City Research Online

City St George's, University of London

Citation: Rybynok, V., May, J.M., Budidha, K. & Kyriacou, P. A. (2013). Design and Development of a novel Multi-channel Photoplethysmographic Research System. In: 2013 IEEE Point-of-Care Healthcare Technologies (PHT). (pp. 267-270). IEEE. ISBN 978-1-4673-2765-7 doi: 10.1109/PHT.2013.6461336

This is the accepted version of the paper.

This version of the publication may differ from the final published version. To cite this item please consult the publisher's version.

Permanent repository link: https://openaccess.city.ac.uk/id/eprint/3545/

Link to published version: https://doi.org/10.1109/PHT.2013.6461336

Copyright and Reuse: Copyright and Moral Rights remain with the author(s) and/or copyright holders. Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge, unless otherwise indicated, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way. For full details of reuse please refer to City Research Online policy.

City Research Online: http://openaccess.city.ac.uk/ publications@citystgeorges.ac.uk

Design and Development of a novel Multi-channel Photoplethysmographic Research System

V. Rybynok[1], J. M. May[2], K. Budidha[3], and P. A. Kyriacou[4], *Senior Member, IEEE*

Abstract— Photoplethysmography (PPG) is a non-invasive optical technique used in detecting blood volume changes in vascular tissue. In recent years, photoplethysmography has generated renewed interest among researchers, particularly due to its potential for widespread clinical applications beyond estimating heart rate and arterial oxygen saturation. Progress in these areas of research is dependent on PPG systems with the ability to record raw photoplethysmographic signals with high signal-to-noise ratio, ideally from more than one channel and one wavelength, for real-time or retrospective analysis. In this work we present the design, development and validation of such a modular PPG system. "Zen PPG"- a portable (16.0 x 10.3 x 5.4 cm) battery operated dual channel, dual wavelength system with the capability to operate with commercial sensors was developed and calibrated using a FLUKE Index 2 SpO_2 simulator. A brief study has been conducted on a small group of healthy volunteers to demonstrate the functionality of the system. Red and Infrared PPG signals obtained from volunteers were used to estimate SpO_2 and heart rate. These results were compared with simultaneously acquired data from a commercial pulse oximeter (Masimo Radical 7). The SpO_2 values showed close correlation between commercial and custom made system (Channel 1: r^2 = 0.978; channel 2: r^2= 0.708).

I. INTRODUCTION

Optical spectroscopic investigations of human tissue and blood date back as far as the late nineteenth and early twentieth century, where Hertzman and Aoyagi are widely credited with introducing Photoplethysmography (PPG) [1]. PPG is a non-invasive optical measurement technique used to detect blood volume changes in peripheral vascular bed [2]. Photoplethysmography is based on the absorption properties of vascular tissue when it is transilluminated by light. The emitted light, which is made to traverse the skin, is reflected, absorbed and scattered in the tissues and blood [2]. The scattered light which reaches the other end of the tissue is detected by a photodetector. The intensity of the scattered light which reaches the photodetector is measured and the variations in the photodetector current are assumed to be related to blood volume changes underneath the probe. These variations are electronically amplified and recorded as a voltage signal called the photoplethysmograph. The photoplethysmograph comprises of a pulsatile ('AC') physiological component synchronized with the cardiac cycle, riding on a slowly varying (DC) baseline [2]. These photoplethysmographs obtained from tissue vasculature by shining light at two different wavelengths (red and infrared) is used in estimating arterial oxygen saturation (SpO2), and this technique is known as pulse oximetry [2].

In recent years, due to the technical advancements in signal processing algorithms, photoplethysmography has gained renewed interest. Particularly since its potential use as a diagnostic tool for measuring physiological variables beyond arterial oxygen saturation and heart rate has been demonstrated. These variables include vascular diagnostics, blood pressure measurement, venous oxygen saturation [3], and fluid response. Another area in which photoplethysmography has gained immense interest is in the development of unique sensor technology, which can be used to estimate physiological variables in conditions of compromised peripheral blood supply [2]. These sensor technologies are usually validated by acquiring data from custom build and manufacturer systems. All these advancements in the field of photoplethysmography are dependent on the ability of PPG systems to produce high quality raw photoplethysmographic signals. Also, as most of these studies are performed in clinical environments such as ITU, ICU and operating theatres it is a tedious process acquiring data from custom made and OEM pulse oximeters simultaneously for real time or retrospective analysis. This illustrates the need for a portable, multi-channel, multi wavelength, multi parametric PPG system.

Hence we propose 'Zen PPG' – A dual channel, dual wavelength PPG research system, which combines the advantages of standardization of instrumentation, compatibility with commercial probes and the ability to customize the system for specific projects. In this paper we introduce the design and development of the proposed technology in detail and provide a preliminary assessment of its performance.

II. METHOD

A modular and constructive design approach was implemented in the design of Zen PPG. The PPG system was constructed to pre-process, record and display raw PPG signals from two channels and two wavelengths on a laptop personal computer. The main parts of the system are: a

Manuscript received 28th September 2012

[1]V. Rybynok is with the School of Engineering and Mathematical Sciences, City University London, London UK

[2]J.M.May is with the School of Engineering and Mathematical Sciences, City University London, London UK

[3]K. Budidha is with the School of Engineering and Mathematical Sciences, City University London, London UK

[4]P.A. Kyriacou is with the School of Engineering and Mathematical Sciences, City University London, London UK (email: p.kyriacou@city.ac.uk)

system bus, PPG modules (current supplies, probe connector board and transimpedance amplifiers) and power supply conditioning board. All the modules were designed to be as simple as possible allowing incremental improvement during subsequent development of the system. The mechanical structure of the system is shown in Fig 1.

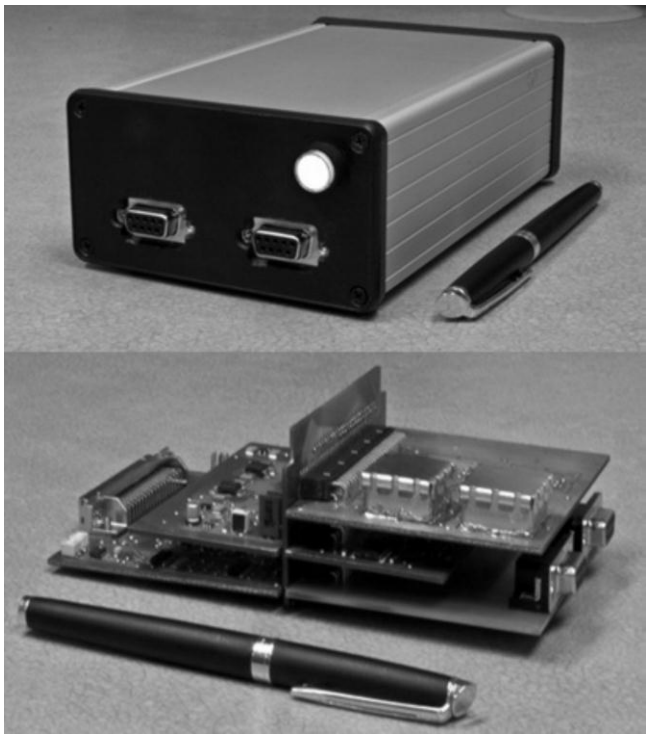

Figure 1. Shows the mechanical structure of Zen PPG

A. Mechanical Construction of the Processing System

Printed circuit boards (PCB) of all the modules along with a dual 9v PP3 battery case were housed in a rectangular portable unit measuring 16.0 x 10.3 x 5.4 cm. Modern surface mount JFET technology has been used for analogue circuitry on all the PCB's. The front of the unit incorporates two standard D9 connectors for connecting two probes, and an on/off switch to control the system. The rear panel consists of a 68-pin serial bus connector for interfacing to a National Instruments data acquisition card and access to two trimmers which can be used to control the LED currents. This modular approach to the design provides efficient troubleshooting and easy customization of the system for specific research projects. For instance, the current hardware multiplexing core board can easily be exchanged with a software controlled core board.

B. Electrical design of Zen PPG

Zen PPG consists of 6 PCB modules, each with specific functions.

1) System Bus: The system bus as shown in figure 1, consists of six (three on each side) receptacle 50 way SAMTEC surface mount connectors. It is designed in such a way that every single pin in any connector corresponds to the same pin in all the connectors. Since all the 50 pins on every connector are the same, it provides a medium of interaction between various modules. All the PPG modules and the power supply conditioning board are furnished with gold plated through-hole right angle 50 way headers which can be inserted into the connectors on the bus board.

2) Power supply module: The whole PPG system is powered with two rechargeable 9v PP3 batteries. The power supply conditioning board generates three different voltage outputs from the ±9v battery supply.

- Positive (MC78M05CDTG) and negative (MC79M05CDTG) voltage regulators generate ±5v supply (INEG and IPOS), which is used for multiplexing and driving LED currents in the system.
- A +3.3v and -1.4v supply is generated using MCP1703T and LT1964ES5 voltage regulators. This supply is used to power all the analogue chips on the transimpedance and core board.
- A digital power supply of 3.3v is generated using a positive voltage regulator (MCP1703T). This supply is used to operate the micro-controller on the core board.

3) PPG Modules: The PPG modules include the core, current source, transimpedance and probe board.

a) Core Module: The core board is the heart of the processing system. An Atmel ATtiny 2313-20SU micro-controller is used as a Master clock and timing generator. The micro-controller is programmed using Atmel STK500 micro-controller programmer. The STK500 can be connected to the micro-controller on the core board by 6-pin ISP header. The micro-controller is programmed to generate digital switching signals at a frequency of 500Hz. These digital signals directly correspond to the LED switching. The PPG system has an added capability of control over LED currents. The LED currents can be controlled digitally on one channel and by using manual trimmers on the other. The digital control over LED currents on channel one is possible by generating an analogue positive and a negative 5V (max) signals from a 16 bit data acquisition card (DAQpad-6015 National instruments corporation, Austin, Texas) and passed into the system via 64 pin NI connector on the core board. These ±5V signals from the DAQ card are passed through a ±5V to ±1V attenuator on the core board and then passed through a dual 4-channel analogue multiplexer (MC1405BD). For the second channel, a positive voltage regulator on the core board generates a 1V signal which is passed through an inverting and a non-inverting trimming attenuator to generate a + and -1V (max) output signals. These signals are then passed through the same multiplexer. The multiplexer generates two digital signals, varying from +1v to -1V depending on the clocks form the micro-controller as shown in Fig 2. The time controlled signals from the micro-controller were also used for synchronizing the demultiplexer that separated the mixed PPG signals. The micro-controller can be programmed to demultiplex PPG's up to four wavelengths along with ambient light. Low pass filters with a cut-off frequency of 40Hz were then used to remove the high frequency switching noise from the demultiplexed raw signals. All the PPG output signals were

then digitised by a 16-bit data acquisition card and displayed on the laptop.

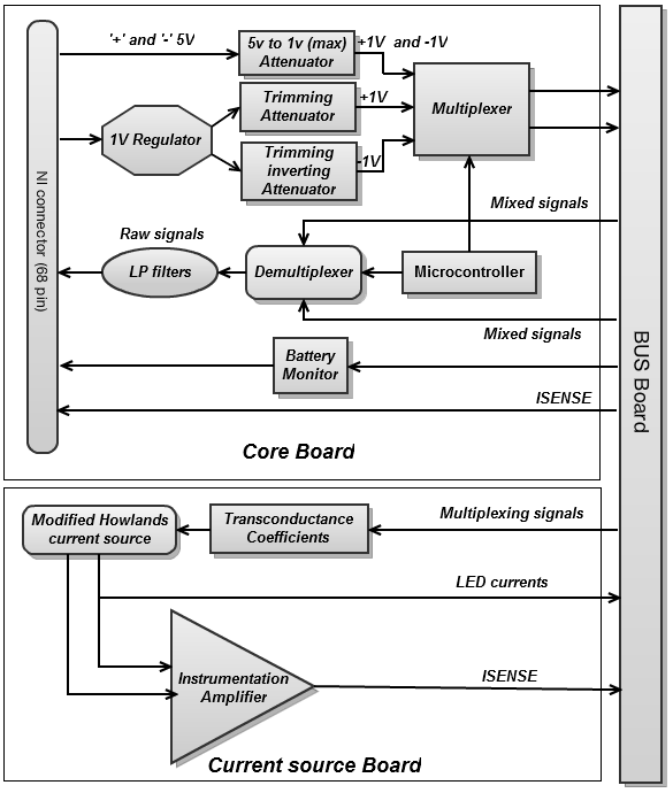

Figure 2. Flow diagram demonstrating the function of Core and current source modules

b) Current Source Module: Two identical current sources drive R (red) and IR emitters on both the channels. Each current source is designed to switch R and IR emitters at 500 Hz (each emitter is switched on every 2ms for an interval of 0.5ms). As shown in figure 2, the transconductance coefficient reduces -1v to 1v multiplexed signals from the core board to +100 mv to -100mV. This is to limit the current to a maximum of 100 mA. These signals are then passed through the transconductance amplifier which converts voltage to current. The transconductance amplifier used in the system is a modified Howland current source with a NPN-PNP transistor. When the current source input signal is positive, the NPN transistor is active and switches one emitter on, and when the input is negative, the PNP transistor is active switching the other emitter on. The system also has an added capability to continuously monitor emitter currents. This is achieved by inputting the voltages before the load resistor and the currents after the load resistor into an instrumentation amplifier as shown in Fig 2. The instrumentation amplifier produces an output voltage equivalent to the current across the LED's, which is passed through the bus into the core board and into the DAQ card for acquisition.

a) *Probe Module:* The probe board consists of two standard D9 connectors. The pin configuration for emitters and photodiode on the D9 connector is exactly the same as the manufacturer probes. This gives the flexibility to use most manufacturer probes with D9 connectors without any additional requirements.

c) Transimpedance Module: The transimpedance module consists of two identical transimpedance amplifiers. The photocurrents from the photodetector are converted into a mixed voltage signal consisting both R and IR PPGs. These mixed signals are then passed through the demultiplexer via the bus. The transimpedance amplifier is a simple Op-Amp with a gain resistor in negative feedback configuration.

4) Preliminary Evaluation and Calibration: Preliminary evaluation of the system was carried out by measuring R and IR PPGs from both the channels using two Masimo SET LNCS DCI adult reusable sensors (Masimo Inc., Irvine, CA, USA). The signals were acquired using 16 bit data acquisition card (DAQpad-6015 National instruments corporation, Austin, Texas). A LabVIEW virtual instrument (VI) was programmed to display the raw PPG signals on the Laptop PC. The ratio-of-ratios ('R' value) was calculated using

$$Ratio\ (R) = \frac{\frac{AC_{Red}}{DC_{Red}}}{\frac{AC_{IRed}}{DC_{IRed}}}$$

The R value was then used to compute arterial oxygen saturation using an empirically derived calibration equation [1].

$$SpO_2 = 110 - 25\ R \qquad (1)$$

A peak detection algorithm was implemented in LabVIEW to measure heart rate from PPG signals. The performance and accuracy of both the channels on prototype system were tested using Index 2 SpO_2 simulator (Fluke Biomedical, Everett, WA, USA).These assessments were performed by using a pre-loaded Masimo calibration curve in the simulator and a Masimo reusable finger probe. The SpO_2 values were decreased from 100% to 70% with 1% resolution, while keeping the heart rate constant at 70 beats per minute. Using the value of SpO_2 obtained from these assessments at each set SpO_2 level, calibration curves for both the channels have been derived. Although, good quality PPG signals and SpO_2 results were obtained using an SpO_2 simulator, in reality saturations values are limited by external, individual and technical factors. So in order to test the functionality and the accuracy of ZenPPG system on individuals, a brief study has been conducted on 7 healthy volunteers (male and female aged 21 - 31). In this study, PPG signals were recorded from first and second fingers of the right hand using two Masimo SET LNCS DCI adult reusable sensors (Masimo Inc., Irvine, CA, USA). These signals were then used to calculate SpO_2 values, which were compared with simultaneously-recorded SpO_2 values from a Masimo Radical-7 commercial pulse oximeter used on the first finger of the left hand.

III. RESULTS

The results of the assessment using both the channels of the ZenPPG system in conjunction with the Masimo probe were used to produce calibration curves as shown in Fig 3. A second degree polynomial was used to derive the following calibration functions:

$$SpO_2\ (Channel\ 1) = -19.49R^2 - 10.47R + 108.9 \quad (2)$$

$$SpO_2\ (Channel\ 2) = -18.98R^2 - 7.811R + 107.7 \quad (3)$$

Where R is the 'ratio-of-ratios' determined from the red and infra-red AC signals

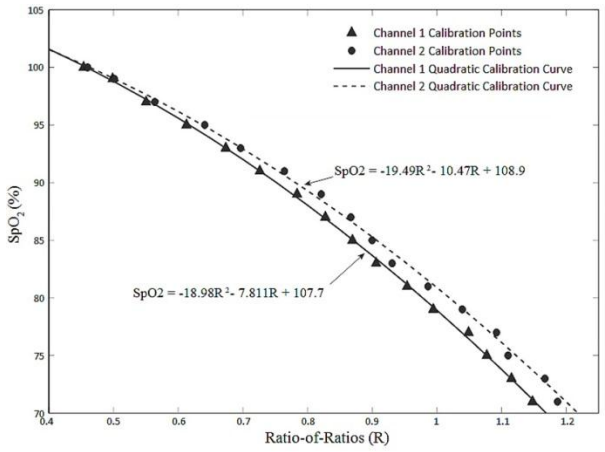

Figure 3. Calibration curve derived using ZEN PPG

Good quality PPG signals were obtained from all seven volunteers. Table 1 shows the SpO2 values obtained from seven healthy volunteers using the ZenPPG system and the commercial pulse oximeter. SpO_2 values were calculated from the raw signals obtained from both channels using equation (2) and (3) derived from Channel 1 and 2. It can be seen that SpO_2 results from the commercial system showed very good agreement with ZenPPG Channel 1 (r^2 = 0.978) and fair agreement with ZenPPG Channel 2 (r^2 = 0.768).

Subject #	Masimo Radical-7 (SpO_2 %)	ZenPPG Ch.1 (SpO_2 %)	ZenPPG Ch.2 (SpO_2 %)
1	95	94.76	95.57
2	99	99.61	98.56
4	97	97.84	97.61
4	98	97.84	94.85
5	95	94.19	92.79
6	98	98.56	97.41
Mean	**97.0**	**97.13**	**96.13**

Table 1: Comparison of SpO_2 values obtained from Masimo Radical-7 pulse oximeter with both the channels in ZenPPG.

IV. CONCLUSION

A novel dual channel and dual wavelength photoplethysmographic system has been developed and tested. The pilot volunteer study proved the ability of the system to produce high quality PPGs and accurately estimate SpO_2 values from either commercial or custom made sensors. A full scale hypoxic study needs to be conducted to accurately calibrate the system and generate new calibration functions. The capability of the system to acquire signals from four wavelengths and four channels with minor effort makes the system highly suitable for a wide range of physiological investigations.

The system possesses various advantages over commercially available devices; the modular design of Zen PPG allows the user to customize the system to any specific project requirements. The dual channel nature of the system gives the user an advantage in terms of complexity by not having to have to stack two pulse oximeters for comparative studies. The availability of digital current over LED currents and the modern JFET technology used in the system makes ZEN PPG power efficient when running from batteries.

REFERENCES

[1] J. G Webster, *Design of Pulse Oximeters*, 1st ed. Bristol: Institute of Physics Publishing, 1996.

[2] P. A. Kyriacou, "Pulse Oximetry in the oesophagus," *Physiological Measurement*, vol. 27, pp. R1-R35, 2006.

[3] Z. D. Walton, P. A. Kyriacou, D. G. Silverman, and K. H. Shelley, "Measuring venous oxygenation using the photoplethysmograph waveform," *Journal of Clinical Monitoring and Computing*, Vol. 24, pp. 295, 2010