NIMBL: Non-Invasive Module for Biomonitoring Live

Kai Ford, Ethan Denner, Benjamin Will, Tyler Takimoto

Dept. of Electrical Engineering and Computer Science, University of Central Florida, Orlando, Florida, 32816-2450

***Abstract* — Whether providing important insights in an emergency or measuring the vitals of a sleeping baby, pulse rate and blood oxygen saturation are common baseline indicators of general health. Many pulse oximeter designs don't allow for the wireless transmission of the measured data for long-term analysis. In the cases where these modules do exist, they are very costly. This paper describes the design process for a pulse oximeter that uses commercially available components to facilitate a convenient measurement and data transmission solution.**

Index Terms — Pulse oximetry, biomedical measurement, mobile devices,

I. Introduction

Pulse oximetry devices measure the oxygen saturation of a user's blood (SpO_2) as well as their heart rate. Oftentimes, these devices use a Photoplethysmography (PPG) sensor to take these measurements. PPG sensors utilize light to detect changes in blood volume in the microvascular bed of tissues and the volume of oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (Hb) [1]. The sensors come in two main form factors: transmissive, where a light source and photodetector are placed on opposite sides of the tissue, and reflective, where the light source and photodetector are placed on the same side of the tissue. Furthermore, reflective PPGs can be grouped into three categories based on the combination of wavelengths their light sources use. These categories are Dual-Wavelength, Triple-Wavelength, and Muli-Wavelength (four or more wavelengths) PPGs.

Dual-Wavelength PPGs are the most common and serve as a convenient example for explaining the basic operating premises of a PPG sensor. Infrared and red light are directed onto a section of tissue (commonly the finger) in either the transmissive or reflective configuration. In the transmissive configuration, light passes through the tissue to the photodetector. In the reflective configuration, the photodetector captures any reflected light from the tissue.
The photodetector will capture a relatively large DC signal and a relatively small AC signal. The DC signal correlates to light reflected or transmitted through non-pulsatile components of the tissue. The AC signal correlates to varying volumes of blood and, consequently, the pulsing of the heart. To measure the heart rate, the DC signal is offset by internal hardware to obtain only the AC waveform and avoid oversaturating the transimpedance amplifier. The fundamental frequency of this AC signal corresponds to the heart rate. To calculate SpO_2, the first step is calculating the ratio of the pulsatile to non-pulsatile signals, known as the perfusion index PI (modulation ratio), for both the infrared and red signals (1)

$$PI = \frac{|AC|}{|DC|}. \tag{1}$$

Next, the ratio of ratios RoR is calculated (2)

$$RoR = \frac{PI_{red}}{PI_{infrared}}. \tag{2}$$

Finally, an empirically derived calibration curve is used to convert the RoR value to a SpO_2 percentage [2]-[3].

The reason why the RoR formula works and why the Dual-Wavelength PPG uses infrared and red light is because HbO_2 and Hb absorb both wavelengths of light differently. Hb absorbs more red light and less infrared light. Conversely, HbO_2 absorbs more infrared light and less red light [4]. A high concentration of Hb causes more red light to be absorbed, resulting in a greater dip in the red AC signal from baseline when compared to the infrared signal. This means PI_{red} is larger than $PI_{infrared}$, which produces a higher RoR. A higher RoR would correspond to a lower SpO_2 based on the calibration curve. The opposite happens with a high concentration of HbO_2.

Triple-Wavelength PPGs introduce a third green wavelength transmission. Green light does not penetrate skin as deeply as red or infrared, meaning Triple-Wavelength PPGs are a more suitable choice for reflective PPGs. The lack of penetration depth and the fact that green light is absorbed more readily by Hb and HbO_2 makes this configuration detect pulse rate with higher accuracy than its Dual-Wavelength counterpart. However, there is not a significant enough difference between the absorption characteristics of green light in Hb and HbO_2 for green light to be useful in measuring SpO_2. So red and infrared wavelengths are still required for this type of sensor [5]-[8]. In Multi-Wavelength PPGs, additional wavelengths can include blue, amber/yellow, a secondary red/infrared, a longer wavelength infrared, etc. These extra wavelengths provide advanced capabilities for the sensor and are well out of scope for this project; thus, further elaboration will be avoided.

II. System Overview of NIMBL

NIMBL is a hand-held pulse oximetry device capable of remotely transmitting measurement data to a base station. The entire system can be divided into three main subsystems: the Main module, the PPG module, and the Charging module. This modular design allows for the removal of the PPG module from the Main module. This allows subsystem updates to be performed without the destruction or alteration of other subsystems.

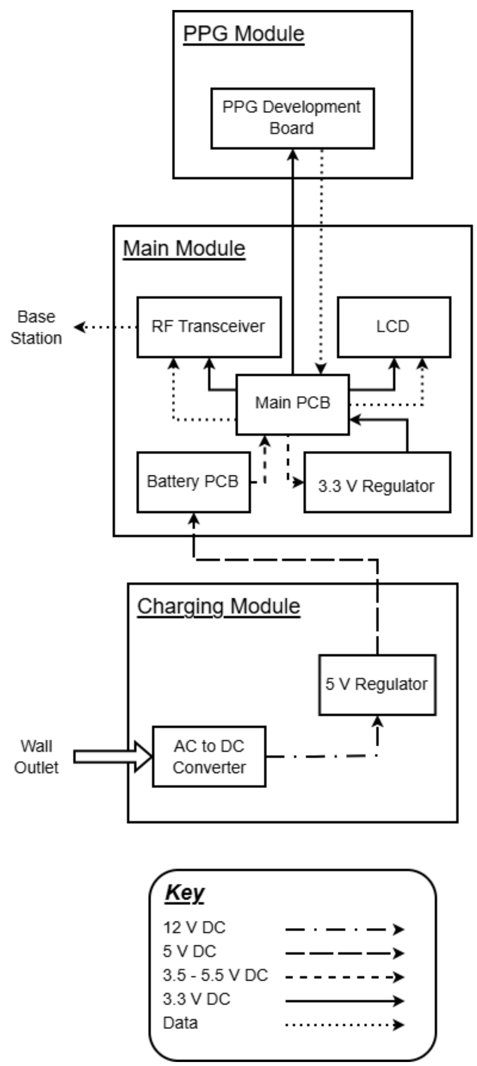


Fig. 1. NIMBL system overview describing the relationships between every subsystem and the key components within.

III. Main Module

The Main module is what the user will hold, as it contains the Main PCB, the RF Transceiver, a Liquid Crystal Display (LCD), the Battery PCB, and a 3.3V regulator PCB to power everything in the main module as well as the PPG module.

A. Main PCB and Display

The Main PCB is the central hub for all peripherals. It interfaces with the MSP430FR2476 microcontroller, PPG module, RF Transceiver, 3.3V Regulator, and the display. The display is the HT1621 pre-built LCD. The power switch for NIMBL was also placed on the Main PCB since the main PCB needed to be placed on the front plate. The Battery PCB and 3.3V Regulator were placed on the back plate due to size constraints of the device's case. The Main PCB also features interfaces to connect the Battery PCB to the power switch, which controls the connection between battery power and the 3.3V Regulator. JST GH connectors are used for each electrical interface with the exception of the RF PCB interface. These connectors are positive latching so that the peripherals can easily and securely be connected and disconnected as needed. Finally, five LEDs are included on the PCB for software debugging.

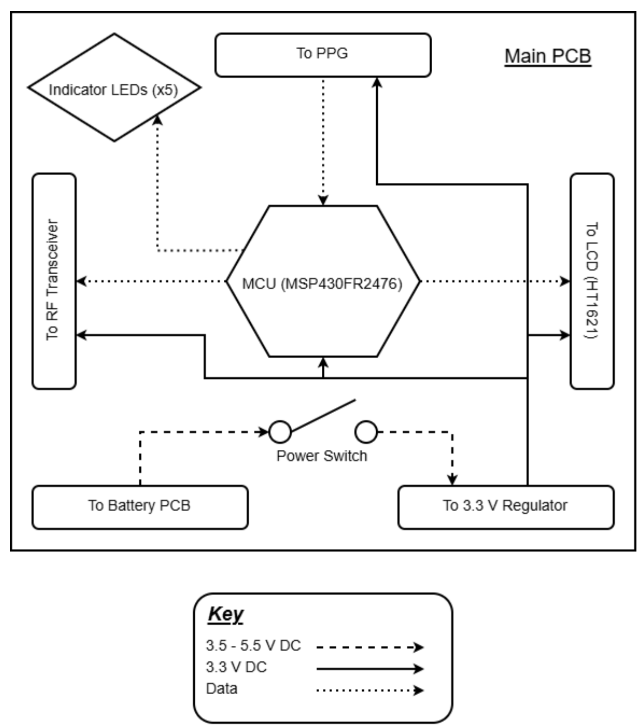


Fig. 2. Main PCB Diagram

B. RF Transceiver

The RF transceiver PCB is built around the CC1101 transceiver module from Texas Instruments. Two 2x10 female headers are used to interface with the main PCB which provide paths for data and power respectively. This board also features a balun network that matches the differential RF output of the IC to an SMA port that will be connected to an antenna. A second copy of the board may be established in combination with the MCU development board connected to a PC to serve as a base station that receives the data from NIMBL.

C. Battery PCB

The battery PCB houses a single 3400mAh lithium-ion battery that serves as the power source for the device and supports direct charging from any 5V source. Charging is handled by the MCP73871 IC, a fully integrated linear charge management controller that is programmed to have a max charge current of 1A. The IC features an integrated power path that allows the system to draw power from the input supply and simultaneously charge the lithium battery if needed. There are three status LEDs driven by the MCP73871 that signal charge status, low battery, power input, indicating any faults that may have occurred.

For safe and reliable operation, the PCB includes a DW01-based protection circuit with dual low-side MOSFETs to prevent overcharging, overdischarging, and overcurrent events. Protection against battery reverse polarity is provided by a separate p-channel MOSFET and Zener diode circuit across the battery terminals, which cuts connection to the output if the battery is inserted with the incorrect polarity.

D. 3.3V Regulator

The 3.3V Regulator uses the TPS564252 synchronous buck converter, which switches at 600 kHz. The regulator was designed to accept 3.5-6V input to drive a 3.3V output. The max output current is 1A. Special PCB design was required for this circuit to function. The two notable techniques used were: a Kelvin connection to the ground pin on the IC for the feedback trace, and copper planes for the input pin, the switching pin, the output pin, and the ground pin. LEDs on the input and output of the regulator's PCB are used to help indicate the board is functioning.

IV. PPG MODULE

The PPG module consists of a pulse oximetry development board enclosed in a 3D printed case. Specifically, the development board is the SparkFun Electronics® Pulse Oximeter and Heart Rate Sensor - MAX30101 & MAX32664 (Qwiic). As the name suggests, this board contains the MAX30101 and MAX32664 ICs. The MAX30101 is the PPG sensor. The MAX32664 processes the raw data from the sensor and converts that information into measurements that can be communicated directly to the MCU. SparkFun also provides public domain Arduino code that serves as an excellent springboard for the project's custom program. The PPG module is physically separated from the Main module so that the user can more easily take measurements, but the PPG is connected electrically via wires.

Faculty permitted the use of pre-made ICs for the PPG sensor due to the advanced circuit design and digital signal processing techniques required to fabricate and obtain reliable measurements from a custom PPG sensor. Additionally, the use of the development board was permitted because mounting the chips to a PCB would be unreasonably difficult with the soldering technology available to the project members.

A. Case Design Considerations

PPG sensors are very sensitive to ambient light, movement, sensor pressure on the tissue, and many other sources of noise. The development board takes care of many of these problems for us, except for the issues relating to the interface between the user and the sensor. The development board was meant to be used as a "plug-and-play" periphery for an Arduino demonstration, not specifically designed to be integrated into a sophisticated system. Thus, many users interface with the sensor using a rubber band or Zip-Tie. This would not be a suitable interfacing method for this project since it would not be very comfortable for the end user, nor would it be reliably consistent in maintaining sensor pressure, reducing movement, and rejecting ambient light. Thus, a special case had to be developed to interface the sensor with the user. When constructing the PPG Module's case, a few key details had to be observed::

1) fix the sensor directly to the tissue,
2) maintain consistent sensor pressure on the tissue that is not too hard or too soft,
3) reduce sensor movement in relation to the tissue,
4) aid in rejecting ambient light,
5) be comfortable for the user, and
6) be able to be docked to the main device when not in use.

To achieve these goals, the case was made of three 3D printed plates. The middle plate has a specially shaped slot for the development board to be pressed into. This slot was designed with extremely tight tolerances to ensure the board would not shift around in the case. The bottom and top plates surround the remaining exposed portions of the board to eliminate ambient light noise when the sensor is in use. The bottom plate features cutouts just small enough for the wires that interface the sensor with the main device to exit the case. These cutouts do not allow ambient light to reach the sensor. The top plate has an elliptical recess to fit a wide variety of fingers from any two directions. At the bottom of the recess is a rectangular cutout barely wider than the MAX30101 IC itself. When the user places their finger in the recess, the sensor is completely covered, and no ambient light can reach it.

All three plates are fixed together with stainless steel bolts that thread into heat set inserts. The overall case size is very small and lightweight to reduce unwanted movement between the sensor and the finger. This small form factor also allows a size #61 rubber band to be wrapped around the case. Using a specific size of rubber band (versus letting the user choose a size) in conjunction with a carefully constructed housing allows for the dialing in of the correct sensor pressure to make measurements consistently observable.

Finally, a rail system is located on one side of the case so that the sensor can easily be attached and detached from the main device without needing to implement special mounting hardware. Friction on the rails keeps the sensor from accidentally separating from the device. These rails are also kept small to reduce weight.

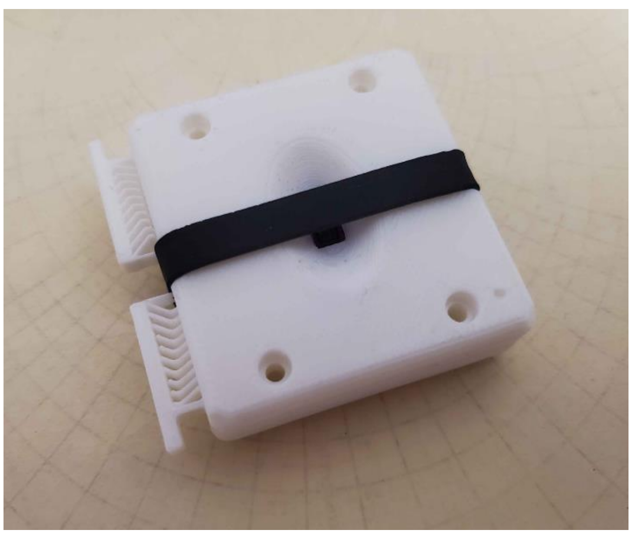


Fig. 3. Prototype model of the PPG module's case.

V. Charging Module

The charging module is an independent charging solution for the main module and serves as a docking station for NIMBL when the device is not in use. It plugs directly into a standard 120V outlet and houses an AC/DC converter, as well as a 5V regulator to deliver power to the device.

A. AC to DC Converter

The AC/DC converter is a commercial off-the-shelf 12V/1.25A LED driver, which converts mains AC power into regulated, low-voltage DC power. The LED driver provides reliable power in a compact form factor without sacrificing any key features such as isolation and short circuit protection.

B. 5V Regulator

The 12V supply from the AC/DC converter is stepped down to 5V using the LM2576-5, a 3A step-down switching regulator. Like the 3.3V regulator mentioned earlier, careful PCB design was required for proper functionality to be secured. Large copper pours and short traces between components were used to minimize loop inductance in the switching path and improve thermal conductivity. To interface with the device, a 2-pin magnetic pogo spring connector is employed for easy alignment and quick connection.

VI. Hardware Details

A. MAX30101

The MAX30101 is a Triple-Wavelength PPG Sensor that integrates the LEDs, photodetector, optical elements, cover glass, ambient light rejection, and low noise electronics required to take raw measurements. It communicates via I2C and uses Analog Devices' OLGA package. The OLGA package is a leadless package with vent holes underneath and between the pins. This means flux is forbidden, and careful application of solder is required to mount this sensor to a PCB without filling the chip with foreign materials and cracking the die. Because mounting this IC to a PCB would be extremely difficult with the equipment available, faculty permitted the use of a development board instead.

B. MAX32664

The MAX32664 is an IC with embedded firmware and proprietary algorithms for digital signal processing and measurement calculation. The chip is intended to pair with Analog Devices' pulse oximetry sensors like the MAX30101. It communicates over I2C with a host MCU. The only available package for this IC at the moment is a QFN package with 0.4 mm pitch. The difficulty of mounting this small package to a PCB is another reason why a development board was permitted to be used instead.

C. MSP430FR2476

The central component of the main module is the Texas Instruments Mixed Signal Processor 430 (TI MSP430). This family of microcontrollers is specially designed for low power embedded systems. In this case, the model chosen was the MSP430FR2476. The MSP430FR series includes Ferroelectric Random Access Memory (FRAM), which lowers power consumption and increases write speeds compared to traditional Flash Memory. Furthermore, typical power consumption is stated to be ~135uA / MHz [9]. As NIMBL should have the capability to host many modules, the MSP's several communication ports are necessary to connect with these peripherals. This MCU also provides several low power modes. For lower power draw some features may be altered, such as reducing the chip's clock speeds. The chip also had a development board implmenetation version that allowed for prototypical testing of the compatibility between several peripherals, ensuring that the design functioned before fabricating any PCBs.

D. HT1621

To display the user's measured vitals, a 6-digit, 7-segmented display controlled by the HT1621 LCD driver was utilized. This display and driver combination, similar to the microcontroller, was selected due to its low power consumption. Having 6 digits is the minimum number required to show the heart rate and blood oxygenation, where each value requires 3 digits to be fully shown. Utilizing a display that shows the necessary information without any extras provides lower power draw.

E. CC1101

The CC1101 is driven by a 3.3V DC signal and communicates with the MCU via SPI. Given a set of instructions to transmit information at a given frequency, power level, and modulation scheme by the MCU, the IC will construct and transmit a corresponding RF signal. Conversely, if reception is desired, the MCU can communicate this to the CC1101. Afterwards, signals that are received by the differential RF ports will be converted to SPI data that can be read by the MCU.

VII. Software Detail

To successfully read, display, and transmit data, the microcontroller software must connect to each component through their respective communication protocol. When communicating with the peripherals, the processor sends bytes of data that controls the action each unit takes. The software was written in such a way that, if errors are observed, diagnostics are simple and the error can be corrected swiftly. If an error prevents further action by the software, this will be reflected on the display.

A. Firmware

The software that is embedded into the device and resides in the microcontroller's FRAM is referred to as firmware. This firmware was written in C++, a low-level language that is designed for performance. The microcontroller is limited to C and C++, but the latter was chosen due to the object-oriented nature of the language which includes great features for improved development. Since there are many parts of the system that need dedicated code, the program is split into four parts. Three of those parts are libraries for the PPG sensor, LCD controller, and RF module. The fourth part is the main section of the system. It connects all three libraries together and controls the whole device. Before elaborating on specific libraries, the software flowchart below depicts the overarching s

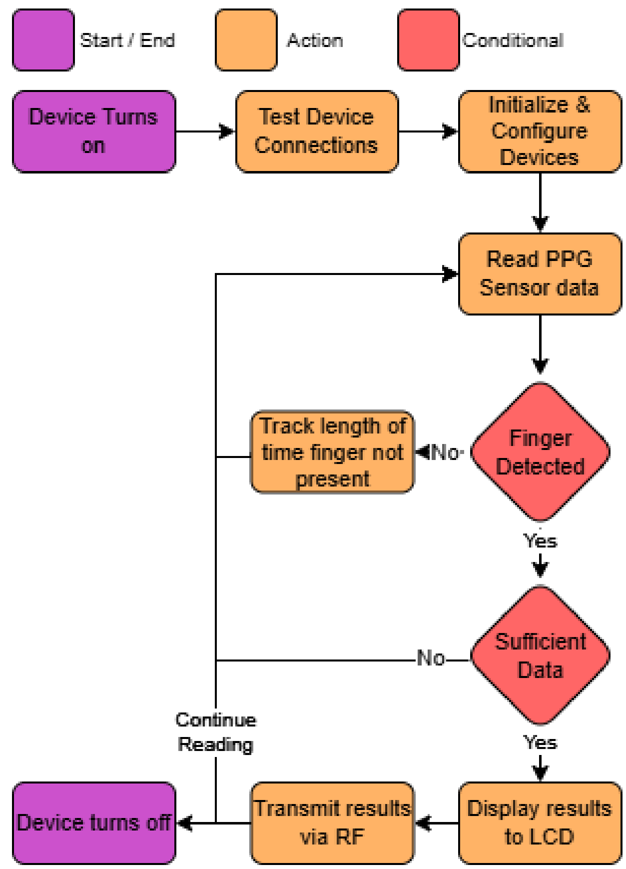


Fig. 4. Software Flowchart for main system.

The main flow is supposed to be simple, as over-complicating the logic can lead to software failures. We always test the connections to our devices, that way our program always knows it can maintain successful communications. As will be discussed later, the protocols must be set with the MSP430, as each peripheral has a set way of dealing with communication protocols. This setup stage has several LEDs to physically show what steps have been completed, giving us proof that the program works.

Once everything is configured and verified, we enter the main loop where we read, show, and transmit the data obtained. To push the program onto the chips, we used TI CCS. By wiring our main PCB with the MSP430FR2476 development board, we can upload the code onto our project. With the main system in mind, we can start to understand the finer details regarding specific sub-systems.

B. PPG Sensor Library

When designing the sensor library, we had to build around 2 elements. The first being I2C communication. Our MCU acted as the master device, with the PPG sensor being the slave device. To initiate communication, we set the MCU's I2C address register to the address of our sensor, that being 0x55. Then we send the write or read bit depending on what action we take. Afterwards, we either send or read bytes respective to the action we specified before. Once we get all the necessary data, or before we receive the last byte, the MCU tells the PPG to stop sending data.

Since the I2C communication was complete, we now had to create functions that enabled the functionality based on the sensor data sheet. This way, we had all options at our disposal even if not necessary in the final design. Since the programs are being uploaded to GitHub publicly, this code could additionally assist other projects that decide to use the PPG sensor with an MSP430 chip. Information in the datasheet told us which bytes to send to achieve a specific result, such as configuring the sensor, reading the sensor data, retrieving the model version of the sensor, and more. The functions were all designed around the basic I2C logic and whether we needed to write or read data from the sensor.

To test if the PPG has been configured correctly, we have run tests comparing the heart rate outputs of our sensor and an Apple Watch SE. Displayed below is a chart describing the error difference in results between the Apple Watch and the PPG sensor. To explain the columns, test is the numbered order of when we recorded these values. Loop time is the delay between obtaining sensor data in seconds. Response time, measured in seconds, is the amount of time it took sensor to return a heart rate and oxygenation reading. Max error shows the greatest distance from two BPM measurements when comparing the Apple Watch to our sensor.

TABLE I
COMPARISON BETWEEN APPLE WATCH AND PPG SENSOR

Test Number	Loop Time (s)	Response Time (s)	Max Error (BPM)
1	4	8.5	11
2	4	16	6
3	4	9	6
4	4	11	2
5	2	6	7
6	2	7	6
7	1	5.5	2
8	1	5.5	7
9	0.1	6	32
10	0.1	6	31

One column not present is the oxygenation levels. With the Apple Watch testing, we were only able to compare heart rate measurements. No way of comparing oxygenation levels was present during the testing. Most of the time, our readings were showing 98% to 100% oxygenation. Pictured below is the vital program logic that deals with obtaining the data we need. All checks occur by sending specified hex codes to the system and retrieving the response byte. We know if the sensor has all data available by checking if the storage for those values is full or not.

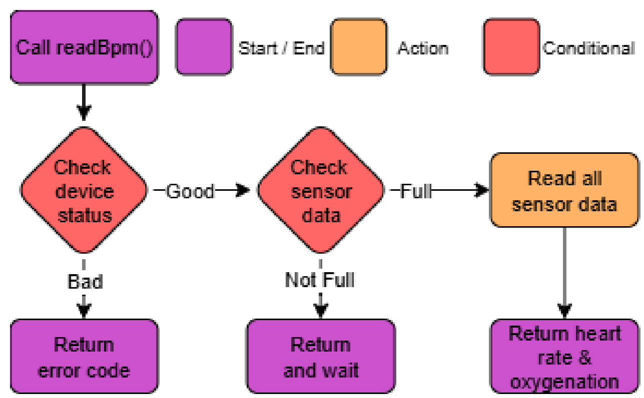


Fig. 5. PPG main logic flowchart.

C. LCD Library

Reading the sensor data is only our first step; to make the information valuable, it must be shown to the user. Like the PPG library, we must approach this library with 2 concepts in mind: 1. How to communicate and 2. Writing the software so our LCD completes its necessary goals. To communicate with the display, a unique protocol was put in place by the HT1621 controller. This communication protocol is extremely similar to Serial Peripheral Interface (SPI), requiring one less wire than traditional SPI. To start communication, we pull a Chip Select (CS) pin low. Once this occurs, we can send bits to our HT1621. Sending bits requires pulling the Write (WR) pin low, where we set the

Data line high or low to represent a 1 or 0. After the bit is sent, pull the WR pin high. When all bits have been sent, pull CS high.

Sending bits tells the LCD controller what actions to take. Provided from the HT1621 data sheet are bit segments that correspond to commands we can execute. The most important of those being to write a number on the display. To achieve this, each digit that we want to write must be split into two, 4-bit segments. This is due to the hardware limitations of the HT1621. Once a single digit has its 8 bits transmitted to the specified location, it will be shown on the display.

Since our LCD is set to display two sets of three digits, the test code was implemented to prove that we could have separate numbers to display correctly onto the screen. The function would start with one set of three digits at 999, and the other at 0. From there, each number would decrement or increment respectively to show all numbers within 3 digits are visible.

D. RF Library

Before we start working on the commands with the radio module, we need to know what configuration settings to apply. To do this, the program SmartRF provides the tools for setting up our configurations and returning the hex codes necessary to achieve our results. The previously mentioned program specifies the hex codes to the radio module we want to implement, working perfectly with the CC1101. After choosing the settings we desire and obtaining the hex codes, we can move onto communicating with the radio.

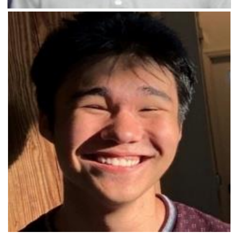
For the RF module, SPI was the communication protocol designated. To achieve this, we first must choose our options for talking with the radio system. Our MSP is the master, initiating data transfers. The CC1101 specifies that data must be sent by most significant bit (MSB) first, as well as stating the clock line must idle low. With these settings, along with the synchronous mode and selecting our sub-master clock for lower clock speeds, we have configured the SPI communication on the microprocessor to communicate with the CC1101. Once that is done, we configure the radio by sending all the hex codes obtained by SmartRF. To communicate on SPI, we pull the CSN pin low, send read / write bit, burst bit, and address bits. After reading the buffer, we can send our byte to read / write from the CC1101. Once all those steps are completed, we successfully communicated with the device. As of writing this, our program can successfully talk to the CC1101 but has yet to transmit data. That is actively being worked on.

VIII. CONCLUSION

With the technologies and practices listed above, we believe this effectively accomplishes the goals of safely measuring, displaying, and wirelessly transmitting a person’s vital information. We have proven that our sensor can read heart rate with an acceptable level of accuracy, whilst displaying the information. This was the toughest part to nail so far, as connecting the MSP to our sensor was not working well for a while. As we approach the final demo, we will: refine the housing design, touch up any hardware designs where necessary, and optimize the software.

BIOGRAPHY

Ethan Denner is a senior Electrical Engineering student at the University of Central Florida. He is planning to obtain a Master of Science in Electrical Engineering at UCF. Also, he intends to pursue a career in RF Engineering.



Kai Ford is a senior Electrical Engineering student at the University of Central Florida who will begin an RF Engineering role at Lockheed Martin in Orlando, FL in the summer of 2026.

Benjamin Will is a senior Electrical Engineering student at the University of Central Florida who plans to begin his career after graduation.

Tyler Takimoto is a senior Computer Engineering student at the University of Central Florida. Currently planning on working full time at Mitsubishi Power in Orlando.

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