Pulse Oximetry - Teaching basic Electronic Sensor Signal Processing in a Medical Context

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***Abstract*—This innovative practice work-in-progress paper presents the outline of a bachelor level medical engineering lab that comprises electronical sensor signal processing. It explains how to teach and educate medical technology students the entire signal processing chain up to medical interpretation based on the practically relevant, widespread example of pulse oximetry. The various analog circuit blocks and the required post-processing with a microcontroller are discussed, as well as the interaction of all blocks to form the pulse oximeter system.**

For this purpose, the students are divided into small teams of three and receive a printed circuit board developed specifically for the experiment. With this board it is possible to extract certain parts of the signal processing measurement chain and analyze them with different tools, e.g. wave generator and oscilloscope. The accompanying handout guides and challenges students through the complex analysis of pulse oximetry, with subtasks to assist them. Tutors are available to support students with questions or if they get stuck.

The aim of this practical exercise is for the students themselves to understand which individual steps are required and how they interact in order to obtain a valid measured value at the end. They learn the practical relevance and application of various electronic components and filter circuits, as well as the subsequent digitization and post-processing with the help of a microcontroller. In addition, the participants will familiarize themselves with the use of various measuring devices. The associated handout and its tasks do not provide step-by-step instructions. The students are encouraged to think creatively in their groups and to engage in group discussions so they understand the problem and find a solution for each subtask. After solving each subtask, the group receives feedback from a tutor who explains whether the solution to the task is right or wrong and whether there could have been smarter ways.

By the end of the exercise, the students will have understood the complete signal path in depths from the sensor to the interpretation of the measured value and all the difficulties involved, based on a modern medical technology application.

***Index Terms*—pulse oximetry, group work, teaching, practical project, signal processing, independent thinking**

I. Introduction

Pulse oximetry has become an indispensable tool in the medical field. It is used to monitor the pulse and oxygen saturation of the blood and can be found in almost every hospital around the world. In particular, it is used to care for anesthetized or comatose patients and reduce the hypoxic risk to the fetus during childbirth [1]. Even in smartwatches and modern health tracking systems, it has become an almost permanent feature. This allows, for example, measuring the effectiveness of the training [2] making it also tangible for students. Due to this high relevance of pulse oximetry in medicine and consumer electronic it can be used as a perfect example in teaching. The students should be motivated for the lab with this practical application. They gain a deeper understanding of an everyday life application and at the same time the function of the individual necessary components. From the control of the actuators, recording of sensor data, to the processing by using various electronic circuits, the students learn all the individual parts of electronic sensor signal processing. Finally, the processed data is digitized and evaluated in a medical context with the help of a microcontroller. After the practical course, not only have disjointed circuit techniques been taught, but all the individual parts come together to form a complete construct - the pulse oximeter.

In the first part of this work, the printed circuit board purpose built for the practical course is presented. This is provided to the students for the experiment and provides the basis for the processing of the individual subtasks, which serve as a guide through the lab. The second part explains some tasks and how they fit into the overall context. Finally, the third section describes the course schedule.

II. Circuit Board

In the first step, commercial pulse oximetry devices were analyzed. It is noticeable that very inexpensive devices in the range of 30 $ contain relatively few analog circuit components and digitize the signal directly. An expensive medical device in the 600 $ range, on the other hand, requires an enormous amount of circuitry to ensure that the signal can be measured without interference, even in the presence of movement or varying levels of sunlight. This means that neither of the two types of device can be used for a practical experiment in the third semester of the medical technology course. In order to teach the basics of signal processing, a simple and clear circuit topology is needed, which however still relies on analog circuits. In summary, the newly developed circuit should have the following properties:

- comprehensible analog circuits
- various complex circuits

- measurements by oscilloscope in the processing chain
- feeding external signals by wave generator
- completed circuits for short subtasks

Figure 1 shows the model of the newly developed circuit board used in the experiment. The individual circuit parts are summarized and labeled in the white bordered rectangles. The signal chain is arranged from left to right, starting with the generation of the LED pulse signal, through processing to the output stage on the right. The microcontroller, which digitizes the signal and outputs the oxygen saturation, the pulse and the wave diagram via the display, is located in the upper middle section. With the help of the rotary potentiometers and switches, various circuit parts can be set for the individual experiments.

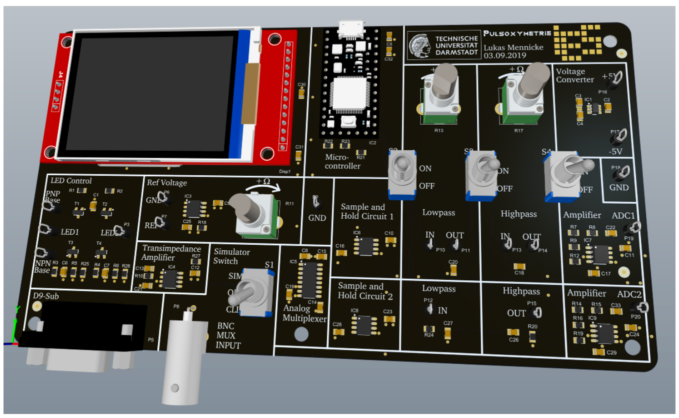

Fig. 1. 3D model of the circuit board

The finger clip sensor is connected at the bottom left of the board. It contains two LEDs, one red and one infrared, and a photodiode, see figure 2. Pulse oximetry is based on Lambert-Beer's law, which defines the absorbance, i.e. the attenuation of monochromatic light as it passes through a homogeneous liquid [3].

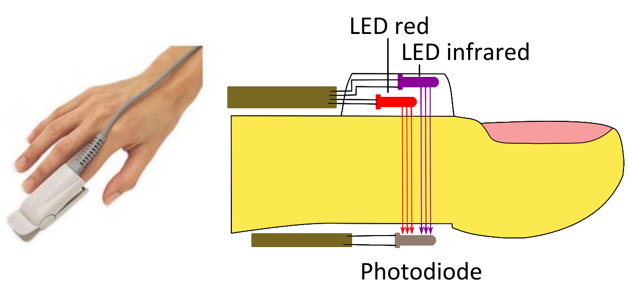

Fig. 2. Fingerclip Sensor [4] [5]

The simplified block diagram in Figure 3 is intended to provide a brief overview of the individual circuit parts. The red and infrared LED in the finger clip is controlled with a combination of PNP and NPN transistors. This allows control of pulse width and amplitude with the microcontroller. The photodiode in the finger clip converts the light intensity proportionally into current, which is then amplified by the transimpedance amplifier and converted into voltage. The following switch can be used to switch between the finger clip sensor and a simulation signal. The simulation allows the individual experiments to be processed even if the students do not wish to carry out measurements on their own bodies.

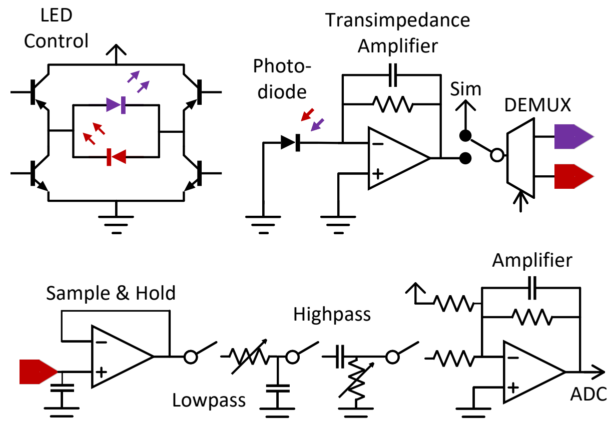

Fig. 3. Simplified overview of the board as block diagram. The path of the infrared signal (marked purple) after the DEMUX is left out. This is identical to the red path (marked red), but does not provide any setting options (potentiometer, switches).

After repeatedly switching between the two LEDs in short (2ms) time intervals, the two signals must be split using a demultiplexer (DEMUX) and a subsequent sample & hold circuit. Figure 4 shows the raw signal from which one can hardly read the heart rate. The envelopes of the raw signal represent the two LEDs. Due to the red and infrared light are attenuated differently by human tissue and blood oxygen saturation, there is an offset between the two signals [6]. After separating and filtering the red and infrared signals, the typical heart rate images of pulse oximeters can be seen. The early separation of the two signals makes the different filtering more vivid for the students.

In one of the signal paths the low- and highpass filters can be extracted with the help of the switches. For different exercises the filter frequencies can be adjusted via the rotary potentiometers. At the output stage, the signal is amplified again and raised to a voltage between 0 and 3.3 V for the analog-to-digital converter (ADC). The microcontroller then calculates the oxygen saturation, the pulse and the wave diagram from the two received signals. These values can be seen on the display.

Picture 5 shows the finished board. The small metal eyelets are used for easier measurement, or signal injection by oscilloscope or signal generator. So that even very cautious students can perform various tests on board without much worry, the individual circuit parts are designed in such a way that hardly any damage is possible even in the event of major operating errors.

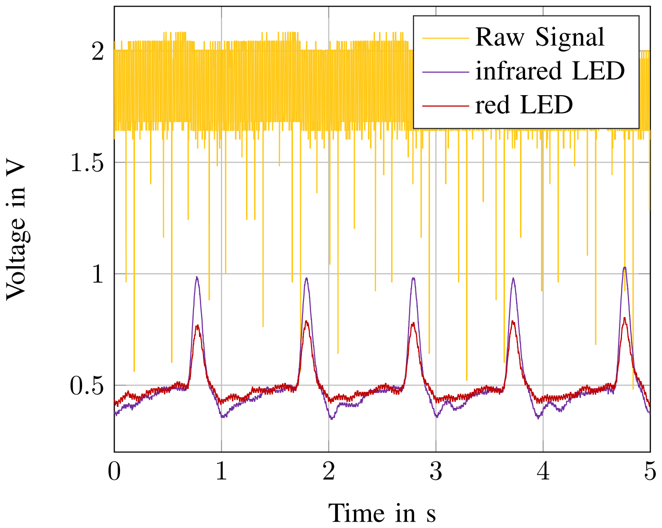

Fig. 4. Measured raw signal before the separation and the individual filtered signals afterwards

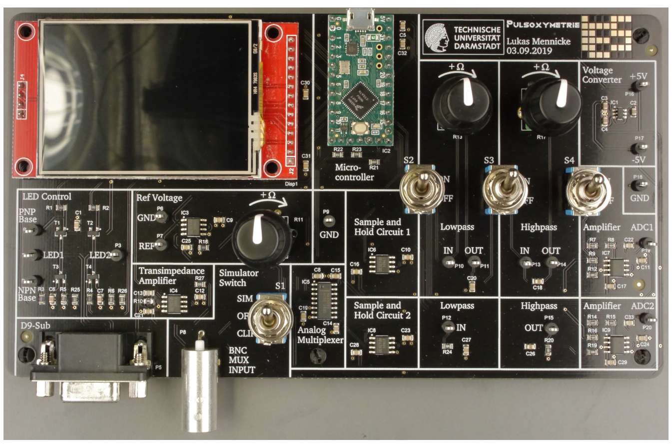

Fig. 5. Experimenters board for the students

III. Tasks

In this part of the paper, the students' tasks are examined in more detail, focusing mainly on the beginning and the end of the lab. The individual parts of the experiment build on each other as far as possible and increase in difficulty. When working on each individual task, it is important that the students are not given a predefined solution path, but work on the tasks themselves in a creative and solution-oriented manner [7]. Students should initially become familiar with the equipment. Subsequently, the tasks guide them through the signal chain in the same way as the further processing of the electrical signal. Finally, the processed signal is analyzed and medically interpreted.

A. Familiarize with the equipment

In the first exercise, students first of all familiarize themselves with the equipment needed for the experiment. The high-pass and low-pass filters are ideal for this purpose. These can be decoupled from the rest of the circuit using the switches and are easy to understand. In the assignment, a few test conditions are given for the use of the signal generator, oscilloscope, circuit board, and the basic use of test leads and probes is explained. For example, a signal from the signal generator must not be fed into the circuit using an oscilloscope probe.

B. Control of the finger clip sensor

The first step in the signal chain is the activation of the LEDs in the fingerclip. For this purpose, a circuit of NPN and PNP bipolar transistors is used, which are controlled by the microcontroller by means of pulse width modulation (PWM). The parameters of the PMW can be changed via the serial interface to the microcontroller. This part of the practical course is intended to give the students the opportunity to apply the theoretical knowledge they have acquired in other lectures on bipolar transistors. This consolidates the knowledge and gives a safer handling [8]. The main focus is on a deeper understanding of transistor circuits and the basic differences between NPN and PNP transistors.

C. Photodiode and signal processing

After the students have dealt with the generation of the signal, the circuit parts transimpedance amplifier, DEMUX in connection with the sample & hold circuit, as well as the active output stage are closely examined in several subtasks. The processed signal can then be digitized by the ADC and further processed in the microcontroller. In each case the functionality, as well as the use, and/or reason for the necessity in the signal processing chain is explained. For example, the fact that the photodiode can be simplified as a current source is discussed in more detail. Since the useful signal is to be converted into a voltage in the further processing of the circuit, a transimpedance amplifier is used. This amplifies and converts the current of the photodiode into a voltage.

D. Medical interpretation

The first run of the practical lab has shown that the medical technology students are particularly interested in the interpretation of the signals in a medical context and work on these task parts with a lot of eagerness. The points of pulse measurement and measurement of oxygen saturation in the blood are discussed. As an important note to students, it is always stated that the test boards are uncalibrated and the measurements of blood oxygen saturation only measure realistically to a small degree. If a student is interested in obtaining correct values, a clinical pulse oximeter is available for measurements.

An example of an exercise task is to determine the total gain of the circuit. Various empirical approaches and equations exist for the analysis of blood oxygen saturation [9], [10]. The equation used involves the logarithm, which is why the gain factor of each component in the circuit is important. Since the students have already dealt extensively with the individual parts, the relationship of all circuit blocks will now be discussed. Based on this point of view, the total gain is to be determined by calculation and measurement, so that in the end a value for the oxygen saturation can be derived from the light pulses detected by the photodiode. In these last parts of the practical lecture, it becomes clear how the interaction of the individual analog circuits can be used to determine a complex measurement system and finally medical values.

IV. Course schedule

This section describes the basic realization of the lab and the ideas and reasons behind it. The most important learning outcomes here are teamwork and solution-oriented work. These two essential skills are in addition to the technical competence indispensable and will also be an important part in the later professional life of engineers. The guiding principle of the course always deals with the fact that the existing problems should be solved costructively in a group. [11], [12]

In order to achieve this, the students are divided into small groups of three participants each before the start of the lab. In this constellation, the processing of the tasks, as well as the follow-up takes place. The preparation takes place individually by means of a handout. The individual parts of the task do not provide a step-by-step solution. The groups should think about the problems themselves and develop their own solutions. During the processing of the different tasks in the laboratory, specially trained tutors are available to answer questions about the experiment and help if the students get stuck. After completion of each small sub-task, there is a short discussion with a tutor. In this discussion, the solution and the approach should be briefly considered. The tutor's task is to determine the correctness or possible errors. In addition, further concepts and possible ways of solving the problem will be discussed.

During the individual parts of the exercise, the students should document their solutions and approaches in short bullet points. The post-processing does not take place as a classical elaboration or report, but via an online platform with multiple choice questions. In the future, the online platform will be expanded so that each group comes up with a new question about the lab. These questions will then be made available to all students to prepare for the exam. In order to motivate students to work on the comprehension questions they have developed themselves even after the completion of the experiment, it will be communicated that one of these questions will appear in the exam.

V. Conclusion

This paper explains a continuously improved practical lab for medical technology students in which they learn from the functional principle of the individual circuit blocks through the application of the overall circuit to the interpretation of the signal based on the highly relevant and widely used example of pulse oximetry.

This course is a uniquely interesting and motivating lab for students. The main focus is on the interlocking of theory and practice, as well as the interdisciplinarity between medicine and electrical engineering on an everyday life application. The students gain a broad spectrum of knowledge from the fundamental electronic sensor signal processing, electrical engineering and medicine. In addition, the enormously important skills of teamwork and independent thinking are fostered in this course. All in all, the students who completed this course will have had a lot of fun and learned a wide variety of skills.

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