Design of a Bluetooth-Enabled Wireless Pulse Oximeter

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Abstract

Capstone courses play a crucial role in Computer Engineering (CE) curricula. The principle purpose of a Capstone project course is to offer a summative opportunity for graduating senior engineering students to apply their professional skills and knowledge in a single experience and prepare them for work. Like many engineering programs, students at Utah Valley University (UVU) complete their requirements for graduation with a semester long capstone design project course. The intention of this course is to apply competencies gained during their first three years toward the solution of an embedded system design problem.

Educational excellence requires exposing students to the current edge of research. To ensure that student projects are along the same trajectory that the industry is moving, educators continually introduce emerging techniques, practices, and applications into the curriculum. Advances in wireless sensors have opened new opportunities in healthcare systems. Sensor-based technology has invaded medical devices to replace thousands of wires connected to these devices found in hospitals. This paper presents the detail of sample project that two CE students have done in the area of wireless sensors.

This sample senior design project successfully created a Bluetooth-enabled pulse oximeter using the MAX 30100 and HC-05 modules. Accurate sensor data was sent over the link to a laptop, which was able to display the Plethysmographic trace waveform, or "Pleth," Oxygen Saturation (SpO_2), and Heart Rate (HR) data. The results mimicked those that would have been received with a wired hospital pulse oximeter, including the waveforms and the accuracy of the data. This allows free movement of patients within their room and floor, easing the discomfort of their hospital stay while still providing health monitoring.

Background Information

Utah Valley University (UVU) is a comprehensive regional university with over 40,000 students charged with serving Utah county, which is the second largest county in the state. UVU has a dual mission – that of a comprehensive university offering 91 bachelor's degrees and 11master's degrees, and that of a community college offering 65 associate degrees and 44 certificates.

Engineering and Computer Science Departments

To meet one of the region's most pressing workforce needs, UVU initiated three new engineering programs in Fall 2018. The new bachelor's degree programs in Electrical Engineering, Civil Engineering, and Mechanical Engineering have joined UVU's established programs in Computer Engineering and Pre-Engineering in a new Department of Engineering. The new programs were immediately popular with students, with 300 students enrolling for Fall 2018. Currently, the new Engineering Department has more than 800 students in five programs, which are housed in that department. Before forming the Engineering Department at UVU, the Computer Engineering program was housed in the Computer Science department, which offers a bachelor’s degree in Computer Science with two areas of specialization – Computer Science (traditional) and Computer Networking. It also offers a Software Engineering degree. The Bachelor of Science in Computer Science program was one of the first Bachelor of Science programs implemented at UVU in 1993.

Capstone Projects in Computer Engineering (CE) Program at UVU

The goal of the projects in our Capstone Design course is to provide our students with a realistic embedded system design experience and to teach them the tools and methodologies that can help them be successful. The following is the Course Description, Course Learning Outcomes (CLO), and traits for our senior design project course:

Course Description: Serves as a project-based capstone course for computer engineering majors. Emphasizes major hardware and software design. Includes identification and completion of a suitable design project to be mutually selected by the faculty supervisor and student. Requires weekly written and oral presentations as well as a final written report and oral presentation.

Course Learning Outcomes:

1. Identify relevant topics from previous courses and then apply them to their project
2. Identify and specify design requirements from general problem descriptions
3. Communicate design ideas and information
4. Demonstrate creative thinking
5. Display information gathering skills
6. Demonstrate oral and written communication skills

Traits: Upon successful completion, students should have the following attitude(s)/traits:

- Confidence in their ability to design.
- Confidence in their ability to communicate technical information effectively.

Our senior design course is structured as a collection of independent or group student projects. This capstone course is offered every semester. Usually, the students in the Computer Engineering program take this course during their last semester. Students either can come up with an embedded system project themselves or work on a project that is given to them by their advisors. The requirements for these projects are as follows:

- Low cost
- Embedded System Design projects
- Can be finished in one semester

Students write a proposal to define problems and identify solutions for their project in addition to the hardware and software that is needed for their project. After several iterations, the advisor approves their project proposal. Then, they begin working on their projects. Students are required to write weekly progress reports and meet with their advisor during a weekly scheduled time for each student. At the end of the semester, they turn in a final written report and a final presentation which is evaluated by several faculties from the department. The following grading rubric is used to assess these projects:

Assessment of the Projects

The project final grade is calculated on a 100-point scale, with the maximum number of points for each area of assessment as follows:

Quality and rigor of research and research paper	25 points
Quality of other deliverables (hardware design, integration, management plan, code, etc.)	15
Degree to which project fulfills requirements specified in project proposal	20
Level of effort	10
Progress reports received on time	10
Quality of oral presentation	20
Total possible points:	**100**

Educational Benefits

The students in the Computer Engineering program are required to take the Senior Design Project course. These projects are completed in a semester. The funding for these projects has been supported through grant proposals written by the faculty member running the course or is funded by the students. There are several benefits associated with these projects, including:

- The technical knowledge gained in putting to use their prior background in computer science and electrical engineering coursework.
- Using concepts from classes in embedded systems design, electronics, networking, digital design, circuit theory, digital signal processing, signals and systems, VLSI design, data structures, computer architecture, and programming classes.
- Knowledge gained from hardware and software interfacing and integration.
- Use of programming languages such as C, C#, Python, Assembly, JAVA, …
- Learning microcontroller’s architecture.
- Using new IDEs.
- Learning how to define system requirements, partition and design into subcomponents, design, build, test, and verify that the system requirements have been met.
- Developing project management skills
- Developing written and oral communication skills and other professional skills.
- Designing and defending a solution to a real-world problem.

Overall, students have positive comments about this capstone course and are benefitted greatly from this experience.

The following is an example of a senior design project which reflect common student projects.

Sample Project

This sample project was a group project. Two CE students worked together on this design. This senior design project describes the realization of a wireless replacement for the traditionally wired pulse oximeter currently found in hospitals, which is used to monitor oxygen saturation and heart rate. This design allows patients freedom of movement and lack of restriction from a traditional wired device to a monitor. This freedom of movement also allows for monitored ambulation which greatly increases patient health and recovery. The first section identifies what pulse oximetry is, or the noninvasive method for monitoring oxygen saturation levels in the blood, and why it is important in the healthcare workplace, with extensive research in identifying parts and materials needed for the design and their compatibility. The second half describes the design, implementation and testing of a Bluetooth capable pulse oximeter prototype using a MAX30100 health monitor sensor, an Arduino microcontroller, and an HC-05 Bluetooth module. This device was connected to a laptop via Bluetooth, and the raw sensor data, as well as the oxygen saturation and heart rate were successfully displayed in a waveform form. This prototype was also tested against existing devices, one wireless and one an in-use wired hospital pulse oximeter for accuracy and reliability. Future implementations are also identified for further progression of this project and what improvements could be made for a more efficient model.

Pulse Oximetry

The practice and study of pulse oximetry has been around since 1983. It was introduced as a noninvasive method for monitoring arterial oxygen saturation in the blood of a patient receiving medical care. Some uses of pulse oximetry include clinical care for the critically ill patient, monitoring of patient during the anesthesia in operations, research of breath state while sleeping, etc. [1]. The research and development of this study consisted of exploring the possibility of a wireless (Bluetooth-capable) pulse oximeter with the exact same functionality as that of the regular wired oximeter, to make the medical process of measuring and monitoring oxygen saturation in the bloodstream more comfortable and less inconvenient for the patient receiving medical care. The main goal was to show why a wireless device is superior to a wired device.

Basic interconnection of components for integrated circuits and microcontrollers were adapted and implemented in order to come up with a workable solution for a wireless pulse oximeter. Pulse oximetry theory was applied with some slight variations in order to have accurate readings of oxygen saturation and heart rate calculation. Various testing methods and interconnection schemes were also applied. These were added on to previously studied designs in order to have a good and working prototype. Additionally, some of the open-source code used to make the design work was modified in order to better fit the needs of the study. The data was displayed using different tools including FlexiPlot, and the Arduino IDE serial monitor.

Normal Oxygen Transport and Oximetry

The need for monitoring the cardiorespiratory vitals as part of the health of a human stem from the biological study of normal oxygen transport in the human body via the pulmonary/respiratory and blood/circulatory systems. The process begins at the consumption or *inspiration* of air through the nose or mouth and ends after the delivery of oxygen to the systems of the body and the subsequent releasing or *expiration* of carbon dioxide from the body and includes several subprocesses. Some of the subprocesses include: ventilatory control, diffusion to blood, bind to hemoglobin, circulation, and diffusion to tissue [2].

Ventilation consists of the breathing in of air and the path the air takes into the lungs via the larynx, the trachea, and the bronchioles. Once inside the lungs, the alveoli diffuse the oxygen to the blood. Figure 1 shows a diagram of the process of ventilation. The diffusion occurs through the hemoglobin, which is used to transport the oxygen that is diffused into the blood. Finally, the oxygenated blood arrives to other tissues in the body to irrigate them and oxygenate them.

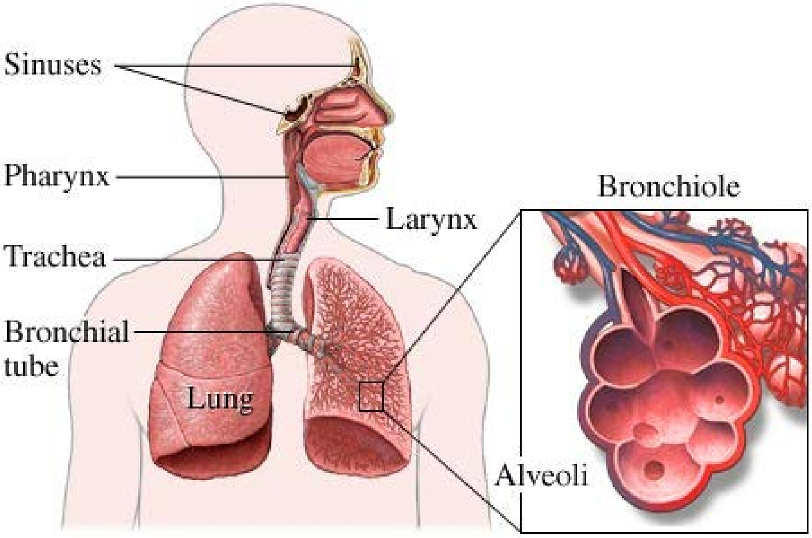


Figure 1: The Respiratory System

The efficiency of this transport mechanism and overall system performance is analyzed and used to calculate the health of an individual within the realm of pulse oximetry. Oxygenated hemoglobin and deoxygenated hemoglobin have different properties, and these are used to calculate the SpO_2 of a person. Oxygenated hemoglobin absorbs more infrared than red light and the opposite is true for deoxygenated hemoglobin. From this, it is clear the reason for why a pulse oximeter uses both red and infrared LEDs, in conjunction with a photodetector in order to calculate the SpO_2 of a person. The equation for this is shown below:

$$SpO_2 = 110 - 25 \times R$$

where “R” is the ratio between the two wavelengths of light (i.e. 950nm for infrared, and 650nm for red). This would be used for determining the final percentage that is displayed for monitoring the oxygen saturation in the blood of the patient that is using the pulse oximeter. [3]

Part of the research on pulse oximeters and the biomedical engineering involved included finding and learning of other projects that used the same technology. One such project included the implementation of a “wireless body area network” (WBAN) for monitoring body temperature, heartbeat, and oxygen in the blood. This consisted of a somewhat sophisticated system that has many functions beyond the reach of the research that was being conducted for this project. However, it had many interesting anecdotes that would be implemented in the research and application for the design in question. For one, the WBAN made use of an Arduino, which was used as the microcontroller for the system architecture [7]. Other researched projects and papers consisted of more detailed explanations of the filtering mechanics and other important aspects that typically go into the processing and displaying of the data that is used to monitor patients' health. Raivis Strogonovs' research on the implementation of a wired pulse oximeter using an ATMEL microcontroller and a MAX30100 sensor had some particularly useful information. Some discernible steps on how to completely read and calculate oxygen saturation were discovered from the reading of this study. The steps are as follows: reading the raw data, removing DC component, using a mean median filter, using a Butterworth filter, detecting the beat, and measuring (balancing the infrared and red currents). Filtering the current gathered from the absorbance of the red LED consisted of only removing the DC component, while filtering using the lowpass Butterworth and mean median was done to the infrared LED absorbance in addition to removing DC [4].

Equipment and Design

The HC-05 module is an easy to use Bluetooth SPP (Serial Port Protocol) module, designed for transparent wireless serial connection setup [5].

Figure 2: HC-05 module with breakout board

The MAX30100 is an integrated pulse oximetry and heart rate monitor sensor. Because of the built-in health monitoring functions, this sensor is ideal for this project design [6].

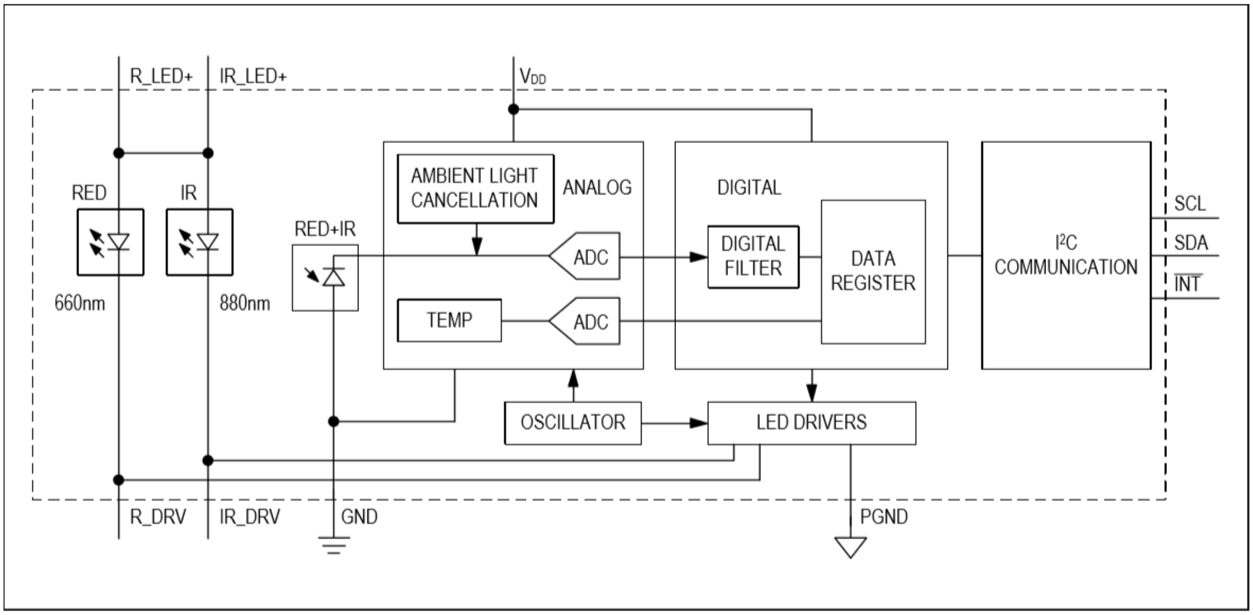


Figure 3: Functional Diagram of MAX30100

Figure 4: MAX30100 with Breakout board

To start reading from the MAX30100, the chip needs to first be set to a mode of operation, for example *SpO_2 + HR* mode, which can be done through the registers [19]. This allows the sensor to detect heartbeats as well as start reading IR and Red-light data through the photodetector. The DC signal needs to be removed from the raw IR data to read the hearth rate and oxygen saturation properly, leaving the AC part only. Only the light absorbance levels from the blood are needed, which means other absorbance from surrounding tissues and anything else in the finger and outside sources that isn't the hemoglobin can be removed. After removing the DC component further filtering to the infrared data needs to be implemented to calculate a pulse. The heart rate is important because the raw data will be oscillating from the heartbeat pumping blood and to calculate the SpO_2 the pulses need to be detected. This is done by mean median filtering, which will give the value change from the average and find the differential of the signal. The detected pulse is where in the data there is a sudden large change in value. Instead of just taking the difference however, this means the median filter will provide further cleanup of the signal for easier reading and processing. A Butterworth filter will then be used to remove higher-level harmonies to best detect the peaks of the heartbeat. Once the signal is passed through the Butterworth filter, it becomes much smoother and easy to detect pulses. From here it becomes easy to calculate heart rate using timestamps. While the raw infrared data is passed through both filters, it isn’t necessary to pass the Red-light data through these filters. Oxygenated hemoglobin absorbs more infrared light, which means it is the only light needed to detect HB [1]. The absorbance of light in the red region of the spectrum is much higher for reduced hemoglobin than for oxyhemoglobin. This means that the readings from the red led will be extremely saturated, which in turn means that the intensity needs to be balanced.

The sensor emits alternating wavelengths of red and infrared light through the finger and measurements are taken. The ratio of the two wavelengths is given by

$$R = (AC_{RMS\ RED} / DC_{RED}) / (AC_{RMS\ IR} / DC_{IR}) \text{ or } R = (\log(I_{AC}) * \lambda_1) / (\log(I_{AC}) * \lambda_2)$$

Where the wavelengths are 950nm for infrared, and 650 nm for red. If the raw data wasn’t passed through the DC filter than the first equation would be needed, but as this project implements a dc filter the second equation was used to theoretically calculate the ratio R. Then that ratio can be used in the following formula to compute SpO_2:

$$SpO_2 = 110 - 25 * R$$

While, this formula is widely accepted as an accurate formula to calculate SpO_2 levels, it only applies to the population in general and so can be more accurate for some people than others. Proper calibration of the sensor would help in realizing the changes than need to be made in the formula as well as ensuring better reliability and accuracy.

The Arduino Pro Mini is a single-board microcontroller, intended to make the application of interactive objects or environments more accessible. It does this by exposing most of the microcontrollers’ I/O pins for use by other circuits. Already in the microcontroller chip is a boot loader that allows uploading programs into the microcontroller memory without needing a chip (device) programmer which makes it very easy to program [7].

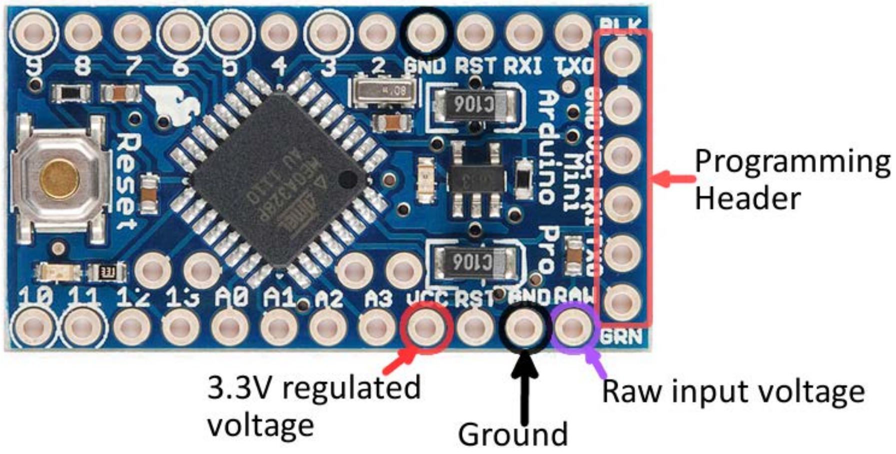


Figure 5: Arduino Pro Mini Board

Testing the Design

Because the MAX30100 only comes with the breakout board and the sensor on it, wires were soldered to the Vcc, GND, sda and scl lines as shown in Figure 4. It was first created in a graphing tool called Fritzing, and then was implemented on the actual sensor. For easier handling and programming, initially an Arduino Uno board was used instead of the Arduino pro mini for testing the soldered connections. The Uno is much larger than the pro mini, and instead of soldering wires it has easy access plugins for wires, which made testing the sensor module faster. A test program was run to initialize the sensor, read values to the registers of the sensor and test the communications between the board and the sensor. After initializing the sensor with the test program, the output shown below was received, which meant that the sensor was operating correctly.

```
Initializing MAX30100..Success

Enabling HR/SPO2 mode..done.

Configuring LEDs biases to 50mA..done.

Lowering the current to 7.6mA..done.

Shutting down..done.

Resuming normal operation..done.
```

After the success of turning on the sensor and receiving the above data, another test program was run to receive LED readings from the sensor. After these tests, the sensor was soldered to the pro mini, connected to the HC-05 Bluetooth module and the data was successfully sent over a Bluetooth link to a laptop computer.

Testing the Sensor Against Other Devices

This design was tested against two other pulse oximeter devices to test reliability and accuracy. It was tested against another wireless pulse oximeter and was also tested against a general use hospital pulse oximeter, to determine wireless vs wired measurements. All three were put on the same hand as shown in Figure 6 to be as close to accurate as possible, with the wireless oximeter design on the middle finger, the hospital pulse oximeter on the pointer finger and the already in use wireless pulse oximeter on the ring finger. The results of all the devices were displayed, shown in Figure 7. In the upper left is the already-in-use pulse wireless pulse oximeter, with SpO_2 at 97% and *BPM* at 78. In the upper right is the hospital pulse oximeter screen showing SpO_2 at 96% and *BPM* at 78. The bottom middle shows the results of this project design with

SpO_2 at 96.3% and *BPM* at 80. Because pulse oximeters have an accuracy range of 2%, clearly shown is the capability of this wireless pulse oximeter design to be just as accurate as a wired hospital pulse oximeter.

```
IR 88.00 | RED 547.00

IR 67.60 | RED 537.6

IR 70.22| RED 505.77

IR 71.35| RED 525.98

IR 73.49| RED 509.71
```

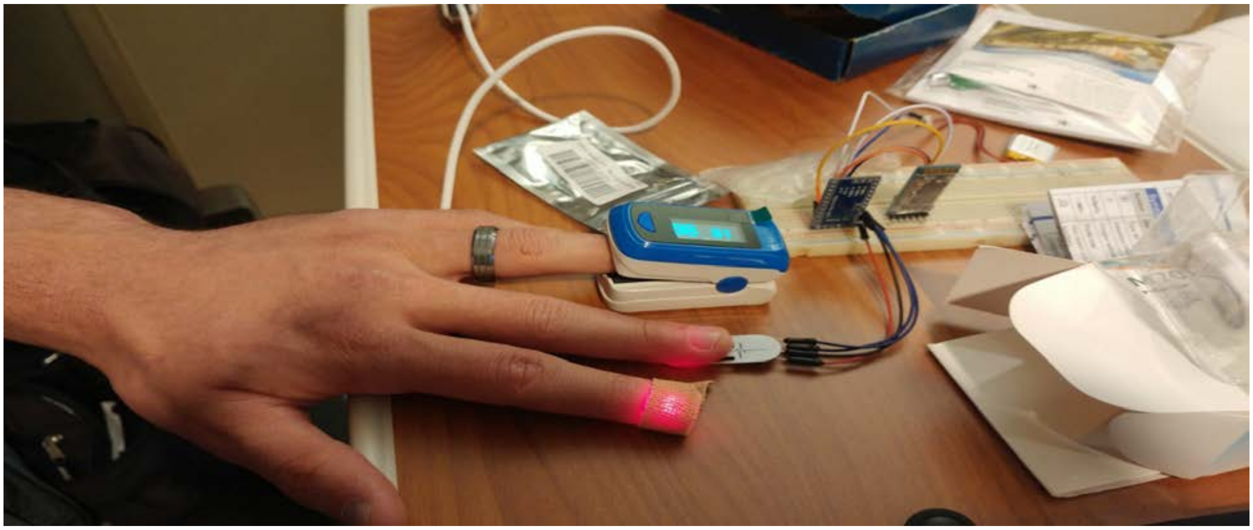
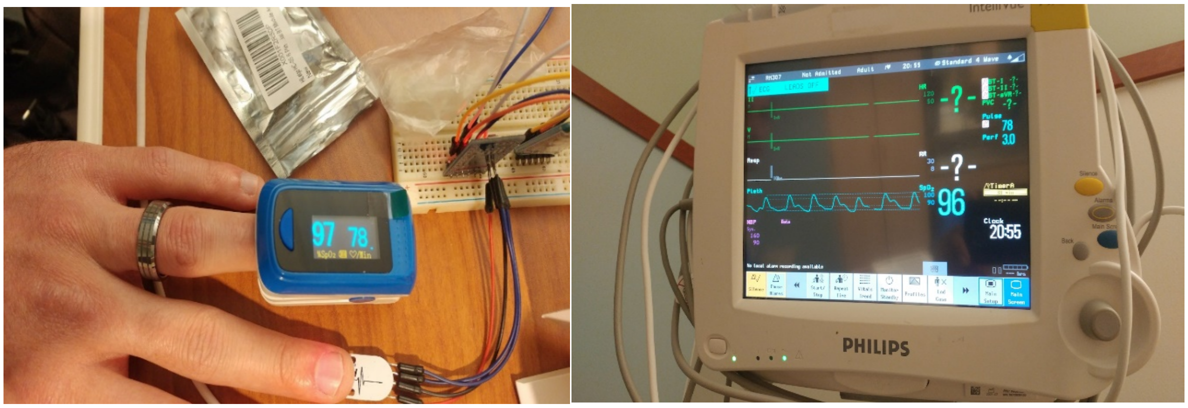
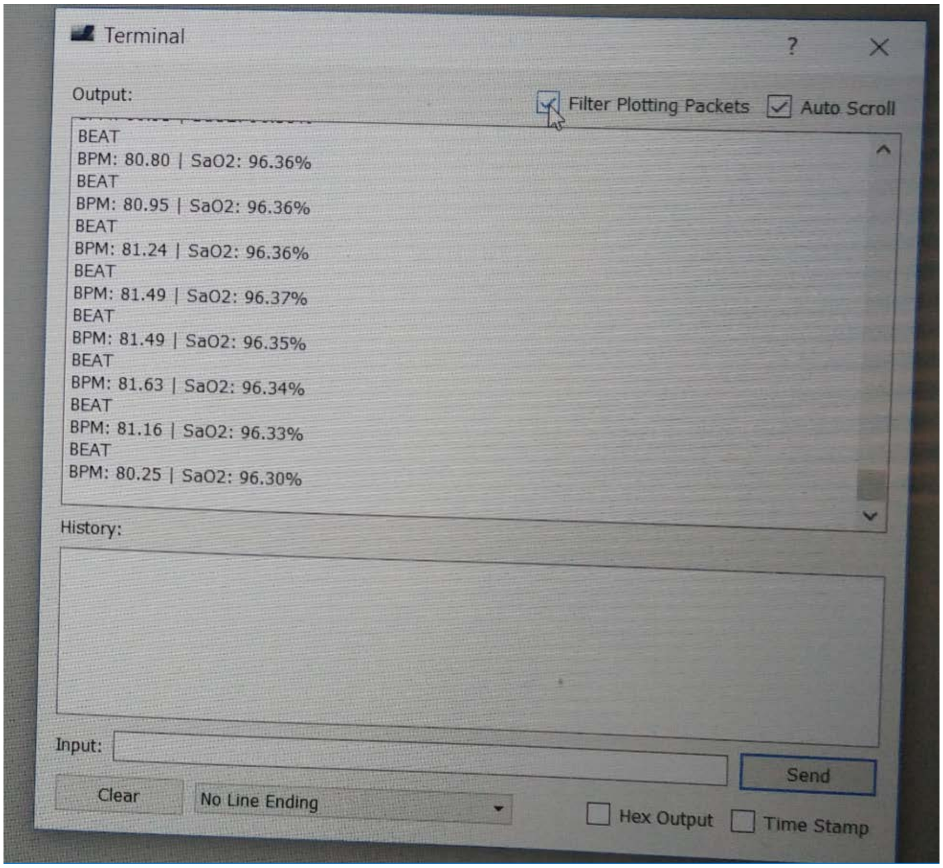


Figure 6: Testing the design against already in use pulse oximeters





☑ Filter Plotting Packets ☑ Auto Scroll

```
BEAT
BPM: 80.80 | SaO2: 96.36%
BEAT
BPM: 80.95 | SaO2: 96.36%
BEAT
BPM: 81.24 | SaO2: 96.36%
BEAT
BPM: 81.49 | SaO2: 96.37%
BEAT
BPM: 81.49 | SaO2: 96.35%
BEAT
BPM: 81.63 | SaO2: 96.34%
BEAT
BPM: 81.16 | SaO2: 96.33%
BEAT
BPM: 80.25 | SaO2: 96.30%
```

No Line Ending ☐ Hex Output ☐ Time Stamp

Figure 7: Results of testing against other devices

Conclusion

This paper described a sample senior design project completed by two senior students in our undergraduate computer engineering program. Students in this course can design systems which are very beneficial such as this simple monitoring system that can improve quality of life of patients in hospitals.

This sample senior design project successfully created a Bluetooth-enabled pulse oximeter using the MAX30100 and HC-05 modules. Accurate sensor data was sent over the link to a laptop, which was able to display the *pleth*, SpO_2 and *HR* data. The results mimicked those that would have been received with a wired hospital pulse oximeter, including the waveforms and the accuracy of the data. This allows free movement of patients within their room and floor, easing the discomfort of hospital stay while still providing health monitoring.

This senior design course is structured as a collection of independent student projects. In order to ensure they have a successful senior design project; our students work rigorously to employ the technical expertise and theoretical knowledge gained during years of study. As a result, this opportunity for self-directed learning is highly rewarding, as each student must design, build, and troubleshoot their fully functional embedded project. Throughout their final semester, these students develop the ability to debug, seek, and find information necessary to understand poorly written documentation. Overall, both student feedback and final presentations indicate that these students have pride in their project accomplishments and have gained confidence in their engineering abilities.

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14. [Figure 7] Photo taken by Luis Paredes.