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Factoring out Racial Bias: Developing a Dual-Sensor System for Pulse Oximetry

ABSTRACT

Pulse oximetry is the practice of measuring oxygen saturation in the blood, often for health monitoring purposes. Oxygen saturation has been widely used in the midst of the COVID-19 pandemic as a key health indicator. Though these devices are easily accessible, there are known factors of unreliability for users with dark skin, especially at low saturation levels. My proposed solution is the development of a dual-sensor system that takes the user's skin color into account in the oxygen saturation reading. We will develop this system by incorporating Arduino-based color sensors and optimizing them to measure skin pigment. This input will then allow adjustment to the readings obtained from a pulse oximeter. Arduino technology allows me to minimize product cost so my device is accessible to the general population. This project will lay the groundwork for inclusive medical technology designing a device which combines color recognition and oxygen saturation Arduino sensors.

PERSONAL STATEMENT

To me, scholarship stems from discomfort: the willingness to face challenges and expand one's knowledge of the world around them. Engaging with service organizations and peers within my local community, outside of the predominantly white town I grew up in, sparked intellectual growth in my youth. Learning about social justice issues specific to my county, such as health and educational disparities in different demographics, made me passionate about equity and led me to question what had caused these injustices and what can be done to solve them.

Several years ago, I was faced with injustice in another sense. After my father received a Lymphoma diagnosis, I witnessed one of the strongest, most active people in my life grow sick. My interest in the medical field grew as I wondered how such a healthy individual could suddenly face such intense medical complications. My senior year of high school, I took a research elective in which students found a local mentor and completed an advanced study. Intimidated and with what slim knowledge I had to offer, I started doing cancer research at UConn Health Center. This experience was very influential as it was my first involvement with research beyond structured classroom experiences. My graduate student research mentor, Gabrielle, challenged me to learn laboratory processes, read and interpret scientific literature, and even present findings to graduate students in the lab, all of which I thought was far beyond my capabilities at seventeen years old.

Gabrielle was a strong role model during this time, as in addition to pursuing her doctoral degree, she prioritized serving minority populations in the Greater Hartford area. Throughout the year, she was preparing a summer program to introduce Black high school students to a lab environment and careers in STEM. Gabrielle inspired me in so many ways, but her efforts incorporating inclusion and accessibility to her love of science sparked my admiration most of all. She used her influence to make a difference in the local community and address educational disparities in Connecticut that I had learned about my whole life.

Transitioning from high school to college, I knew I wanted to engage all aspects of my passions within and outside of the STEM field. A very meaningful experience has been working in the Kernodle Center for Civic Life as a Service Ambassador. Planning and leading service events in Burlington and engaging in reflection with my peers on difficult topics has allowed me to grow immensely. Even though I have volunteered my entire life, being exposed to the diverse beliefs of students from all over the country with unique challenges has changed my perspective on the true meaning of service and reinforced my intrinsic motivation to help others. Furthermore, I have engaged with mentorship, as Gabrielle and many others have helped me tremendously in the STEM field. Meeting upperclassmen engineers through clubs, classes, and other spaces was very constructive in my development as a first-year student, motivating me to return the favor to underclassmen as I continue to grow with Elon's engineering program.

My personal growth has always been stimulated by a mixture of intellectual challenge and mentored support: a blend that the Lumen Prize offers at a high level. This experience would facilitate my ambitions to make a difference in the world and medical community, and help me explore my many passions as a function of one larger project.

PROJECT DESCRIPTION

Focus:

When the devices and practices of the modern day healthcare system are investigated in even basic ways, it is clear that they were designed with only certain populations in mind, while other populations were not considered [1]. These discrepancies are part of a larger system of institutional injustice that has historically affected our country and the world. We now find ourselves at a fascinating time in history, where these injustices are being brought to the forefront of medical research and creative solutions are required to propel the medical community forward. In an intersection between racial equality and bioengineering, this project aims to tackle unreliability in a common health monitoring device by taking user skin color into account in its measurements, providing users with a more accurate reading.

Pulse oximeters are just one example of a medical device that fails to work on people of all skin pigments [1]. The universal need for these devices has been heightened in recent years, with pulse oximeters being one of the recommended household health monitoring devices for the Covid-19 Pandemic, which lowers oxygen saturation in infected populations [2]. Though these devices are affordable, accessible, and easy to use for the general public, due to the reliance on light wave capture through the fingertip, there is an effect of overestimation of oxygen saturation with darker skin pigments, especially at low oxygen saturation levels [1]. Multiple sources have reported that skin color results in inaccurate pulse oximetry readings [2, 3]. Research has shown that these devices are between two and three times as likely to provide an inaccurate reading to a person of color [1]. There is existing data surrounding the direct effect of skin color on the accuracy of pulse oximeters, with one study providing data on biases in three common pulse oximetry devices on patients of different skin colors [3]. Conducted by researchers at the University of California San Francisco, patients of self-reported dark and light skin tones were subjected to various pulse oximetry measurements. Data was found suggesting clinically significant bias, especially at lower oxygen saturation levels [3]. Unless more data is published within the time frame of this project, the data in the referred study, which is attached at the end of this application, will serve as the basis for the known relationship between skin color and pulse oximetry readings [3]. This relationship will inform the Arduino code developed for the device in its integration of inputs of both skin pigment and oxygen saturation measurements.

This is not the only evidence of bias in these devices: there have been many related studies conducted. Another heavily-cited study examined the effect of several factors on pulse oximetry measurement accuracy, including dark skin pigmentation, gender, and sensor type [3]. Many conclusions were drawn from this study, including major discrepancies in accuracy of these measurements at low oxygen saturations. Up to 10% differences in pulse oximetry readings at saturation levels under 80% for patients with dark skin were observed in several different oximeters [3]. These results are significant in proving bias within oxygen saturation sensors, further proving the need to adjust or redesign the highlighted technology. The unreliability of these devices is known, and recent reviews and studies of the technology state that oxygen saturation readings from pulse oximeters cannot properly indicate health status on their own and more evidence must be cited that a patient is healthy or experiencing dangerously low oxygen levels [3].

In a recently published review of the topic, the need to address this issue is highlighted, with inaccurate means of pulse oximetry being identified as harmful for the Black community in the midst of the COVID-19 pandemic [1]. Though the discrepancy in accuracy of these devices on different skin pigments has been present since their creation over 30 years ago, the widespread infection of COVID-19 has demonstrated the true impact that non-inclusive medical devices can have [1]. It is even suggested that unreliable pulse oximetry readings was a contributing factor to disproportionate mortality rates for Black populations, as it led to improper treatment in these populations and sometimes unnecessary intubation [1]. The effects of these devices on the monitoring of the pandemic have been well-studied. “Occult hypoxemia” refers to patients with arterial oxygen saturation below 88%, despite pulse oximetry reading between 92% and 96% [2]. A recent study done at the University of Michigan, and corroborated with 2015 evidence from thousands of patients in intensive care units, compared pulse oximetry readings with arterial blood sample measurements, examining the tested populations for occult hypoxemia [2]. Though some cases of occult hypoxemia occurred in participants who self-reported as both Black and White, the frequency of undetected hypoxia was much higher in Black patients. The difference was nearly threefold [2].The results of the study warn that in the management of COVID-19 and oxygen supplemental levels, reliance on these pulse oximeters can be detrimental, especially for Black patients [2].

It is proposed that if the inaccuracy of these devices is known, this information can be used to appropriately adjust oxygen saturation readings based on skin color so that a more accurate reading can be given. Arduino technology is capable of accomplishing this goal, as Arduino-compatible color recognition and oxygen saturation sensors already exist and are fairly inexpensive. However, both existing sensors can be modified to optimize functionality for the specific purposes of the proposed device. The available color recognition sensor works based off of an RGB color code, as it takes input from light with red, green, blue, as white color filters. However, there are other existing color codes that are better suited to provide information about skin color. The YUV color world, which can be obtained through mathematical conversions from RGB units, has been used in other contexts to enhance skin color recognition [4]. Adjusting the existing RGB color recognition sensor to better suit the purpose of reading skin color will be a major focus of the proposed product.

Additionally, the location of the fingertip to take pulse oximetry readings has also been put up to question. In addition to skin color introducing interference to pulse oximetry sensors, many other factors have been identified to interfere with the device. Even certain manicures and beauty treatments involving a user's hands can cause these devices to overestimate oxygen saturation [5]. The redesigning of pulse oximeters allows for more flexibility with where the measurement is taken from on the patient, adding additional benefits of inclusivity to the proposed product. If there are existing factors that could pose issues for the device, such as traditional reading sites being amputated or tattoos or nail polish on the fingers, the sensor can be adjusted to take measurements from a different part of the user's body.

Scholarly Process:

A preliminary literature search has already been conducted, but review of related scholarly work will be a priority for the duration of the proposed project. Interviews with people who have first hand experience with this problem will also be an important step in the scholarly process for this design. For example, physical therapists who use pulse oximeters at their practice and face the issues of unreliability that these devices pose for their patients and appropriate diagnoses of medical care can provide valuable insight for this project.

The Engineering design process has also been used in the proposal of this design by doing general research, consultations with practicing physical therapists, and ideation of possible solutions. Many of the beginning stages of the design process were completed under the structured environment of coursework associated with Engineering Design for Service, which I took in the Fall 2021 semester and introduced me to the topic of bias in pulse oximetry. This design process will be continued throughout the prototyping and development phases of this project, and adjustment of the proposed design based on feedback and procured information will occur.

This process of pursuing the development of a dual-sensor oximetry system will be challenging, and will require application of knowledge from many classes I have taken in addition to information I seek outside of my traditional coursework. I will be intellectually stimulated by this project, as having the opportunity to pursue this work at a high level and be reviewed by others at Elon and in the wider scholarly community will be an invaluable experience to a future career in medical device development, and as a scientist in general.

Proposed Products:

The main goal of this project will be the technical creation of a working dual-sensor color recognition & pulse oximeter prototype. This will include the development of Arduino code that integrates inputs from both a color recognition sensor and an oxygen saturation sensor. Additionally, a human-participant research study on the reading of different skin colors by this device will be conducted, and a research report detailing the results of the study and accompanying data analysis will be written. Finally, scholarly work aimed for publication in a scientific journal will be created, in addition to a poster presentation intended for conference and research forum presentation.

FEASIBILITY

This project is ambitious, but is realistic for an undergraduate student to accomplish in two years. I have basic familiarity with Arduino devices in general and some experience with the proposed sensors, and will use this existing background to extend my knowledge as a first step in my design process. Additionally, we lack the ability to test a pulse oximetry sensor for accuracy against hospital-grade oxygen saturation sensors, that rely on patient blood samples. However, we will access existing data on the direct effect of skin color on pulse oximeters, which can be utilized in the code for this sensor. The proposed human participant study on the detection of skin pigment by Arduino sensors will aim to have participants with a wide variety of skin colors. In order to recruit a diverse population of participants, I will tap into resources on campus like the CREDE, in addition to patients of practicing physical therapists that have been consulted on this project.

Additionally, the human participant study proposed in this project will require an IRB review. Considerations and planning for this process have already commenced by reviewing the recommended IRB handbook and human participant study resources. The proposed study relies on participants of a wide range of skin types. People interested in participating may be asked to self-report their skin color, to ensure that participants are selected from a variety of skin pigments. The intention of the study will be fully explained to participants beforehand in order to minimize harm and eliminate ambiguity as to why the participant's skin color is being read. The sensor reading itself is completely non-invasive and should take no more than five minutes to complete. In addition to directly benefitting from having a more reliable pulse oximeter as a result of this project, participants will be entered into a raffle for the chance to win one of two $30 Amazon gift cards. Information about the study and the product development it will serve will be explained to participants in verbal and written form through a waiver, and the participants will have the opportunity to raise concerns or have questions addressed in both of these forms. Data will be saved with a photograph of the participant's skin or numeric value associated with the participant's skin color, not saved under their names or any personal information from them. The records of this data will be kept virtually by myself and my research mentor for at least the duration of my undergraduate experience, terminating Spring 2024. Once the device is calibrated and the data is no longer needed, or wider data sets are available about the detection of skin color by Arduino sensors, the data can be deleted from the virtual files associated with this research study. The end goal of this research study is to contribute to the calibration of a medical device. An update on the development of this biotechnology will be sent to all participants upon completion of the project. To the best of my knowledge, the plan of conduct for this research conforms to the policies and procedures for the use of human participants at Elon University.

BUDGET

-Funds for research participants, 2 $30 gift card in raffle ($60 total)

-Arduino programming textbook ($30)

-International Conference on Advanced Bioengineering and Biotechnology in NYC (hotel $120/night, food $50/day, round trip flight ~$163 , conference fees $1000, total budget $2000)

-Publication fees ($1,350-$2,250)

-Pulse oximeters ($12 each, $24 total)

-For the purpose of reverse-engineering, and comparison to Arduino recreation

-Arduino Uno ($20)

-Color recognition Arduino sensor ($14)

-Pulse oximetry Arduino sensor ($7)

-Tuition relief ($7,500/year, $15,000 total)

-Includes budget for summer tuition ($571/credit hour) and potential overload credit hours over the school year ($1,329/credit hour)

PROPOSED EXPERIENCES and PRODUCTS

	Experiences	Products
Summer 2022	I will prepare for advanced Arduino programming by reading a textbook. I will also familiarize myself with the mathematical conversions between RGB and YUV color worlds and prepare to incorporate these conversions to the Arduino code for the color recognition sensor. I will enroll in one credit hour of LUM 4998: Thesis Research during this term.	Arduino code incorporating RGB to YUV color code conversions
Fall 2022	I will continue programming the color recognition Arduino sensor and use design process skills to optimize the sensor's	Color recognition Arduino sensor that is ready for testing on human participants

	functions. In addition, I will prepare for the proposed human participant study that will help calibrate the color sensor and recruit participants. I will enroll in one credit hour of LUM 4998: Thesis Research during this term.	& list of 50 participants for proposed skin color calibration study
Winter 2023	I will aim to complete the proposed human participant study and corresponding data analysis, which I will then use to calibrate the sensor. I will enroll in two credit hours of LUM 4998: Thesis Research during this term.	Data correlating user skin color and the corresponding reading on the color recognition Arduino sensor
Spring 2023	I will troubleshoot any potential errors with the color recognition Arduino sensor and begin assembling the pulse oximetry Arduino sensor on the same device. I will enroll in one credit hour of LUM 4998: Thesis Research during this term.	Calibrated color recognition Arduino sensor and attached pulse oximeter & an integrated code that incorporates both inputs
Summer 2023	I will wrap up code development as needed. I will also begin preparing my work for presentation in the form of a scholarly article and poster presentation, and begin researching journals to submit to and research conferences to apply for.	Completed code and fully assembled dual-sensor system & drafts of scholarly article and research poster
Fall 2023	I will continue working on scholarly materials and submit my work to scientific journals and research conferences of interest. I will enroll in one credit hour of LUM 4998: Thesis Research during this term.	Scholarly article, research poster, & research conference applications
Winter 2024	I will use this time to address feedback on my work, and plan for any additional studies or adjustments to improve my project. I will enroll in one credit hour of LUM 4998: Thesis Research during this term.	Response to feedback on scholarly work & research conference applications
Spring 2024	I plan to attend at least one research conference in this term. I will also leave time to address feedback on my work and finalize scholarly article and research poster as necessary. I will enroll in one credit hour of LUM 4998: Thesis Research during thi	Finalized scholarly article and research poster

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