BOxy: A Cost-Effective Blood Oximeter

Beau Hsia, Derrick Wang, Navid Shaghaghi, and Zhiwen Zhang
Ethical, Pragmatic, and Intelligent Computing (EPIC) Laboratory
Santa Clara University, Santa Clara, California, USA
{bhsia, dwang1, nshaghaghi, zzhang}@scu.edu

***Abstract*—In third-world countries, there are efforts that push for the increased availability of pulse oximeters for monitoring critical health conditions. Currently, it costs African hospitals 500 USD to replace their current oximeters, and 250 USD to repair small malfunctions, due to the outrageously high shipping costs for both the machine and its spare parts. There is a great need for oximeters that are cost effective, easy to maintain and repair, portable, and convenient. With the proliferation of the Internet of Things (IoT) these requirements can easily be met. However, the benefits of IoT have not yet reached critical mass in rural, isolated, or impoverished parts of the world. Therefore, even though the recent years have seen a plethora of wireless clip-on fingertip pulse oximeters on the market, the cost and reliability on a Bluetooth connection with a cellphone are still considerable and sometimes prohibitive factors. At the time of this writing, simple yet reliable SPO2 sensors exist for around 2 USD yet the cheapest pulse oximeter with Bluetooth capability is around 30 USD and WiFi enabled devices are not available in the general consumer market. BOxy, is Santa Clara University's Ethical, Pragmatic, and Intelligent Computing (EPIC) Laboratory's effort to produce the most cost-effective Blutooth and WiFi enabled pulse oximeter using readily available and supported off-the-shelf components so that communities and health workers in rural, isolated, and impoverished regions of the world can easily purchase or build and certainly repair their own pulse oximeters rather than rely on costly or uncertain products or shipping costs.**

Keywords–Blood Oxygen Meter (SpO$_2$); Oximeter; Internet of Things (IoT); Infrared.

I. INTRODUCTION

Pulse oximetry noninvasively measures a patient's blood-oxygen level (SpO2) by analysing absorbed or reflected light from red oxygenated hemoglobin or from blue de-oxygenated hemoglobin in one's pulmonary circulation [1]. From this optical information, the device calculates the person's blood oxygen level using highly specific algorithms [2] to account for undesirable absorbance values as it passes through venous blood, or adipose, endothelial and epithelial tissue [1]. Pulse oximeters are commonly used in clinical settings, where health professionals monitor the level of oxygen in a patient's blood, which is of paramount importance especially when the patient is undergoing artificial ventilation due to compromised lung capabilities or is under general anesthesia [3]. [4] sites that there are at least eight clinical applications of this technology, including detection of hypoxemia, assessing pulmonary gas exchange, and measuring blood pressure, among other uses. Pulse oximeters are also extensively useful in pediatrics [5] for monitoring pneumonia and other conditions, which has been proven to reduce child mortality rates [6]. Pulse oximetry has also been described as "one of the most important advances in respiratory monitoring" [7]. The availability of this technology provides a viable alternative to arterial blood samples, which are invasive [7]. Outside the medical clinic, pulse oximeters are also used for measuring sleep apnea in adult sleep studies [8] and for detecting pneumonia in resident homes [9].

In third-world countries, there are efforts that push for the increased availability of pulse oximeters for monitoring critical health conditions [10]. Currently, it costs African hospitals 500 USD to replace their current oximeters, and 250 USD to repair small malfunctions, due to the outrageously high shipping costs for both the machine and its spare parts [11]. There is a great need for oximeters that are low-cost, easy to maintain and repair, portable, and convenient.

In Sections II and III some limitations and existing efforts for producing reliable cost-effective pulse oximeters are explored. Sections IV and V delineate the implementation of BOxy and some initial results respectively. And Section VI provides a road map of future additions and changes to BOxy which will transform the system from a prototype to a product.

II. LIMITATIONS

There are currently some limitations to pulse oximters applications, as they have not been proven to be effective for anemia, methemoglobinemia, vasoconstriction, motion artifact, hypotension, and carboxyhemoglobinemia [12]. However, there have been efforts to manage the discrepancies that arise due to motion artifacts, including those proposed by Masimo technologies, which allows for continuous monitoring in the face of poor tissue perfusion and patient movement [13]. Current oximeter standards hold that oximeters inaccuracies are inherent, and can only be reduced by a certain degree [14].

III. RELATED WORK

There have been many recent efforts to improve current designs of the pulse oximeters that try to reduce its cost, increase its accuracy, increase its portability, etc. Attempts to create a smartphone based oximeter using a smartphone's flashlight and camera to capture the reflectance and refraction of the light ray as it traverses through a finger have not been entirely successful because of various technological barriers, such as the smartphone camera's inability to accurately detect infrared radiation [15]. Furthermore, such direct-detection methods using a smartphone can not extend to continuous monitoring even if their accuracy levels increase dramatically.

Researchers have also tried to create a micro-oximeter that could be placed on someone's fingernail, made from flexible biomaterial [16]. Although this design could prove to be convenient for continuous measurement, no price range was specified. It seems reasonable to speculate that such a device would be priced highly due to the inherently high cost of flexible and compact biomaterials and biosensors being used.

Hewlet Packard corporation developed a smaller more portable family of pulse oximeters for clinical use in 1997

 ISBN: 978-1-61208-814-3

which were at the time revolutionary [17]. However, with the proliferation of cell phone technology in the past decades, much cheaper and more portable oximeters have been produced since. For instance, [18] is a low-cost oximeter that is linked to a smartphone display via a headphone jack connection. While this product is certainly a great step forwards in terms of usability and economics, a Bluetooth connection proves necessary because many current high-end smartphones lack a headphone jack altogether in favor of more sleek designs and features such as being waterproof. Furthermore, a bluetooth connection extends the range of operatability by eliminating entangled wires.

Finally, versions of continuously monitoring oximeters do exist, but some require peculiar placements, such as on one's eyeglasses [19], forehead [20], neck [21], or ear canal [22].

IV. Device Development

As the need for a cost-effective Bluetooth enabled oximeter is apparent, a prototype of such an Internet of Things (IoT) device using off-the-shelf components was undertaken by Santa Clara University's Ethical, Pragmatic, and Intelligent Computing Laboratory.

A. *Hardware*

The prototype comprises of a single-board microcontroller (Arduino UNO REV3), a sensor chip (MAX30102 Pulse Oximeter Sensor Module [23]), and a Bluetooth module (HC-05 Bluetooth Serial Module [24]). In the first iteration, these components were connected via extensive jumper wiring, and with a breadboard simplifying the entire construction, ensuring stable connections and accurate feedback.

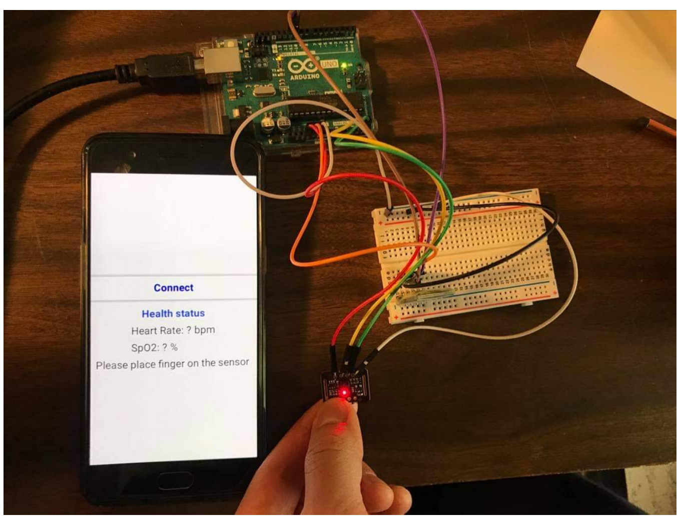

Figure 1. Blood oximeter prototype.

Figure 1 shows all the necessary components and their relevant connections and Figure 2 shows a simplified schematic of the system showing all the necessary connections. During operation, the system is completely independent and powered internally using a 9V battery. This could be replaced with a rechargeable battery source for environmental or economic reasons.

The sensor module is present on the exposed portion of the device surface, and uses an LED light to obtain blood

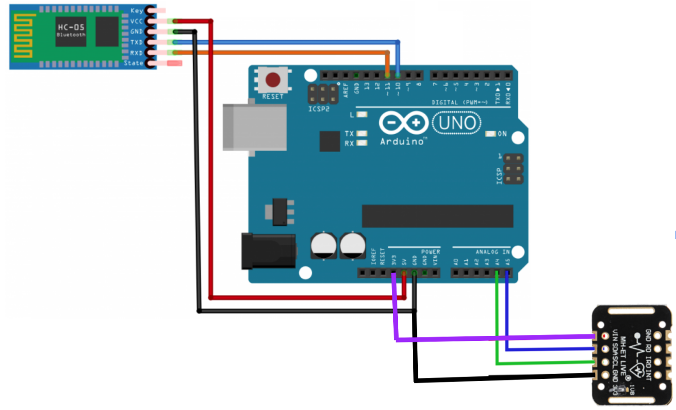

Figure 2. Blood oximeter Schematic.

Oxygen level readings through the skin noninvasively. The LED emits electromagnetic frequencies in the range of red and infrared light, which is the optimal range for hemoglobin SpO_2 analysis. Due to the constraints of human vision to light wavelength of approximately 720nm, the light emitted by the sensor appears red and looks like a laser, but is completely safe for human vision due to the sensor's low power output.

1) Design: In accordance to frugal and minimalist design principles, the hardware has been simplified as much as possible. Not only will having fewer parts lower the costs associated with building and manufacturing the device, it will also increase the ease at which users could repair or replace the parts due to normal wear and tear per prolonged use.

The software for the device has also been designed with usability and simplicity in mind. The device software has been completely abstracted away from the user, and implements an advanced signal processing algorithm to generate data quickly and efficiently in the Arduino micro-controller, which has limited computational power.

Finally, a minimalist smartphone application has been implemented in a way to maximize ease of use while conserving resources, in terms of energy, storage, and computational power. Since the computational data filtering and analysis algorithm are housed solely on the microcontroller, the user's smartphone needs only to display the information obtained via Bluetooth, freeing up computational resources to other applications, perhaps running in tandem. The user interface is completely intuitive and provides all the necessary instructions for all the tasks from connecting to the device, to optimally placing one's finger on the sensor, to obtaining the blood oxygen content reading from the device.

2) Materials: The prototype features the following items, listed along with their prices:

- Arduino UNO REV3: 5.49, Banggood
- HC-05 Bluetooth Serial Module: 3.99, Banggood
- MAX30102 Pulse Oximeter Sensor Module: 2.10, Ali Express
- 8 Breadboard wires: 0.12 (1.5 cents each), Newegg

The total cost of the materials is 11.70 which at the time of this writing, is about a third of the cost for the cheapest Bluetooth enabled fingertip pulse oximeter available for purchase in the

 ISBN: 978-1-61208-814-3

United States. As will be discussed further in the Future Steps section below, the cost of this pulse oximeter can be reduced even further.

B. Software

The program for the device includes calculations provided for the MAX 30102 chip in the ”SparkFun MAX3010x Sensor Library”. Bluetooth functionality and data communication was incorporated into this code, and the size of the variable arrays was reduced to decrease the static random access memory usage to alleviate memory shortcomings on the microcontroller. To enable Bluetooth communication between the Arduino and phone, an app was designed using the MIT App Inventor website.

V. RESULTS

During the prototype testing phase, the oximeter was able to successfully show readings of blood oxygen level and heart rate. However, sometimes the user had to wait a moment before the oximeter would calibrate and display correct values. When the oximeter is unable to obtain data or if it detects an unrealistic SpO2 or heart rate measurement, such as if the user’s finger is not on the sensor, it displays question marks and instructs the user to re-position their finger.

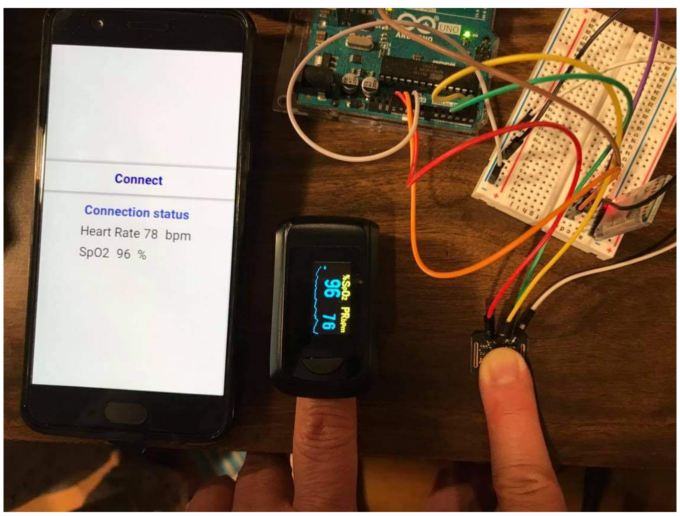

Figure 3. Blood oximeter results side by side

As depicted in Figure 3, the accuracy of the readings were tested against a commercially available fingertip Pulse Oximeter. Due to the extenuating circumstances brought about by the COVID-19 outbreak at the time of this writing, the device was not mass-tested, but the available data obtained from limited tests indicated a great degree of accuracy.

Accurate readings were however punctuated with intervals of higher variability in the blood oxygen and heart-rate readings displayed. There are several factors that could contribute to the periods of reading volatility; the most important of which being the difficulty of stabilizing a finger on the sensor for an extended period of time without some sort of support mechanism such as an alligator clip (common in medical instrumentation) or straps that immobilize the sensor across the skin (common in athletic and fitness monitoring equipment). Slight movements of the finger caused the chip to measure inaccurate values, which resulted in the intervals of inconsistent readings observed on the smartphone application display until the finger comfortably rests on the sensor for long enough. Building a case to surround the components and thus allow the faster resting or immobilization of the finger tip on the sensor will alleviate this issue.

VI. FUTURE STEPS

A. Shrinking Circuitry Size

The Arduino Uno microcontroller used for the current working prototype, is considerably large and thus reduces the portability of the device. To reduce the size of the system, there are several possible alternatives that can be used. One option is the placement of the Arduino Uno board with smaller boards such as the Arduino Nano or Pro Mini. These two boards are primarily the same, with the only major difference being a substantial decrease in size. In addition, the Arduino Nano is available at a cheaper price (3.29 from Banggood). A second alternative is the combination of two of the components by utilizing an Arduino microcontroller with built-in Bluetooth capability. This would also effectively make the device smaller due to the elimination of the extra Bluetooth module used in the current prototype design. In addition, these microcontroller modules are available at prices cheaper than estimated costs for the separate microcontroller and Bluetooth modules.

B. Addition of WiFi capability

Another way to increase the portability of the oximeter is to enable it to work completely separate from the phone. The addition of a WiFi module would enable the device to connect directly to a web service and store its readings. These readings could then be pushed to a web or mobile GUI for the user’s viewing or aggregated and graphed for trend building and analytics as part of the medical record of an athlete or patient for instance. In case of no WiFi connectivity, the device could take advantage of the microcontroler’s internal memory to store its readings and to push them to the server once WiFi signal becomes available again.

At the time of this writing, arduino compatible development boards with both Blutooth and WiFi radio modules onboard in the form of Dual Core CPU with Low Power Consumption MCU ESP-32S are available for 2.08 USD which provides more functionality in a smaller form factor and at cheaper cost. The use of such a board would effectively reduce the prototype cost to less than 9 USD while increasing its functionality to include WiFi capability as aforementioned.

C. Custom PCB

In making the device more stable and practical for use, the use of a custom Printed Circuit Board (PCB) will be required. This will not only eliminate the need for wires and the breadboard, but also provide stability in electrical connections between the components. PCBs can also enable a decrease in size of the device and make installation more effective and convenient.

Furthermore, the design and fabrication of a custom PCB with all electronic components onboard would reduce the cost drastically during mass production as it would be a single purpose board and not need the general purpose design and components of the commercially available microcontroler development boards aforeused and aforementioned.

D. 3D Printed Casing

The addition of a casing would provide more structural support for the device and contribute to the visual aesthetic. A 3D printed casing would also protect the internal components from collecting dust or otherwise natural weathering by the external environment. A 3D printed casing was not produced for the proof of concept prototype but is under design for the smaller sized prototype which uses an ESP32 development board.

E. UI Design

Improving the app design and the user interface will benefit the userfriendliness of the device. Furthermore, providing a graph showing the trend based on multiple data points over time will be more useful and beneficial to a person that requires or prefers periodic monitoring of their heart rate and blood-oxygen levels. And lastly, it will be more practical to include instructions for the most effective usage of the device in order to provide a guide as well as troubleshooting steps to the users.

F. User Testing

To make sure that the device measures heart rate and SPO2 levels properly across a variation of scenarios, sufficient user testing is necessary. In testing BOxy's prototype, due to limitations outlined by COVID-19 restrictions, this was not possible. In the development of future designs and additions delineated above, extensive user testing will be carried out more robustly in order to verify the reliability and viability of the device.

VII. Conclusion

BOxy is a cost effective, portable, convenient, and easy to repair pulse oximeter built from readily obtainable components. These features enable the development, deployment, and maintenance of reliable SPO2 sensing in low income, remote, or technologically isolated communities. There is still great room for improvement, as delineated in the future steps section above, but the initial results have proven the possibility of building such an oximeter. With the progress shown thus far and the remaining improvements delineated above, BOxy has the capability of playing a role in preserving the lives of patients worldwide as the need for an oximeter with BOxy's attributes to be available to monitor the pulmonary health of pediatric and geriatric patients in remote rural areas and impoverished nations is very pressing.

Acknowledgment

Many thanks are due to Santa Clara University's department of Bioengineering as well as the Frugal Innovation Hub for their continued support of the project.

References

[1] M. Yelderman and W. New, "Evaluation of pulse oximetry," Anesthesiology: The Journal of the American Society of Anesthesiologists, vol. 59, no. 4, 1983, pp. 349–351.

[2] T. Rusch, R. Sankar, and J. Scharf, "Signal processing methods for pulse oximetry," Computers in biology and medicine, vol. 26, no. 2, 1996, pp. 143–159.

[3] K. K. Tremper and S. J. Barker, "Pulse oximetry," pp. 98–108, 1989.

[4] A. Jubran, "Pulse oximetry," Intensive care medicine, vol. 30, no. 11, 2004, pp. 2017–2020.

[5] J. W. Salyer, "Neonatal and pediatric pulse oximetry," Respiratory care, vol. 48, no. 4, 2003, pp. 386–398.

[6] T. Duke, R. Subhi, D. Peel, and B. Frey, "Pulse oximetry: technology to reduce child mortality in developing countries," Annals of tropical paediatrics, vol. 29, no. 3, 2009, pp. 165–175.

[7] A. Jubran, "Pulse oximetry," Critical care, vol. 3, no. 2, 1999, p. R11.

[8] N. Netzer, A. H. Eliasson, C. Netzer, and D. A. Kristo, "Overnight pulse oximetry for sleep-disordered breathing in adults: a review," Chest, vol. 120, no. 2, 2001, pp. 625–633.

[9] K. S. Kaye, M. Stalam, W. E. Shershen, and D. Kaye, "Utility of pulse oximetry in diagnosing pneumonia in nursing home residents," The American journal of the medical sciences, vol. 324, no. 5, 2002, pp. 237–242.

[10] C. King et al., "Opportunities and barriers in paediatric pulse oximetry for pneumonia in low-resource clinical settings: a qualitative evaluation from malawi and bangladesh," BMJ open, vol. 8, no. 1, 2018, p. e019177.

[11] M. W. Weber and E. K. Mulholland, "Pulse oximetry in devloping countries," The Lancet, vol. 351, no. 9115, 1998, p. 1589.

[12] J. E. Sinex, "Pulse oximetry: principles and limitations," The American journal of emergency medicine, vol. 17, no. 1, 1999, pp. 59–66.

[13] J. M. Goldman, M. T. Petterson, R. J. Kopotic, and S. J. Barker, "Masimo signal extraction pulse oximetry," Journal of clinical monitoring and computing, vol. 16, no. 7, 2000, pp. 475–483.

[14] M. Nitzan, A. Romem, and R. Koppel, "Pulse oximetry: fundamentals and technology update," Medical Devices (Auckland, NZ), vol. 7, 2014, p. 231.

[15] S. Tomlinson, S. Behrmann, J. Cranford, M. Louie, and A. Hashikawa, "Accuracy of smartphone-based pulse oximetry compared with hospital-grade pulse oximetry in healthy children," Telemedicine and e-Health, vol. 24, no. 7, 2018, pp. 527–535.

[16] J. Kim et al., "Miniaturized battery-free wireless systems for wearable pulse oximetry," Advanced functional materials, vol. 27, no. 1, 2017, p. 1604373.

[17] S. Kästle, F. Noller, S. Falk, A. Bukta, E. Mayer, and D. Miller, "A new family of sensors for pulse oximetry," HEWLETT PACKARD JOURNAL, vol. 48, 1997, pp. 39–47.

[18] C. L. Petersen, H. Gan, M. J. MacInnis, G. A. Dumont, and J. M. Ansermino, "Ultra-low-cost clinical pulse oximetry," in 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, 2013, pp. 2874–2877.

[19] F. Braun et al., "Evaluation of a novel ear pulse oximeter: Towards automated oxygen titration in eyeglass frames," Sensors, vol. 20, no. 11, 2020, p. 3301.

[20] G. Comtois, Y. Mendelson, and P. Ramuka, "A comparative evaluation of adaptive noise cancellation algorithms for minimizing motion artifacts in a forehead-mounted wearable pulse oximeter," in 2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE, 2007, pp. 1528–1531.

[21] M. Peng, S. A. Imtiaz, and E. Rodriguez-Villegas, "Pulse oximetry in the neck-a proof of concept," in 2017 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, 2017, pp. 877–880.

[22] J. P. Buschmann and J. Huang, "Pulse oximetry in the external auditory canal–a new method of mobile vital monitoring," IEEE Sensors Journal, vol. 12, no. 3, 2011, pp. 671–676.

[23] "Arduino heart rate monitor using max30102 and pulse oximetry," 2019. [Online]. Available: https://makersportal.com/blog/2019/6/24/arduino-heart-rate-monitor-using-max30102-and-pulse-oximetry

[24] "Hc-05 datasheet — bluetooth transceiver module," 2019. [Online]. Available: https://maker.pro/custom/tutorial/hc-05-bluetooth-transceiver-module-datasheet-highlights