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# Wearable, Wireless Reflectance-Sensing Pulse Oximeter

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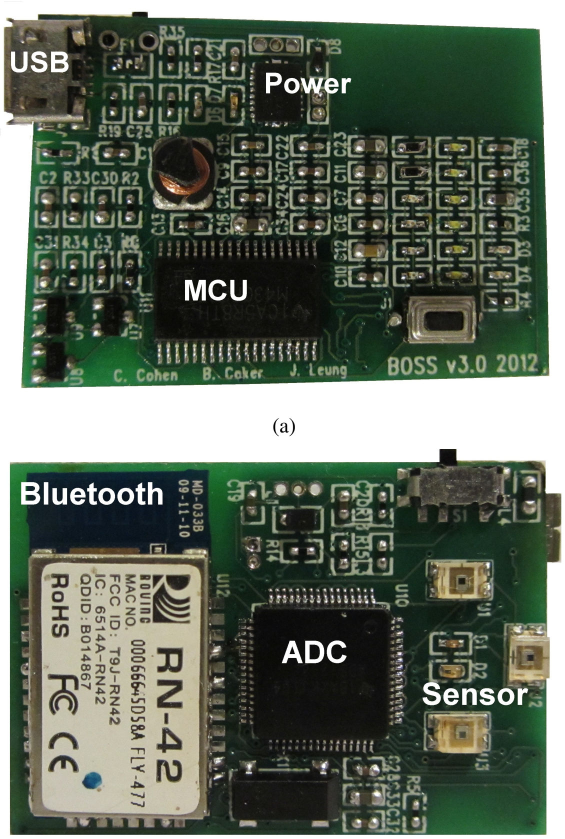
*Abstract*— **As body-area networks grow in popularity, the design of a low-power, user-friendly, non-invasive vital sign monitor is critical. In this work, we integrate concepts of low-power electronics, wireless telemetry, and reflectance sensing to a continuously-monitoring, wearable pulse oximeter. The primary objective of this system is detect the important vital signs of blood oxygenation levels ( $SpO_2$ ) and pulse rate through the user's wrist. The unit is compact enough to fit within a wristband, providing the freedom to continue performing other hands-on activities. Data is periodically collected from the device and transmitted to a Bluetooth-enabled smartphone for processing, where an application provides feedback to users with regards to their $SpO_2$ level and pulse rate.**

## I. INTRODUCTION

Pulse oximetry provides a noninvasive method to measure and monitor oxygenation of hemoglobin [8], more commonly referred to as $SpO_2$. The widespread usage of pulse oximetry and its ability to capture oxygen saturation levels has caused it to become known as the fifth vital sign [4] (the first four being pulse, respiration rate, body temperature, and blood pressure). Furthermore, oximetry using near-infrared spectroscopy on the forehead has been used to measure brain activity in the prefrontal cortex [1]. It has also been used for cuff-less sensing of blood pressure [19], which can be calculated by measuring the the time delay between pulse waves at two different body locations [16], thus requiring the use of two connected pulse oximeters. The basic technology behind pulse oximetry can be combined with only a few other sensors to potentially monitor all of the vital signs.

Because of this, there is ongoing research into making pulse oximeters smaller and more efficient. A conventional pulse oximeter is attached to a user's finger, making it very inconvenient for day to day activities. This limits number of measurements to those that the user initiates, which for many users would be infrequent and inconsistent due to the inconvenience. Therefore, the design of a wearable device that is capable of continuous, noninvasive pulse oximetry and does not impede a users everyday activities is desirable. To this end, size, weight, cost, and ease of use are all important factors in influencing the widespread adoption of such a device.

In addition to the everyday user that is interested in self-monitoring, there are a number of specific applications in which a wearable and continuously monitoring pulse oximeter would be useful. Oxygen saturation and heart rate are closely monitored during sleep studies, by pilots and climbers at high altitudes, on patients under anesthesia, and on hospital inpatients. For inpatients and sleep studies in particular, conventional pulse oximeters are attached to a nearby machine via long wires. For sleep study patients, a wearable pulse oximeter would allow them to sleep more naturally, without being restricted by those wires. Inpatients would no longer have to roll a large monitoring machine behind them when moving around the hospital. In both cases, a wearable pulse oximeter could potentially allow the monitoring to be done from a patients home, affording more comfort to the user and using up less hospital resources.



(a)

(b)

Fig. 1: Device prototype (top/bottom).

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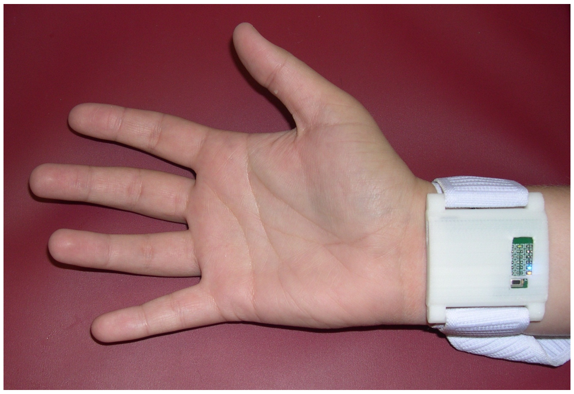


Fig. 2: Device in wristband enclosure

## II. SYSTEM DESCRIPTION

### A. *Sensor*

The design to detect oxygen saturation levels using reflectance pulse oximetry is similar to a conventional transmission based design, in which light absorption is detected at the wavelengths of red (660nm) and infrared (940nm). Rather than sensing the amount of absorbed light on the opposite side of the measurement location (such as an ear or finger), the sensors in a reflectance system are placed on the same side as the light source and detect the light that bounces back, which changes with the pulse waves and oxygenation levels. With this method, the location of the pulse oximeter is expanded to other locations such as the wrist, forehead, and chest.

As shown on the board in Fig. 1(b), three photodetector packages surround the red and infrared LEDs to ensure that as much of the reflected light as possible is captured by the sensors, increasing the signal-to-noise ratio [5]. The sensors are turned on by the microcontroller only when a measurement is taken in order to minimize their overall power consumption. Lowpass filters are also utilized at the sensor output to remove noise injection from high frequency signals.

### B. *Data Transmission*

After the reflected light is converted to a voltage by the sensor, the signal is passed through the filters to a high resolution analog-to-digital converter (Texas Instruments ADS1298). The digital output is transferred and stored in a microcontroller (Texas Instruments MSP430) using the SPI communication protocol. The stored data is transmitted via a serial Bluetooth module (Roving Networks RN-42) to a connected Bluetooth-enabled smartphone or computer for processing.

Various sleep modes are used in order to reduce power consumption in the system. The Bluetooth module and the ADC are controlled by the microcontroller such that these two components are in a low power sleep mode until woken up for data collection. The chosen microcontroller is an ultra-low power microprocessor that operates at approximately 50uW/MHz. Additionally, backend digital signal processing and computation is leveraged inside the computer or smartphone in order to eliminate the need for processing power in the wearable system.

TABLE I: Design components with active power values

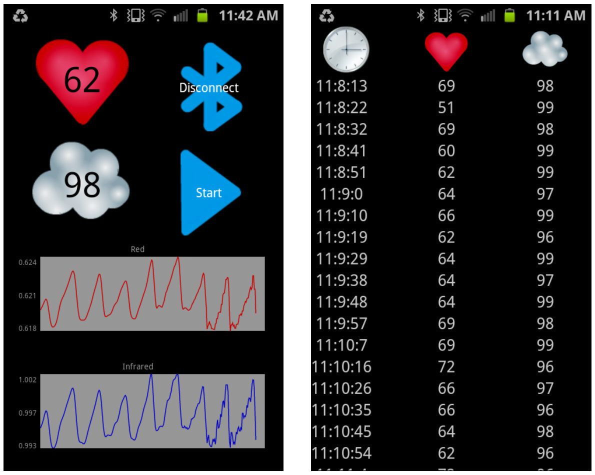
| **TAOS TSL13T** | |
|---|---|
| Description | Light-to-Voltage Converter |
| Irradiance responsivity | 24 mV/($\mu$W/$cm^2$) |
| Power Consumption | <3.63 mW |
| **650nm Kingbright LED** | |
| Description | Red LED |
| Characteristics | Current: 0.8mA Voltage: 2.5V |
| Power Consumption | 2mW |
| **940nm Kingbright LED** | |
| Description | Infrared LED |
| Characteristics | Current: 0.5mA Voltage: 2.5V |
| Power Consumption | 1.25mW |
| **Texas Instruments ADS1298** | |
| Description | Analog-To-Digital Converter |
| Characteristics | 8-channel, 24-bit |
| Power Consumption | 6 mW |
| **Texas Instruments MSP430** | |
| Description | Microcontroller |
| Characteristics | 16-bit Ultra Low Power |
| Power Consumption | 891 $\mu$W |
| **Roving Networks RN-42** | |
| Description | Wireless Interface Module |
| Characteristics | Class 2 Bluetooth 2.1 |
| Power Consumption | <100 mW |
| **Texas Instruments BQ25010** | |
| Description | Power Management IC |
| Characterisitics | 150mA Synchronous Buck Converter |
| Charging | 500mA USB Charger |

### C. *Processing*

Once the data is transferred over Bluetooth to the smartphone or computer, processing is performed and the results are displayed on the graphical user interface seen in Fig. 3(a). Processing utilizes a peak detection algorithm [6]. With a calibrated threshold voltage, the algorithm detects the peaks of the digital signal. The distance between each peak is the period of a heartbeat, which is simply extrapolated into beats per minute. To ensure accurate data, multiple photodetector channels of the device undergo the peak detection algorithm, and any channels that exhibit low signal-to-noise ratio (SNR) are thrown away. The average of the usable data is represented as the heart rate on the graphical user interface. However, if a viable pulse cannot be detected, the data capture runs again and the threshold voltage is recalibrated. In order to then calculate the $SpO_2$ percentage, the following equation is implemented to provide a ratio as an intermediate value:

$$Ratio = \frac{Red_{AC}/Red_{DC}}{Infrared_{AC}/Infrared_{DC}} \tag{1}$$

This ratio is then compared against a lookup table for $SpO_2$ values, as shown in Fig. 4. A healthy person will have an $SpO_2$ percentage between 93 and 100 [7]. The relationship between the ratio and $SpO_2$ percentage is linear



| | | |
|---|---|---|
| 11:8:13 | 69 | 98 |
| 11:8:22 | 51 | 99 |
| 11:8:32 | 69 | 98 |
| 11:8:41 | 60 | 99 |
| 11:8:51 | 62 | 99 |
| 11:9:0 | 64 | 97 |
| 11:9:10 | 66 | 99 |
| 11:9:19 | 62 | 96 |
| 11:9:29 | 64 | 99 |
| 11:9:38 | 64 | 97 |
| 11:9:48 | 64 | 99 |
| 11:9:57 | 69 | 98 |
| 11:10:7 | 69 | 99 |
| 11:10:16 | 72 | 96 |
| 11:10:26 | 66 | 97 |
| 11:10:35 | 66 | 96 |
| 11:10:45 | 64 | 98 |
| 11:10:54 | 62 | 96 |

(a) (b)

Fig. 3: Smartphone user interface

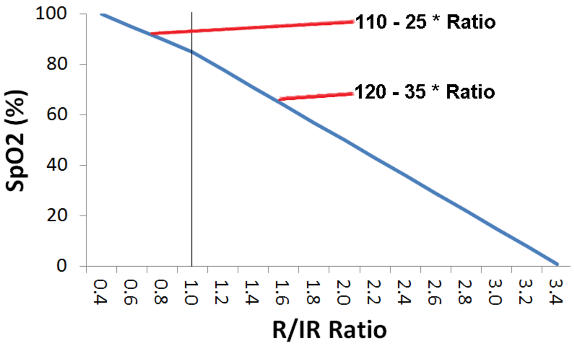


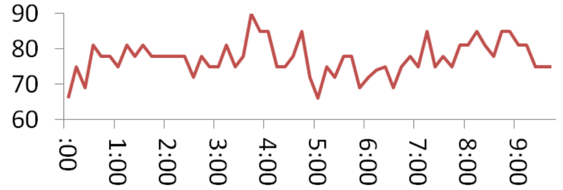
Fig. 4: Calculated Ratio vs $SpO_2$ percentage

in this region, so the percentage is easily found from the calculated ratio.

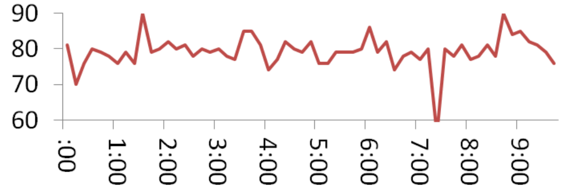
## III. RESULTS

This pulse oximeter prototype recorded data for ten minutes alongside two commercially available pulse oximeters [18] [21]. The two commercial options collected data from the fingertip, while the prototype measured at the wrist on the same hand of the resting test subject.

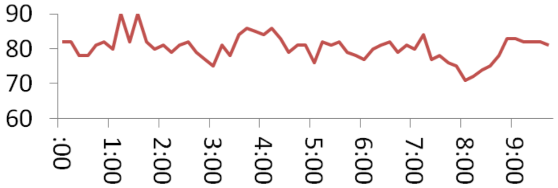
The resulting heart rate data is seen in Figures 5(a), 5(b), and 5(c) respectively. The accuracy of both of the commercial pulse oximeters is 2bpm for pulse and 2% for $SpO_2$ [18] [21]. As expected, a person's heart rate varies over time, and this fluctuation can be seen in all three devices. The pulse oximeter prototype measured an average pulse of 78 bpm over the ten minute span. Comparatively, the first commercial pulse oximeter measured an average of 79 bpm, and the second commercial pulse oximeter measured an average of 80 bpm. These results show that the pulse oximeter prototype is of similar accuracy to commercial devices with regard to heart rate. Comparing the average $SpO_2$ values between the three devices shows a similar result. The pulse oximeter prototype measured an average $SpO_2$ value of 97.5% over the ten minute span. The commercial options measured 98.0% and 97.7%, respectively [18] [21].



(a) Pulse oximeter prototype



(b) Commercial pulse oximeter 1



(c) Commercial pulse oximeter 2

Fig. 5: Pulse (beats per minute) vs Time (minutes)

At this point in development, motion artifacts cause signal integrity issues. This is not a problem unique to this device, but a problem of the optical measurement method required for pulse oximetry. If the user is moving, it becomes more difficult to get an accurate measurement. While this is not ideal, plans to minimize this problem are discussed in the following section.

## IV. FUTURE WORK

Wrist movement between the test area and the sensor can cause noise artifacts in the collected sensor data [9] [10]. To resolve this issue, a motion sensor will be included on the next device revision. User movement can then be accounted for during processing, resulting in more accurate and consistent data overall [1]. In addition, a digital filter will be used in to remove noise at frequencies that are outside the normal pulse frequency range.

Ideally, the final device will be improved such that it captures additional vital signs, creating a portable device with a wide variety of applications. Respiratory rate can be calculated through the mean of wavelet transforms [13], which is a software addition. Blood pressure can potentially be added by looking at the pulse transit time via the use of two sensors. Emotion and anxiety can be obtained through sweat level and galvanic skin response [22]. Furthermore, by adding an additional temperature sensor, body temperature can be determined. The resulting device would be a wearable system that can monitor all of the main vital signs of a user.

In order to make it even more user friendly, reducing the size of the design (without compromising the data quality) is an important goal. The current board dimensions are 3.99 cm by 2.77 cm, fitting in a plastic enclosure with elastic wristband to comfortably and securely attach the device to the user as shown in Fig. 2. Although the device is currently small enough to be wearable, having it small enough to fit within a wristwatch or thin band is desirable.

While the current device involves using off the shelf components, the design of an ASIC would lead to the greatest improvements in size, power, and design optimization.

## V. CONCLUSIONS

The wearable system designed is an improvement upon the conventional pulse oximeter. The device combines modern technology to continuously measure oxygen saturation levels on different parts of the human body. It also has the potential to implement more sensors and encompass all of the vital signs. Furthermore, the onboard Bluetooth module allows data to be transmitted wirelessly to a smartphone, a powerful processor that more and more people are already carrying around. As technologies become more readily available and body sensing networks attract more interest, a low powered continuously monitoring pulse oximeter that does not limit the users ability to perform day-to-day activities is highly desirable.

## REFERENCES

[1] R.K. Albright, B.J. Goska, T.M. Hagen, M.Y. Chi, G. Cauwenberghs, and P.Y. Chiang. Olam: A wearable, non-contact sensor for continuous heart-rate and activity monitoring. In *Engineering in Medicine and Biology Society,EMBC, 2011 Annual International Conference of the IEEE*, pages 5625 –5628, 30 2011-sept. 3 2011.

[2] Qing Cai, Jinming Sun, Ling Xia, and Xingqun Zhao. Implementation of a wireless pulse oximeter based on wrist band sensor. In *Biomedical Engineering and Informatics (BMEI), 2010 3rd International Conference on*, volume 5, pages 1897 –1900, oct. 2010.

[3] Danielle Cohen. The 5th vital sign. *RTmagazine*, Oct. 2005.

[4] Guowei Di, Xiaoying Tang, and Weifeng Liu. A reflectance pulse oximeter design using the msp430f149. In *Complex Medical Engineering, 2007. CME 2007. IEEE/ICME International Conference on*, pages 1081 –1084, may 2007.

[5] S.B. Duun, R.G. Haahr, K. Birkelund, and E.V. Thomsen. A ring-shaped photodiode designed for use in a reflectance pulse oximetry sensor in wireless health monitoring applications. *Sensors Journal, IEEE*, 10(2):261 –268, feb. 2010.

[6] J.D. Edwards and M.A. Preston. Forces in screen-secondary linear reluctance motors. *Magnetics, IEEE Transactions on*, 24(6):2913 –2915, nov 1988.

[7] Philips Electronics. Understanding pulse oximetery spo2 concepts. *Philips Medical Systems*, Jan. 2003.

[8] R.C. Gupta, S.S. Ahluwalia, and S.S. Randhawa. Design and development of pulse oximeter. In *Engineering in Medicine and Biology Society, 1995 and 14th Conference of the Biomedical Engineering Society of India. An International Meeting, Proceedings of the First Regional Conference., IEEE*, pages 1/13 –1/16, feb 1995.

[9] M.J. Hayes and P.R. Smith. A new method for pulse oximetry possessing inherent insensitivity to artifact. *Biomedical Engineering, IEEE Transactions on*, 48(4):452 –461, april 2001.

[10] Nellcor Puritan Bennett Inc. Oxygen saturation: The 5th vital sign. *Nellcor*, 2001.

[11] P. Jalan, B.R. Bracio, P.J. Rider, and H. Toniolo. Rapid prototyping of pulse oximeter. In *Engineering in Medicine and Biology Society, 2006. EMBS '06. 28th Annual International Conference of the IEEE*, pages 5579 –5582, 30 2006-sept. 3 2006.

[12] W.S. Johnston and Y. Mendelson. Investigation of signal processing algorithms for an embedded microcontroller-based wearable pulse oximeter. In *Engineering in Medicine and Biology Society, 2006. EMBS '06. 28th Annual International Conference of the IEEE*, pages 5888 –5891, 30 2006-sept. 3 2006.

[13] J.M. Kim, S.H. Kim, D.J. Lee, and H.S. Lim. Signal processing using fourier wavelet transform for pulse oximetry. In *Lasers and Electro-Optics, 2001. CLEO/Pacific Rim 2001. The 4th Pacific Rim Conference on*, volume 2, pages II–310 – II–311 vol.2, 2001.

[14] P Leonard, T F Beattie, P S Addison, and J N Watson. Standard pulse oximeters can be used to monitor respiratory rate. *Emergency Medicine Journal*, 20(6):524–525, 2003.

[15] K. Li and S. Warren. A wireless reflectance pulse oximeter with digital baseline control for unfiltered photoplethysmograms. *Biomedical Circuits and Systems, IEEE Transactions on*, PP(99):1, 2011.

[16] Kejia Li and S. Warren. Initial study on pulse wave velocity acquired from one hand using two synchronized wireless reflectance pulse oximeters. In *Engineering in Medicine and Biology Society,EMBC, 2011 Annual International Conference of the IEEE*, pages 6907 –6910, 30 2011-sept. 3 2011.

[17] M. Maattala, A. Konttila, E. Alasaarela, and Wan-Young Chung. Optimum place for measuring pulse oximeter signal in wireless sensor-belt or wrist-band. In *Convergence Information Technology, 2007. International Conference on*, pages 1856 –1861, nov. 2007.

[18] Santa Medical. Finger pulse oximeter sm-110 with carry case and neck wrist cord.

[19] Robin P Smith, Jrme Argod, Jean-Louis Ppin, and Patrick A Lvy. Pulse transit time: an appraisal of potential clinical applications. *Thorax*, 54(5):452–457, 1999.

[20] Inc. Smiths Medical PM. How can spo2 readings differ from manufacturer to manufacturer.

[21] Crucial Medical Systems. Oled cms50d fingertip pulse oximeter and oxygen meter.

[22] T. Westeyn, P. Presti, and T. Starner. Actiongsr: A combination galvanic skin response-accelerometer for physiological measurements in active environments. In *Wearable Computers, 2006 10th IEEE International Symposium on*, pages 129 –130, oct. 2006.

[23] Chao Yang, Zengyou He, and Weichuan Yu. Comparison of public peak detection algorithms for maldi mass spectrometry data analysis. *BMC Bioinformatics*, 10(1):4, 2009.