D. Laqua*, C. Brieskorn, J. H. Koch, M. Rothmayer, S. Zeiske, M. Böttrich, S. Ley, and P. Husar

FPGA controlled artificial vascular system

Abstract: Monitoring the oxygen saturation of an unborn child is an invasive procedure, so far. Transabdominal fetal pulse oximetry is a promising method under research, used to estimate the oxygen saturation of a fetus non-invasively. Due to the nature of the method, the fetal information needs to be extracted from a mixed signal. To properly evaluate signal processing algorithms, a phantom modeling fetal and maternal blood circuits and tissue layers is necessary. This paper presents an improved hardware concept for an artificial vascular system, utilizing an FPGA based CompactRIO System from National Instruments. The experimental model to simulate the maternal and fetal blood pressure curve consists of two identical hydraulic circuits. Each of these circuits consists of a pre-pressure system and an artificial vascular system. Pulse curves are generated by proportional valves, separating these two systems. The dilation of the fetal and maternal artificial vessels in tissue substitutes is measured by transmissive and reflective photoplethysmography. The measurement results from the pressure sensors and the transmissive optical sensors are visualized to show the functionality of the pulse generating systems. The trigger frequency for the maternal valve was set to 1 per second, the fetal valve was actuated at 0.7 per second for validation. The reflective curve, capturing pulsations of the fetal and maternal circuit, was obtained with a high power LED (905 nm) as light source. The results show that the system generates pulse curves, similar to its physiological equivalent. Further, the acquired reflective optical signal is modulated by the alternating diameter of the tubes of both circuits, allowing for tests of signal processing algorithms.

Keywords: fetal pulse oximetry; artificial vessel system; tissue phantom; artificial pulse wave

*Corresponding Author: D. Laqua: Technische Universität Ilmenau/Biosignal Processing Group, Ilmenau, Germany, +49 3677 69-2860, E-mail: daniel.laqua@tu-ilmenau.de
C. Brieskorn, J. H. Koch, M. Rothmayer, S. Zeiske, M. Böttrich, S. Ley, P. Husar: Technische Universität Ilmenau/Biosignal Processing Group, Ilmenau, Germany, E-mail: carina.brieskorn@tu-ilmenau.de, jan-hannes.koch@tu-ilmenau.de, markus.rothmayer@tu-ilmenau.de, steve.zeiske@tu-ilmenau.de, marcel.boettrich@tu-ilmenau.de, sebastian.ley@tu-ilmenau.de, peter.husar@tu-ilmenau.de

1 Introduction

A lack of oxygen can lead to serious damage in brain development of the fetus before or during labor and delivery. There is still no procedure to determine the fetal oxygen saturation non-invasively. Invasive methods are a risk for mother and fetus and only will be acceptable in case of a strong suspicion of a risk for the fetus.

There is no reliable description in literature for the light modulation when passing the pulsating vessels of mother and fetus. This however is an essential premise for separating the pulse wave curve from mother and fetus.

Due to these uncertain conditions, a realistic phantom is needed to analyze the nature of transabdominal fetal pulse oximetry in detail. A phantoms allows to generate predefined and deterministic conditions and can be used to evaluate signal processing algorithms. Two separate artificial blood circuits are needed to simulate fetal and maternal pulse curves and further analyze photoplethysmographic signals.

Complex phantoms with various interdependent actuators and sensors require a suitable, real-time controlling system. It is difficult to meet properties of real-time systems with computer-based solutions. Embedded systems or field-programmable gate arrays (FPGA) are an appropriate solution for such a task. The architecture has a high real-time performance for controlling peripheral components.

Oura et al. [1] and Parlikar et al. [2] developed an extremely compact mock circulation system, which can simulate artery blood circulation and generate a pulse wave with very small amounts of blood. The patent for a blood vessel model for medical training from Umezu et al. [3] includes an artificially fabricated tube as simulated vessel partly buried in a base. The patent of Holdsworth et al. [4] for a computer controlled positive displacement pump produces a physiological flow stimulation. In a previous investigation, we tried to generate pulsatile waveforms with a roller pump and a stepping motor [5]. The resulting waveforms contained an unacceptable oscillation, induced by the roller pump. An alternative approach is described by Laqua et al. [9]. A pre-pressure system in combination with controllable valves allows to generate the pulse curves without oscillation, close to the physiological equivalent.

The work of Jurovata et al. [6] describes the light transport, photon trajectory and the interaction in tissue. Therefore, a Monte Carlo simulation has been implemented in Matlab to evaluate the light distribution and the penetration depth without patients.

In order to examine the optical properties of tissue, Suzaki et al. [7] investigated the relation between optical density (defined as O.D.) of whole blood and hematocrit by transmission spectrophotometry during pulsating blood perfusion. The optical characteristics of artificial tissue were investigated by Ley et al. [8].

2 Material and methods

The block diagram as shown in Fig. 1 describes the improved hardware concept using a CompactRIO from National Instruments. The system includes a processor and an FPGA and can be customized for various tasks adding different hardware modules. In the case of the phantom, we use two different types of modules. Firstly, NI 9401 digital I/O-modules, which are connected to all the controllers symbolized by red lines and secondly, NI 9239 analog modules used for data acquisition (green lines).

However, lets take a closer look at the single components. For regulating the stepper motors two controllers (SMCI12 from Nanotec Electronic GmbH & Co KG) are used. Programming of the controllers is done via a RS-485 interface and allows to adjust the driving profiles of the motor. The CompactRIO-System triggers the driver by two digital signals as higher level controller.

The proportional valves are used to generate the pulse curves. They are controlled by PWM signals, generated by
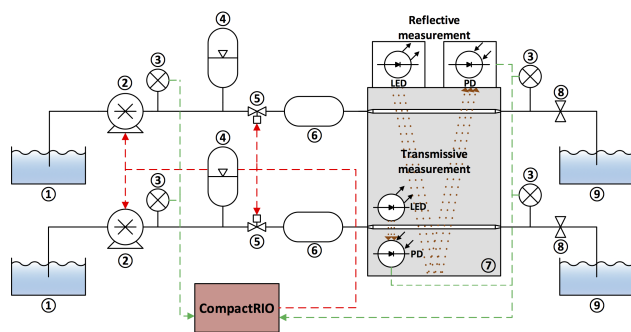
Figure 1: Improved hardware concept using a CompactRIO from National Instruments including an embedded processor and an FPGA; components: (1) Reservoir, (2) Roller pump, (3) Pressure sensor, (4) Pressure tank, (5) Proportional valve, (6) Compliance, (7) Artificial tissue with fetal (lower) and maternal (upper) circuit, (8) Resistance, (9) Catch tank
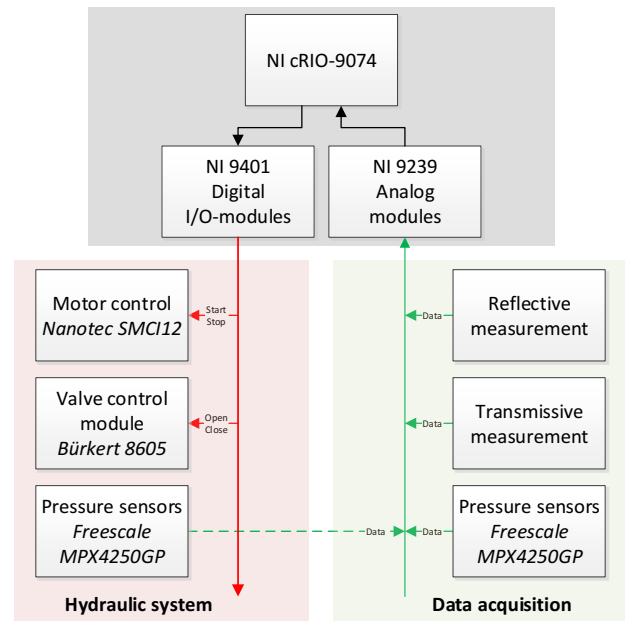

Figure 2: Hydraulic control for the proportional valves to generate the pulse curves and the control for the stepping motor modules with the roller pumps; Data acquisition for the pressure sensors and the optical sensor elements

two control modules (Fig. 2). These modules are connected to the CompactRIO using an RS-232 interface.

The experimental model to simulate the maternal and fetal blood pressure curve consists of two identical circuits. Each of these circuits is split into a pre-pressure system and into an artificial vascular system. Two proportional valves control the flow and separate the pre-pressure system from the secondary sub-system. The non-linear extension characteristic of the aorta, the so called Windkessel function, is reproduced by the compliance in the artificial vascular system. To simulate the total peripheral resistance of the Windkessel model a resistance element is used. For the determination of the outcome flow two different types of clamps are used for the maternal and fetal circuit. An explicit description of the two sub-systems and the elements of the systems can be found in a previous work [9]. The tissue phantom consists of transparent silicone tubes with an internal diameter of 5 mm and a wall thickness of 0.5 mm, which are molded in the artificial tissue made of silicone.

The measurement system in detail is described by Laqua et al. [9]. The dilation of the artificial fetal and maternal vessels in tissue substitute is measured by transmissive photoplethysmography. Two LEDs are used to irradiate the artificial vessels with light in the infrared range, respectively. A photo detector acquires the transmitted optical signal, modulated by the alternating tube. In addition,
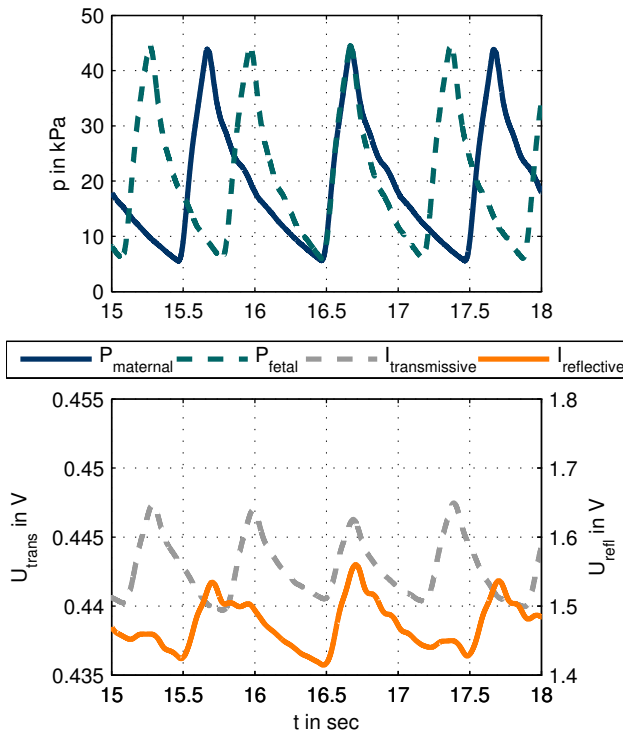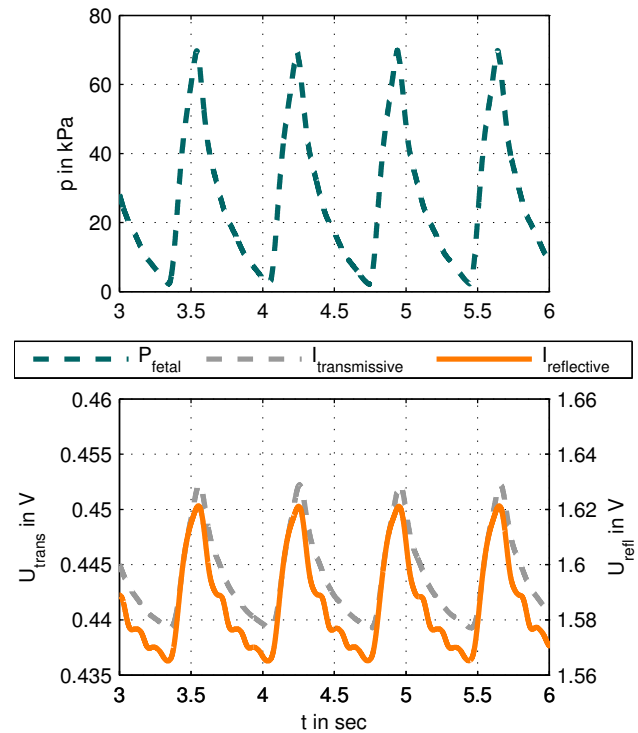
Figure 3: Artificial pulse waves for mother and fetus; the upper part of the diagram shows the maternal and fetal pressure measurements; In the lower part of the diagram the reflective and transmissive plethysmographic measurements are depicted

Figure 4: Artificial pulse waves with solely the fetal circuit active; the upper part of the diagram shows the pressure measurement of the fetal pulsatile curve; In the lower part of the diagram the reflective and transmissive plethysmographic measurements are depicted

pressure sensors are integrated, for gathering the maternal and fetal pressure curves as a reference for the plethysmographic measurements.

The signals from the pressure sensors of the fetal and maternal vascular system, as well as of the pre-pressure system is acquired by the analog input module NI 9239. Furthermore, a second module is used for photoplethysmographic data acquisition.

To reproduce the optical properties of the maternal and the fetal tissue, tissue substitutes have been developed. Therefore the different types of tissues, like skin, muscle or fat, are represented by one layer, so that there is one maternal and one fetal layer. The amniotic liquor is modeled by an extra layer. RTV silicone rubber is used as a solid carrier material, because its refractive index is similar to the refractive index of human soft tissue. Moreover the mechanical properties can be varied by changing the mixture of the RTV silicone rubber. Light scattering and light absorption reproduced by adding Titanium dioxide and cometic powder, mixed into the carrier material. The maternal and fetal tissues differ in the concentrations of the additives. The studies of the optical properties of the additives were conducted in a previous work. [10]

The individual layers, which represent the maternal and fetal tissues and the amniotic liquor, are poured into a wooden box, so that the tissue phantom is measuring 215 mm x 200 mm x 52 mm (L x W x H).

3 Results

Fig. 3 shows the measured simulated pulse waves for mother and fetus. The upper part of the diagram shows the maternal and fetal pressure measurements, which range from 5 to 45 kPa. The trigger frequency for the maternal valve was set to 1 per second, and the fetal valve to 0.7 per second. It can be seen that a peak is reached after a short while which decays over a longer time period. A dicrotic pulse is visible in both curves. The curve therefore resembles the human arterial blood pressure curve. In the lower part of the diagram the plethysmographic measurements are depicted. The data was superimposed by high frequency disturbances and was therefore filtered with a Chebyshev low-pass filter with a pass frequency of 5 Hz and stop frequency of 25 Hz before plotting. As expected,

the transmissive measurement corresponds qualitatively to the fetal pulse curve, as it was measured in the same circuit. The peaks in both measurements occur at the same time.

The reflective curve, which was obtained with a high power LED as constant light source with a wavelength of 905 nm, is obviously more complex. It is modulated by the diameter changes of both artificial vessels. The curve rises and decays according to the pressure in both vascular systems. It is noticeable that the influence of the maternal pulses is higher than the fetal. This is due to the fact that the maternal tube is closer to the surface of the tissue substitute and consequently closer to the light source and the sensor respectively. Yet the possibility is given to decompose the reflective curve to gain the pulse wave curves of the single systems. To assess the influence of a single pressure curve a measurement with solely the fetal circuit active was conducted. This measurement can be found in Fig. 4. In the regions after the peak it can be seen that the reflective measurement is very sensitive to pressure changes.

4 Conclusion

In this contribution a phantom for producing plethysmographic curves, which is controlled by an FPGA based CompactRIO System from National Instruments, has been developed. It contains two independent liquid closed loops, which reproduce the maternal and fetal pulse waves in tissue substitutes. The data acquisition and recording of the sensors is executed by the FPGA-system. The sensor system and the tubes were poured into tissue substitute made of silicone. Beside the optical sensor system, a capacitive sensor system has also been integrated. However, the connection to the cRIO-system is still outstanding, but will be realized as future work. As a future perspective an artificial blood substitute shall also be applied. At the moment this blood substitute is still under development. Furthermore, a new artificial tissue substitute phantom should be built, which reproduces the bending of the belly during pregnancy.

Author's Statement

Conflict of interest: Authors state no conflict of interest. Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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