Deep-PPG
Optimization of PPG signal acquisition

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Aim

Aim of the project Deep-PPG is to improve the robustness of wearables by using VCSEL as a light source and simulations of photon-tissue interactions for optimizations.

Introduction

Wearables are increasingly used in daily life and have become an important part of today's modern lifestyle. In particular, smartwatches are part of daily life for many and contribute to a healthier lifestyle through real-time recordings of vital parameters. They are not only used in the daily life of consumers but also increasingly in care and medicine. Particularly in pandemic times, wearables could give users early warning of complications or health risks. By analysis of the photoplethysmographic (PPG) curve a variety of vital signs can be determined. However, today's wearables do not reach the required clinical standard due to lack of robustness. Motion artifacts, energy consumption and stray light are just some of the known shortcomings of the current state of the art [1,2].

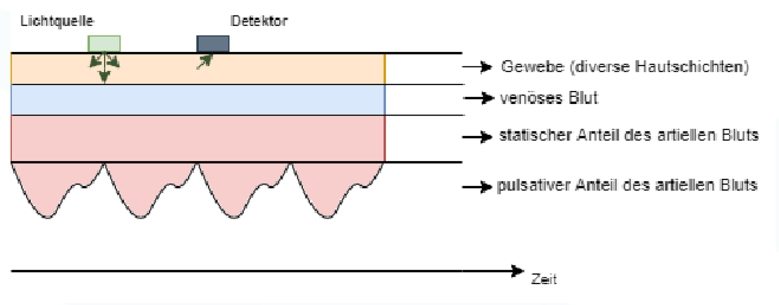


Figure 1. Light absorption in tissue and resulting PPG curve

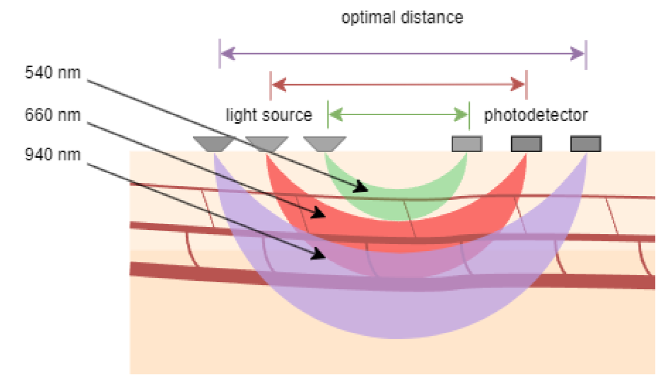
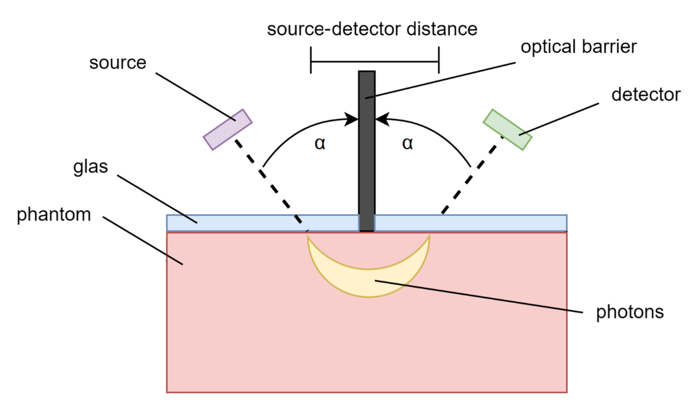


Figure 2. Tissue-photon interaction and wavelength-dependent photon propagation

Method

In the project Deep-PPG in cooperation with ALU Freiburg and ams OSRAM, Vertical Cavity Emitting Lasers (VCSEL) are evaluated as a new and more robust light source to record the PPG curve. For this purpose, the optimal distance between emitter and detector is needed. Using Monte Carlo (MC) simulations, photon-tissue interactions are simulated and the optimal distances are determined. Based on this, a wrist wearable has been developed from scratch. The simulations will also provide information about the susceptibility to interference and the signal quality of the new light source.

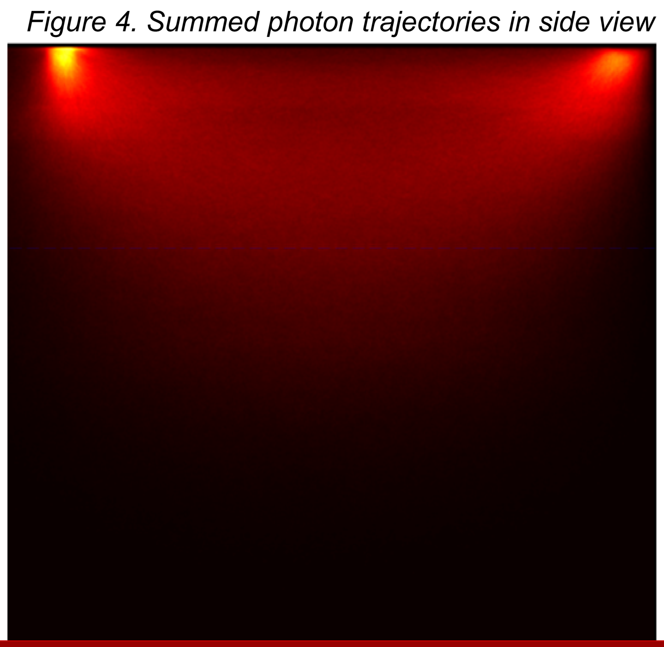
Figure 3. Developed tissue model (skin with blood vessel and sensory system)



Development photon simulation framework

The MC model consists of four main components: anatomical structure, physical model of absorption and scattering, optical parameters of tissue and emitter/sensor properties. It simulates the propagation of photon packets in tissue (composed of several layers).

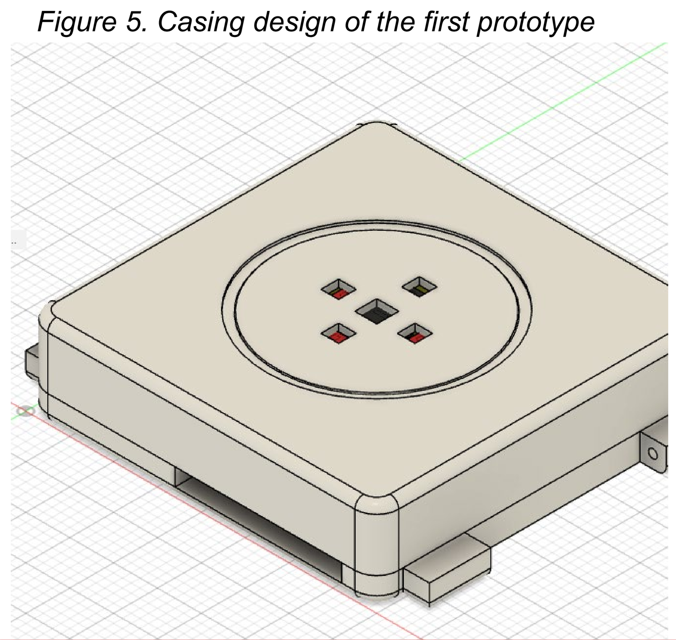
Figure 4. Summed photon trajectories in side view



Validation of optimal sensor layout

The penetration depth, the distribution of the photon energy as well as the emission of these are to be analysed. Different wavelengths with various distances are simulated with 10E10 photon packets in each anatomical model.

Figure 5. Casing design of the first prototype



Prototype development

The wearable contains two sources, LED and VCSEL, as well as two wavelengths in the red and infrared spectral range. An analog front end IC controls these and the signal is recorded by a photodiode. A direct comparison is possible due to the high resolution of the signal acquisition.

Figure 6. Several wearables

Subject study & evaluation VCSEL

The subject study provides insight into the expected increase in robustness by using VCSEL in an environment that is as real as possible. Furthermore, it will be investigated whether VCSEL can reduce the power consumption of wearables at constant or improved SNR.

Results

- **Validation photon simulation framework**

Table 1. Validation of the developed Monte Carlo simulation framework with analytical and simulated results.

Source	R_T [-]	Error [-]	T_T [-]	Error [-]
Case 1				
Giovanelli [5]	0.2600	-	-	-
Prahl et al. [6]	0.2607	0.00170	-	-
Our model	0.2605	0.00038	-	-
Case 2				
van der Hulst [4]	0.09734	-	0.66096	-
Prahl et al. [6]	0.09711	0.00033	0.66159	0.00049
Our model	0.09682	0.00036	0.66163	0.00041

- **Validation prototype developement**

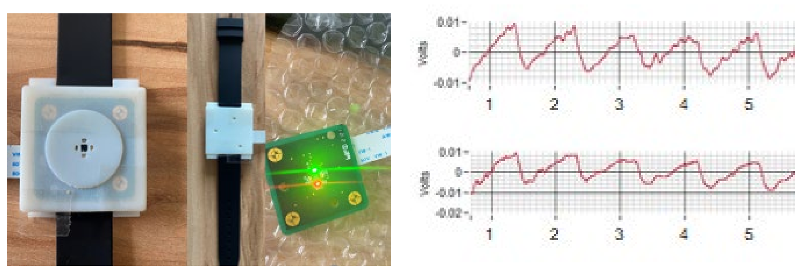


Figure 7. Left: Developed prototype. Right: PPG recordings of LED (top) and VCSEL (bottom) IR.

- **PPG signal analysis depending on sensor placement and wavelength**

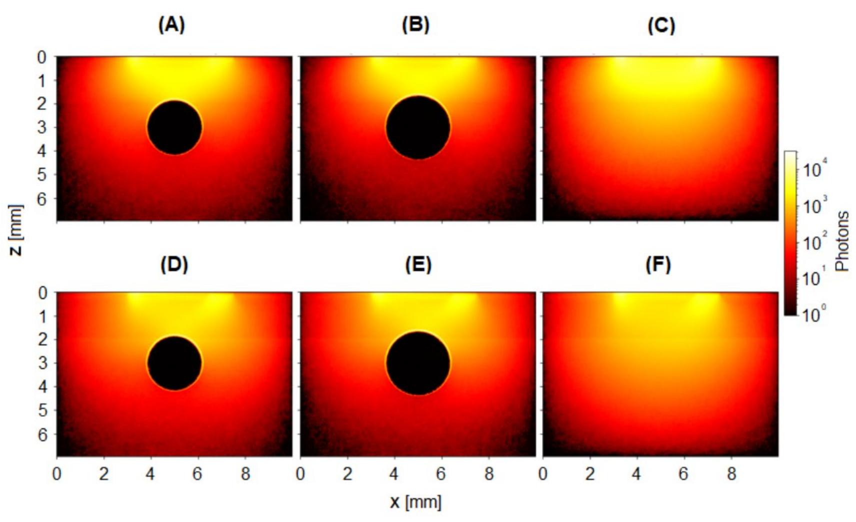


Figure 8. Summed trajectories of detected photon packets at 660 nm (Plots A-C) and 940 nm (Plots D-F). (A,D): Regular blood vessel. (B, E): Dilated blood vessel. (C,F): Simulation without blood vessel.

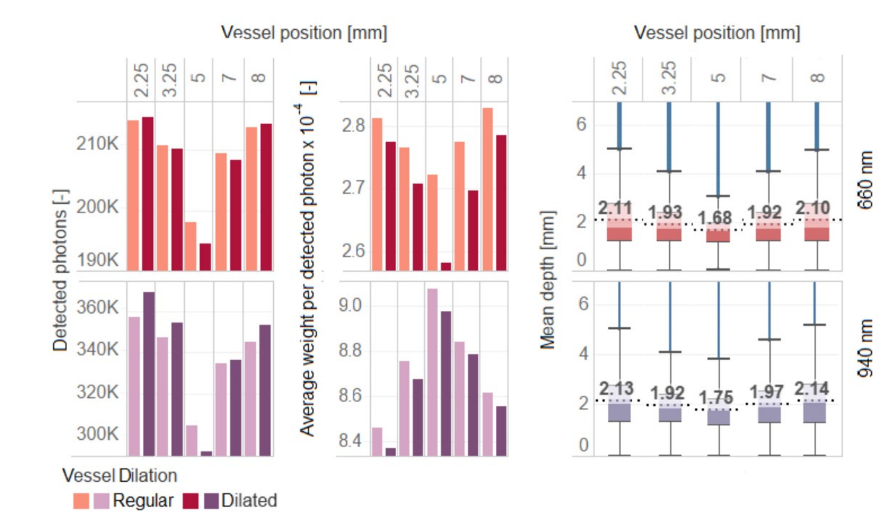


Figure 9. Simulation results for wavelengths of 660 nm and 940 nm, Including non-dilated & dilated blood vessels. Left: Total detected photon packets. Middle: Average weight of detected photons. Right: Average penetration depth. Average maximum penetration depth is indicated by dashed lines.

- **Comparison of PPG signals in skin phantom and MC Simulations**

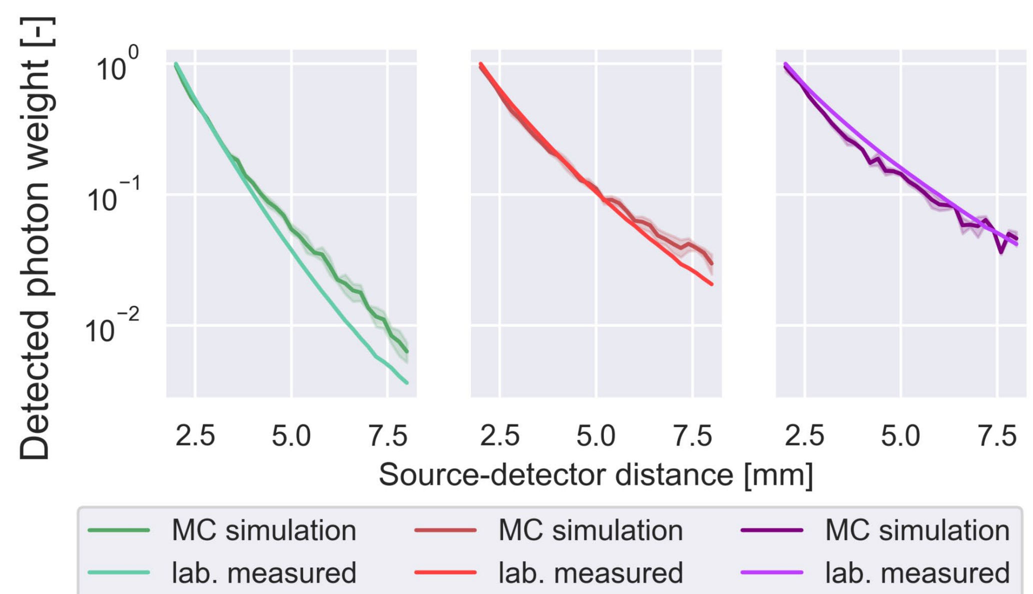


Figure 10. Comparison of laboratory measured DC level and MC simulated DC level normalized to the maximum value at 2 mm over a source-detector distance of 2 to 8 mm. Wavelength' used are 520, 637 and 940 nm.

Discussion

- **Validation MC simulation framework**

The developed MC simulation framework is in agreement with reference values taken from literature within limits of error. Details are shown in Table 1.

- **Prototype development**

The prototype is functional and a signal is detectable (see Figure 7). However, signal quality is still poor. Identified shortcomings, such as missing optical barrier, material of the casing, rigid wristband, ..., will be eliminated by further improvements.

- **PPG signal analysis depending on sensor placement and wavelength**

Detected photon packets pass through tissue in a banana curve depending on wavelength, as shown in Figure 8. The blood vessel blocks photon packets from passing directly through it. The further the blood vessel reaches into the banana curve of photon packets, the more it influences the detected signal. Due to a reduced average penetration, the blood vessel does not extend as far into the banana curve at 660 nm compared to 940 nm. Consequently, the blood vessel influences the detected photon packets depending on its depth and position. The intensity of the effect is wavelength' dependent due to the penetration depth as well as scattering and absorption properties. The average penetration depth shows that the blood vessel is moreover responsible for a decrease in penetration depth. The more photon packets hit the blood vessel, the larger is the signal difference between regular and dilated state. The position of the blood vessel relative to light source and detector influences the detected signal by increasing photon absorption. To maximise the PPG signal, light source and detector should be symmetrically placed over a large blood vessel.

- **Comparison of PPG signals in skin phantom and MC Simulations**

We compared laboratory measured reflective DC signal levels of a porcine skin phantom and MC simulations. Both the measurements and simulations demonstrated the relationship between penetration depth and source-detector distance. As source-detector distance increased, signal level decreased linearly in log-scale. The source-detector distance has an impact on penetration depth and information content of PPG signals. By utilizing the simulation, we can investigate the effects of source and detector angles on the PPG signal and optimize the received signal.

A first prototype to record the PPG curve using VCSEL and LEDs as well as a simulation framework was developed and validated. The next steps include the improvement of the prototype to perform the subject study as well as the exploration in the field of photon-tissue simulations.

Acknowledgement

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Literature

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