

# 6.111 Final Project Proposal

## HeartAware

Michael Holachek and Nalini Singh  
Massachusetts Institute of Technology

### 1 Introduction

Pulse oximetry is a popular non-invasive method for monitoring a person's blood oxygen saturation. By measuring the amount of light absorbed by a user's finger, it is possible to calculate the oxygen level in the bloodstream. This periodic signal can then be processed to reveal information about a user's heart rate [1].

Standard pulse oximetry systems use an LED and photodiode pair that clips across a user's thumb or index finger. This sensor is connected to control circuitry that drives the LED and converts the voltages read from the photodiode to relative light absorption by the oxygen bloodstream. The data then flows through signal processing logic to detect peaks and calculate heart rate. Finally, an output interface, such as an LCD screen, displays the signal and important related metrics. Modern pulse oximeters range from small and cheap consumer-grade informational sensors to robust medical-grade machines used in emergency rooms and secondary care facilities.

HeartAware will implement a pulse oximetry system with a user-friendly audiovisual interface on the Nexys 4 DDR FPGA board. The system will process the input pulse oximeter signal to identify peaks in the signal and calculate the patient's heart rate using this data. Then, the processed oxygen saturation waveform and calculated heart rate will be displayed on a monitor. Additionally, the user's calculated heart rate will be periodically announced through a recorded voice played through the audio output.

If time allows, we will implement more sophisticated signal processing for calculation of additional metrics, such as heart rate variability. Other possible features include a longer period view of the oxygen saturation data, as well as the ability to save captured pulse data to an SD card.

Disclaimer: this device will not be designed for medical use.

## 2 System Overview

HeartAware is comprised of five main elements, shown below in Fig. 1. Each of these elements is described in the sections below.

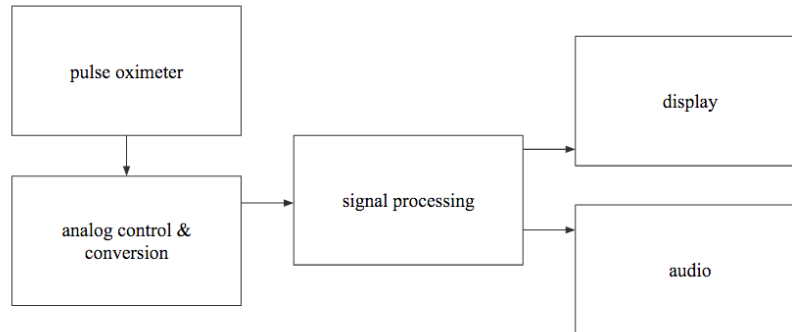


Figure 1: A simplified block diagram of the five system modules.

### 2.1 Pulse Oximeter (Michael)

The pulse oximeter sensor is a finger clip consisting of a red and infrared Light Emitting Diode (LED) and a photodiode. With appropriate driving circuitry, the LEDs will shine light through the user's finger and measure the absorbed light with a photodiode. Because oxygenated hemoglobin absorbs less light than pure hemoglobin, it is possible to convert the absorbed light to a reading of the level of oxygen saturation in the user's bloodstream [2].

### 2.2 Analog Control and Conversion (Michael)

The pulse oximeter will be connected to an analog driving circuit, designed by Prof. Hom, to translate light pulses into a rough oxygen saturation signal. This initial signal will then be processed through an op amp to scale and offset the voltage to an appropriate level. To convert the voltage to a digital signal, we will use an 8-bit ADC. To allow for greater modularity and portability, we will integrate all required external circuitry on a custom Printed Circuit Board (PCB).

### 2.3 Signal Processing (Nalini)

The oxygen saturation signal from the sensor will be analyzed in order to calculate patient heart rate in real-time. The R wave, representing ventricular depolarization of the heart, signifies the strongest peak in the oxygen saturation signal for each heart beat [3]. The elapsed time between

successive R waves will be calculated using an algorithm for real-time detection developed by Pan and Tompkins [4]. This RR interval will be converted to a value for the current heart rate. The noise-reduced signal and the current heart rate calculation will be passed to the display and audio modules for presentation to the user.

## 2.4 Display (Michael and Nalini)

The display module will use the VGA interface of the Nexys 4 to display the main user interface of the system, which will consist of the HeartAware branding, animated graphic sprites, a custom font, the processed oxygen saturation waveform, and a readout of the current calculated heart rate.

## 2.5 Audio (Michael)

The audio module will generate a beep every time the user’s heart rate peak is detected, as well as a periodic announcement of the heart rate (e.g., “one-hundred fourteen beats per minute”). These sounds will be mixed and output to the 3.5mm audio output jack available on the Nexys 4.

# 3 Implementation

At the top level, our system will have four states, shown below in Fig. 2.

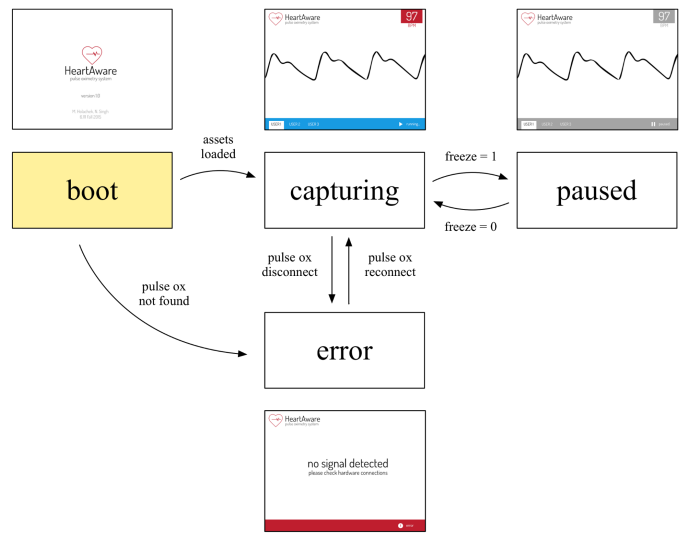


Figure 2: Top-level FSM of the HeartAware system.

The system will start in a boot state, where it will load graphic and audio assets from the SD card and check to ensure the pulse oximeter is connected. At anytime during boot or capturing mode, if the sensor is not connected, the system will transition to an error state. Once the pulse oximeter is connected, the system will begin or resume capturing mode, where the user’s live heart data is displayed. Should the user desire further analysis of a certain set of samples, a paused mode can be entered by toggling a switch.

Our system is meant to provide information to casual users, not medical professionals. As a result, our design is primarily intended to be intuitive to use. We will not focus on being absolutely precise or reliable, as these goals would require design and testing beyond the scope of this project.

A detailed block diagram of the entire system is shown below in Fig. 3.

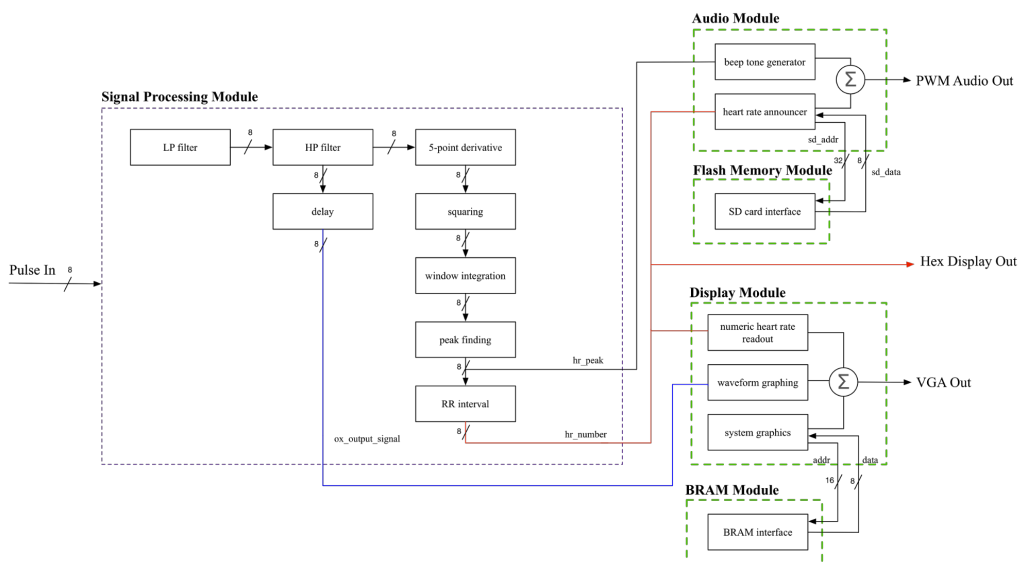


Figure 3: A detailed block diagram of the various system modules with interconnects and data lines labelled.

### 3.1 Pulse Oximeter (Michael)

We plan to use a Welch Allyn finger pulse oximeter, which has single red and IR LEDs that emit light through the user’s finger to a photodiode receiver. For HeartAware, we plan use only the red LED and not the IR LED, since infrared wavelengths are much less effective than red wavelengths at detecting differences in oxygenated and deoxygenated hemoglobin [2]. The sensor is terminated with a D-sub 9 connector.

### 3.2 Analog Control and Conversion (Michael)

The D-sub 9 connector on the pulse oximeter sensor will connect to a custom 2 layer PCB with an analog driving stage, an intermediate op amp filtering stage, and an analog-to-digital conversion stage.

The analog driving stage will consist of several passive components as well as four JFET op amps to drive the red LED depending on the voltage output of the photodiode. This design was provided by Prof. Hom. Because the output of this submodule was originally meant to be plugged into a microphone input jack, the signal is relatively low in amplitude and does not have sufficient offset for proper digitization by the ADC. Thus, we include an op amp filtering stage with a gain and new offset, which results in about a 1Vpk-pk signal at a 2.5V offset.

Next, we will use the ADC0804, an 8-bit parallel output analog-to-digital converter with a 0-5V range, to convert the voltage into a digital value. This converted data signal and miscellaneous control signals will be connected to the Nexys 4 through two 2x6 Digilent Pmod connector ports.

Schematic capture and PCB layout will be done in Altium Designer; a diagram of the PCB is shown in Fig. 4. All components will be surface mount packages. Boards will be sent out for fabrication; assembly will be completed by us with a solder stencil, solder paste, tweezers, and reflow oven.

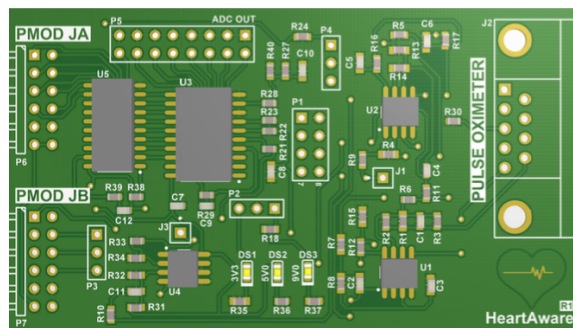


Figure 4: Custom PCB with analog control circuitry.

### 3.3 Signal Processing (Nalini)

We will implement an algorithm for real-time QRS complex detection developed by Pan and Tompkins on the Nexys 4. First, a bandpass filter, comprised of cascaded low and high pass signals, will eliminate noise from the pulse oximeter signal. Next, a five-point derivative of the reduced-noise signal is calculated. The derivative is squared to obtain a positive signal, with higher frequencies amplified. Finally, this squared derivative is run through a moving window integrator. The end of the rising edge of the resulting integrated signal corresponds to the peak of the R wave, and successive R peaks are used to calculate the RR interval corresponding to a particular heart rate [4]. Each of these filtering stages are shown in Fig. 5.

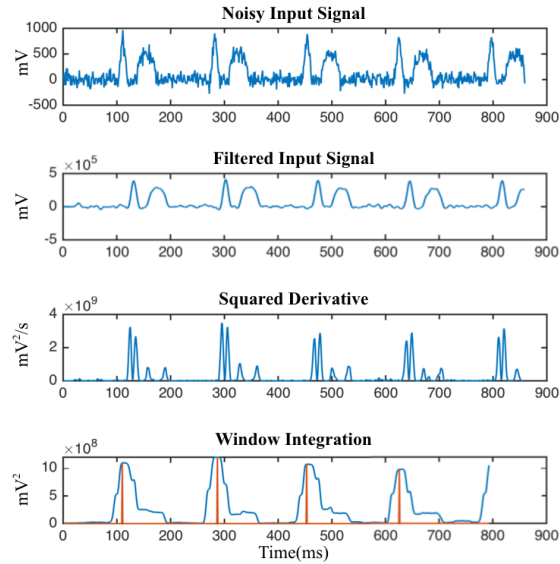


Figure 5: Various filtering stages of the pulse oximeter input signal.

### 3.4 Display (Michael and Nalini)

The display output will contain two major elements: a graph of the oxygen saturation signal and a numeric readout of the current heart rate. Additionally, the top of the display output will contain HeartAware branding, current system mode (boot, paused, running, or error), and an animated heart graphic. This display will run at 1024x768 resolution in 4 bit color, giving a possible 4096 colors for our interface.

The oxygen saturation display block will continuously receive individual values from the processed pulse oximeter signal temporarily stored in internal FPGA BRAM. Approximately 1,000 of these samples will be plotted on the screen at any given time. The screen will refresh gradually from left to right as new samples are processed, overwriting values previously stored in memory.

The three-digit digital numeric readout of the heart rate will be overlaid on the top right of the screen. We plan to use a custom font in a COE file loaded from BRAM.

The branding and animation graphics will be displayed in a panel at the top of the screen. These graphics will also be stored in BRAM.

### 3.5 Audio (Michael)

The PWM audio output will play two types of sounds: a brief tone upon the detection of a heart rate peak, and an announcement of the heart rate every few seconds. The tone will be a brief 100ms

beep, triggered by the `hr_peak` pulse sent by the signal processing module upon detection of a peak. It will be a simple 440 Hz sine wave tone implemented by a waveform lookup table.

For the verbal announcement of heart rate, we will record the English numbers from “forty” to “one hundred ninety nine” as well as the phrase “beats per minute.” These uncompressed wav files will be stored on an SD card connected to the Nexys 4. Using an SD card read module, every few seconds the module will look up the audio files corresponding to the current heart rate, load the files into BRAM, and play the correct sequence of sounds.

It is crucial to ensure that the beep and the verbal heart rate announcements do not interfere with each other so sounds are not cut off. Thus, our audio mixer submodule will take both sounds as input, and control which sounds play at what time, as well as with what volume. The mixer will pause the announcement if a beep needs to sound, then resume it after the beep.

## 4 Timeline

Each of the tasks for this project will be completed according to the schedule in the Gantt chart in Fig. 6.

	Week 10/26	Week 11/2	Week 11/9	Week 11/16	Week 11/23	Week 11/30	Week 12/7
Project Proposal & Requirements	Both						
Analog Circuitry & PCB	Michael						
Signal Processing		Nalini					
Display Output			Both				
Audio Output			Michael				
Integration & Testing				Both			
Alternate Filters				Nalini			
UI Improvements, Night Mode						Michael	
Final Testing & Buffer						Both	

Figure 6: Gantt chart with anticipated task schedule.

## 5 Key Challenges

There are a few potential issues of note during the implementation of HeartAware. In particular, the signal obtained from the pulse oximeter varies in amplitude and absolute value between different fingers; the signal processing methods used for this project must be robust to these variations. Additionally, it will be challenging to ensure that all graphical and audio assets can be loaded efficiently from a storage medium to RAM.

## 6 Resources

HeartAware will run on the Digilent Nexys 4 DDR board with a Xilinx Artix 7 FPGA. Apart from this device, this project will require a pulse oximeter, analog circuitry to drive the pulse oximeter and get a continuous oxygen saturation signal, and an analog to digital converter to convert the output signal from the pulse oximeter to a digital signal usable by the FPGA. For a breadboardable implementation, all required circuitry was provided by Prof. Hom. For our custom HeartAware PCB, we will provide the circuit board, components, and required tools to assemble it.

Additionally, the project will require a VGA monitor and speaker with a standard consumer-grade 3.5mm jack input. We plan to use the VGA port on the LCD monitors in lab for the display interface. Speakers are also available for use in lab.

## 7 Conclusion

HeartAware is a simple and user-friendly oxygen saturation and heart rate monitoring system on the Nexys 4. This system will include signal processing for peak detection, output display on a VGA monitor, and output audio via a speaker. We aim to create a project that will better help users understand their heart rate. If time allows, we will explore more sophisticated peak-detection methodology on the FPGA, implement data save or screenshot capture options, and introduce more involved graphics and animations for the VGA display.

## References

- [1] G. Ingram and N. Munro, "The use (or otherwise) of pulse oximetry in general practice," *British Journal of General Practice*, vol. 55, no. 516, pp. 501–502, 2005.
- [2] S. Lopez and R. Americas, "Pulse oximeter fundamentals and design," *Free-scale Semiconductor, Inc., application note document number: AN4327 Rev*, vol. 1, no. 09, 2011.
- [3] E. A. Ashley and J. Niebauer, "Conquering the ecg," 2004.
- [4] J. Pan and W. J. Tompkins, "A real-time qrs detection algorithm," *Biomedical Engineering, IEEE Transactions on*, no. 3, pp. 230–236, 1985.