed a wearable ring-type pulse oximeter with a reflective coating to reduce power consumption and enhance sensitivity. Through simulations and experiments on subjects with typical Asian skin types, they found that the reflective ring outperformed the non-reflective one in light intensity detection. However, the study's accuracy is uncertain due to variable LED-PD angles caused by ring flexibility and changing finger-diameters, and limited SpO_2 ranges (SpO_2 > 95%) [3].

Bor-Shyh Lin et al. designed a ring-shaped finger-base pulse oximeter to detect optimal placement for the optical components due to anatomic differences between the finger base and the fingertip. The optimized placement of the optical components, resulting from a performed simulation, was used to conduct a study that demonstrated comparable results to reference measurements performed with a commercial fingertip pulse oximeter. However, they considered the placement of the optical components depending on the anatomical structures and did not investigate the angle dependency of the SpO_2 estimation [4].

Previously conducted work showed the theoretical presence of angle dependency in SpO_2 estimation with a Monte-Carlo simulation. This result led to the need for a practical validation of this angle dependency. Therefore, this work aims to analyse it in a practical study with a self-made ring-shaped PPG sensor. The photodetectors (PDs) of the sensor are placed within the ring at various angles with respect to the LEDs. The PPG sensor was tested in a hypoxia- study with five subjects, obtaining calibration curves for each LED-to-PD combination. The validation of this theoretically shown angle-dependency would influence further research in this field since they did not have been researched in this way before.

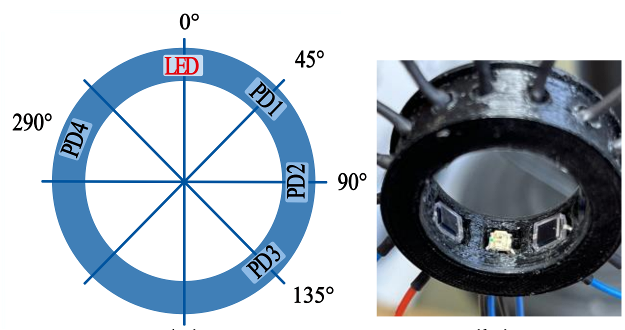
2. Methods

The developed system consists of the PPG sensor, a PCB containing an analogue front-end (AFE), and a microcontroller to control the LEDs and read the values from each PD. The values were acquired and processed using MATLAB (Version R2022b, Mathworks, Massachussets, USA).

 ISSN: 2325-887X DOI: 10.22489/CinC.2024.260

2.1. Ring-shaped Sensor

The ring-shaped sensor was 3D-printed using PETG, and the optical components – a bicolour LED and four PDs - were inserted into the ring at four different angles from the centre of the LED to the centre of each PD: 45°, 90°, 135°, 290°. Fig. 1 depicts the resulting sensor design. We employed a bicolour LED (SML-LX2530SRELC-TR from ITW Lumex Inc., Illinois, USA) with a wavelength of 660 nm for red and 940 nm for infrared light [5], and BPW34 PDs from "Vishay Intertechnology Inc." (Malvern, USA), which offers a spectral bandwidth ranging from 430 to 1100 nm with a peak sensitivity at 900 nm [6]. The used ring-shaped sensor has a diameter of 20 mm and a width of 12 mm and includes five cavities for the optical components.



(a.) (b.)

Fig. 1: (a.) Positioning of optical components, (b.) Ring- sensor with optical components

2.2. System description- Hardware

Fig. 2 depicts the hardware setup, which involves the ring-shaped PPG sensor, a Microcontroller (Arduino V3, Arduino SA, Corso San Gottardo 6A CH-6830 Chiasso, Switzerland) and an AFE ("Oximeter-Click", Mikroe, Belgrade, Serbia).

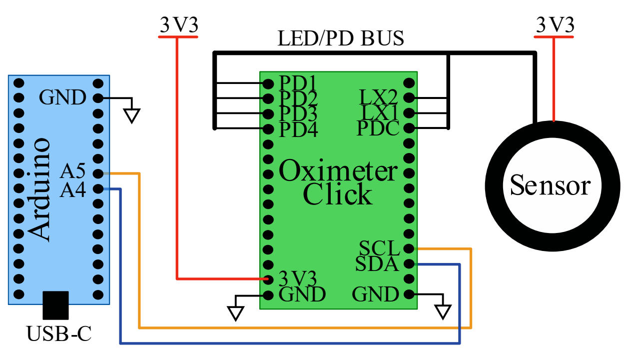


Fig. 2: Hardware setup consisting of an Arduino and an AFE module to communicate with the sensor

The Arduino was used for Inter-Integrated-Circuit (I^2C) communication between the Oximeter-Click, and the PC. The Oximeter-Click contains already built in LEDs and a PD. However, for this work, these components were disconnected to allow the connection of the two external LEDs and four external PDs from the ring. The Oximeter-Click includes an ADPD105 module (Analog Devices, Massachusetts, USA). With the ADPD105, various configurations can be set through several programmable registers, since it provides two timeslots with adjustable settings for the LEDs and the PDs [7,8].

2.3. System description – Software

The register settings of the ADPD105 were adjusted using the Arduino IDE (Version 1.8.18) for the measurements conducted in the study. Direct register reading was enabled to collect the streaming data from the sensor. The two LEDs of the sensor illuminated alternately in timeslot A and timeslot B, respectively, with a pulse width of 3 µs and eight light pulses per 30 µs period for each timeslot. PD1 to PD4 were activated during timeslot A and timeslot B, and an offset for each PD was set to achieve similar initial signal values. The AFE integration window settings were adjusted according to ADPD105 datasheet recommendations, with a 4 µs integration window and 16 µs integration window offset for both timeslots. The gain of the trans-impedance amplifier (TIA) of the ADPD105 was set to 100 kΩ and the V_{bias} to 1.27 V. The AFE normal mode was activated to use all components of the signal chain (TIA, band pass filter (BPF), Integrator and analog-to-digital-converter (ADC)).

To collect the streaming data from the PDs during the measurement, the Arduino went through a 240-second-long loop of serial data acquisition for all four PDs in each timeslot. The data, including timestamps, were saved in Python (Version 3.10 (64-bit)) as a CSV file. For further data processing, the CSV file was imported into MATLAB (Version R2022b, Mathworks, Massachussets, USA).

2.4. Software – Data Processing

The collected data was interpolated to obtain equidistant samples, since the timestamp intervals varied in their length, achieving a sampling frequency of 100 Hz.

Subsequently, the dataset for each PD was separated into an AC and a DC component, respectively. The separation of AC and DC was performed with Butterworth filters of 4^{th} order. A bandpass filter was used to obtain the AC signal between 0.5 and 4.5 Hz. The

DC part was obtained using a lowpass filter with a cutoff frequency of 0.1 Hz. The envelopes of the AC signal were used to determine the amplitude of the respective AC part. The AC amplitude of the signal of red and IR light was determined over time and, finally, the ratio-of-modulation (R) could be determined using the equation R= $(AC/DC)_{red}/(AC/DC)_{IR}$ [1]. These R-values were plotted against each other and linearized to obtain a calibration curve.

2.5. System Validation – Hypoxia Study

A hypoxia study was conducted on five young healthy subjects between the ages of 27 to 31 comprising one female and four males. Each subject was suitable for the hypoxia study following a stress test supervised by a physician. The developed ring-shaped sensor was placed on the middle finger of the right hand, and a reference SpO_2 clip-sensor, connected to the patient monitor Intellivue MX700 by Philips (Koninklijke Philips N.V., Amsterdam, Netherlands), was placed on the index finger of the left hand.

The position of the sensor varied among subjects and for some subjects, an air gap was observed between the finger and the ring-shaped sensor since there was only one size of the ring available. The positioning and the placement for each subject are illustrated in Fig. 3. When an air gap showed, the subjects were told to press the sensor onto the finger with their thumb. To increase the perfusion of the fingers of one subject the fingers were placed on a heat radiator, as documented in Table 1.

To decrease the SpO_2 of the subjects they wore a breathing mask covering their nose and mouth, connected to the "CellAirOne hypoxia therapy device" (TUR Therapietechnik GmbH, Rostock, Germany) which varied the SpO_2 from 99-100% to approximately 85%. This procedure took about four minutes, during which the measurement of the ring-sensor and reference clip-sensor was performed simultaneously.

Subject	Sensor position	Heat	Air Gap
1	A	yes	yes
2	C	no	no
3	B	no	no
4	C	no	yes
5	C	no	no

Table 1: Setting for the study

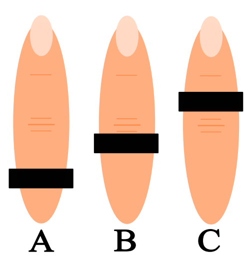


Fig. 3: Sensor placement

3. Results and Discussion

The analysis of the raw measurement data revealed significant differences in the signal quality. A difference between PD1 (45°) and PD2 (90°) is noticeable, as well as between the signal quality of red and IR light. An observable noise in the signal may be attributed to the airgap between the sensor and the finger. The apparent difference between the signal quality for red and IR light is expected since the used PD had its peak sensitivity at 900 nm, which is closer to IR than red light.

The comparison of the processed data shows a variation in the amplitudes between the different PDs. For instance, the amplitude of the AC component of the PD at 135° was approximately 40 and the amplitude of the PD at 290° approximately 200. That can be attributed to different amount of light reaching each PD.

Additionally, a varying amplitude over time can be noticed for single PDs. Specifically, there is an increase in amplitude over time for subject 4 but a decrease in amplitude over time for subject 1. These trends could be due to pressure variations since both subjects applied pressure onto the sensor.

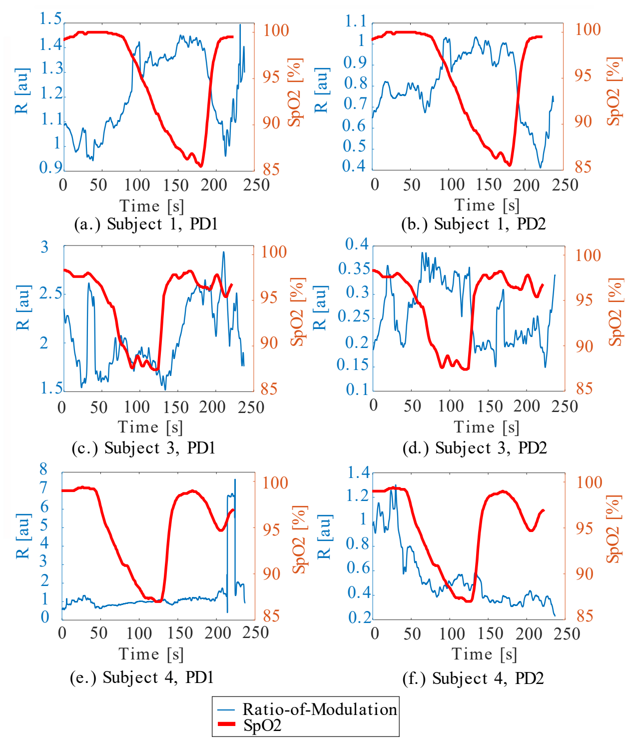


Fig. 4: R-value and SpO_2 of PD1 and PD2 for subjects 1,3, and 4

In Fig. 4, the SpO_2 and R-values are plotted over time for subject 1, subject 3, and subject 4 for PD1 (45°) and PD2 (90°). A decrease of the reference SpO_2 from approximately 100 % to approximately 86-88 %, and the following increase of SpO_2 could be observed in all plots shown in Fig. 4. For subject 1, the typical corresponding variation from R and SpO_2 could be observed, where R increases for a decrease of SpO_2.
Observations of the plots (a.) and (b.) in Fig. 4 revealed a

difference in the R-value for PD1 and PD2. PD1, located at 45° receives reflected light, and it presented R-values ranging from 0.9 to 1.5. In contrast, the R-value of PD2, which is located at 90° and therefore receives reflected and transmitted light, ranges from 0.4 to 1.1. Fig. 5 shows the calibration curves of the PD at 45° and the PD at 90° of subject 1. The difference in the calibration curves indicates a possible angle dependency. Similar behavior of the R-values, though less pronounced because of massive artifacts, was observed for subject 3 in Fig. 4 (c.) and (d.).

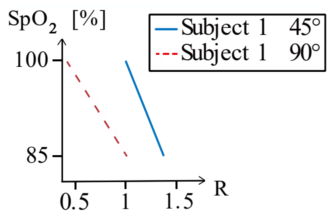


Fig. 5: SpO_2 plotted against Ratio-of-modulation for subject 1 for the PD at 45° and 90°

Another notable observation is the inconsistency of the R-value. In plot (b.), it is visible that the R-value for approximately 92% SpO_2 is 1 at 70 seconds and approximately 0.7 at 190 seconds. This is a massive error since R should remain constant for the same SpO_2 since the physiological characteristics of the measured size should be the same.

An additional characteristic that should be highlighted is in the first 50 seconds of plot (f.) in Fig. 4, where SpO_2 is relatively constant while R is unsteady. This anomaly may occur due to variable pressure on the sensor, as subject 1 and subject 4 applied pressure onto the sensor. Zhang et al. detected a pressure dependency of R and a subject-dependent peak of the R at different contacting pressures. Additionally, Sim et.al. mentioned that a PPG sensor applied with pressure could deform blood vessels and therefore alter the signal amplitude. This finding could explain measurement difficulties since the ring-shaped sensor was only available in one size and the pressure may have differentiated over time for subjects 1 and 4 or too much pressure was put onto the ring due to bad fitting [9,10].

4. Conclusion

The aim of this work was to develop a ring-shaped pulse- oximeter to validate the theoretically found angle-dependency in SpO_2 estimation. The developed sensor included two LEDs and four PD, which were located at 45°, 90°, 135°, and 290°. A hypoxia study was performed on five young and healthy subjects. Following, the collected data was processed and analysed. This work shows a possible angle dependency in SpO_2 but also the need for optimisation, since previously mentioned difficulties, including a universal ring size and variable pressure applied by the subjects, led to unreliable measurements and following difficulties in the analysis. For further research, it is recommended to customise the ring-shaped sensors for each subject to increase signal quality and comparable PPG data from different angles. Analysing the data collected with the improved setup could yield a significant advance in understanding the origin of PPG signals and enhancing accuracy in clinical settings.

References

[1] I. Badiola, V. Blazek, V. Jagadeesh Kumar, B. George, S. Leonhardt, and C. Hoog Antink, "Accuracy Enhancement in Reflective Pulse Oximetry by Considering Wavelength-Dependent Path Lengths," *Physiol. Meas.*, vol. 43, no. 9, p. 2, Sep. 2022.

[2] V. Blazek, J. Kumar V., S. Leonhardt, and M. Mukunda Rao, "Studies in Skin Perfusion Dynamics: Photoplethysmography and its Applications in Medical Diagnostics," pp. 60 – 62, Singapore: Springer, 2021, ISBN: 9789811554490

[3] M. G. Joo, D. H. Lim, K. Park, J. Baek, J. M. Choi,and H. W. Baac, "Reflection-Boosted Wearable Ring-Type Pulse Oximeters for SpO2 Measurement with High Sensitivity and Low Power Consumption," Biosensors, vol. 13, no. 7, July 2023.

[4] L. Bor-Shyh, H. Cheng-Yang, C. Chien-Yue, and L. Jiun-Hung, "Design of a Finger Base-Type Pulse Oximeter," The Review of scientific instruments, vol.87, no. 1, Jan. 2016

[5] ITW Lumex Inc., Illinois, USA, "SML-LX2530SRELC-TR SMD LED Bicolor," https://www.lumex.com/datasheet/SML-LX2530SRSGC-TR, Access on: 12/01/2023.

[6] Vishay Intertechnology Inc., Malvern, USA, "BPW34, BPW34S Silicon Pin Diode," https://www.vishay.com/docs/81521/bpw34.pdf, Access on: 12/07/2023.

[7] Analog Devices, Massachusetts, USA, "Photometric Front Ends ADPD105/ADPD106/ADPD107 (Rev. A)," Access on: 10/30/2023

[8] Mikroe, Belgrad, Serbia, https://www.mikroe.com/oximeter-click, Access on: 2/12/2024.

[9] X F. Teng, and Y T. Zhang, "The Effect of Contacting Force on Photoplethysmographic Signals," *Physiol. Meas.*, vol. 25, no. 5, p. 1323, Aug. 2004.

[10] J. K. Sim, B. Ahn, and I. Doh, "A Contact-Force Regulated Photoplethysmography (PPG) Platform," AIP Advances, vol. 8, no. 4, p. 1, Apr. 2018.

Address for correspondence:

Lara J. Reichelt
Lehrstuhl für Medizinische Informationstechnik, Helmholtz-Institut, RWTH Aachen, Pauwelsstr. 20, 52074 Aachen
lara.reichelt@rwth-aachen.de