Wireless Wearable Electrocardiogram (WWECG)

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Group 9

Project Overview

The Wireless Wearable Electrocardiogram is a portable cordless solution for recording and displaying cardiac activity.

The WWECG system is comprised of two arm mounted sensors and an external processing hub. The wrist mounted sensors use medical grade disposable wet electrodes to obtain a signal from the body and transmit it wirelessly to the hub. The hub processes and analyzes the signal with algorithms to detect QRS complexes, heart rate, and any arrhythmia. This information is then transmitted to an Android application via Bluetooth LE for the user to monitor.

Motivations

- Biomedical Focus
  - Members would like to pursue careers in wearables and biomedical technologies
- Eliminate need of wires attached to processing unit typical within conventional ECGs.
- Provide a wearable biomedical sensor that can sense and display the heart's electrical activity in more robust environments.
- Improve comfort for user attached to electrocardiogram.
- Improve arrhythmia detection by implementing algorithm to notify user of possible detection.
- Create a proof of concept prototype that does not utilize right leg driven circuitry

Design Challenges

Certain considerations need to be taken to ensure accurate results with an ECG. The signal must be contaminated by as little noise as possible. Typically ECG signal amplitude is measured in microvolts. Any noise present in the system can overshadow the desired signal and lead to incorrect representation of our signal.

- Main Sources of Noise
  - 60 Hz (Power Line Interference) Noise
  - Motion Artifact Noise
  - Muscle Noise
  - Common Mode Noise
- Sampling Synchronization
  - Typically ECGs are processed synchronously due to being hardwired to their processing units. In order to maintain accuracy we need to ensure synchronization of sampling prior to Bluetooth transmission.

Goals and Objectives

The overall objective of this project is to create a fully functional wireless ECG that allows the user to move about freely and monitor their heart activity.

- Hands free arm mounted device
- Live mobile application that stores and displays user data
- One hour of monitoring when fully charged
- Comfortable device that gives the user free range of motion
- High resolution image of the users data in a graphical format
- Notify user of possible cardiac health concerns (arrhythmia, atrial fibrillation, etc.)
- Provide an accurate representation of heart’s rhythm, QRS complex locations, and calculation of heart rate.

Specifications

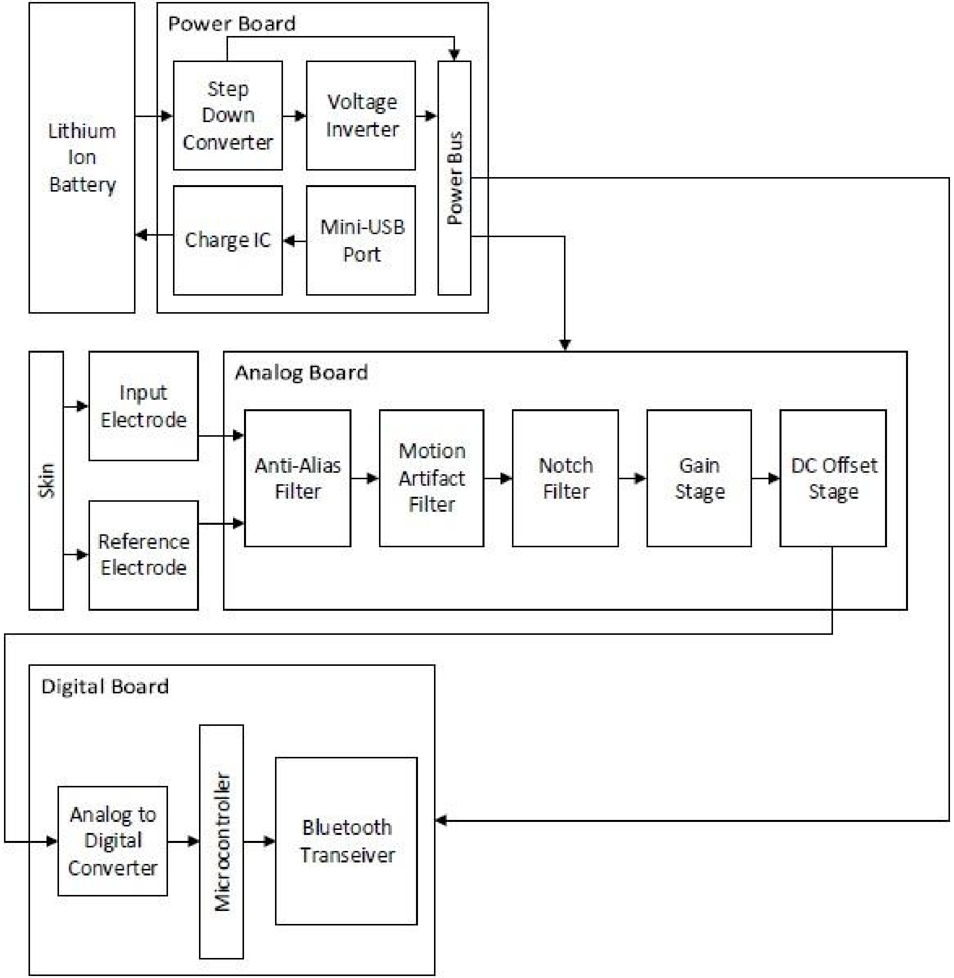
Dimensions (Wrist Sensor) Dimensions (Hub)	110mm x 120mm x 15mm 250mm x 250mm x 25mm	
Runtime	Li-Ion 3.7 V 150mAh battery	1 Hour
Weight (Wrist Sensor)	< 1.5 lb	
Frequency Response	.5 Hz to 100 Hz	
Sampling Rate	250 Samples Per Second	
Sampling Resolution	16 Bit	
ECG Channel	1 Channel	
Recording Method	Continuous	
Functional Distance	2 Meters	

Project Responsibilities

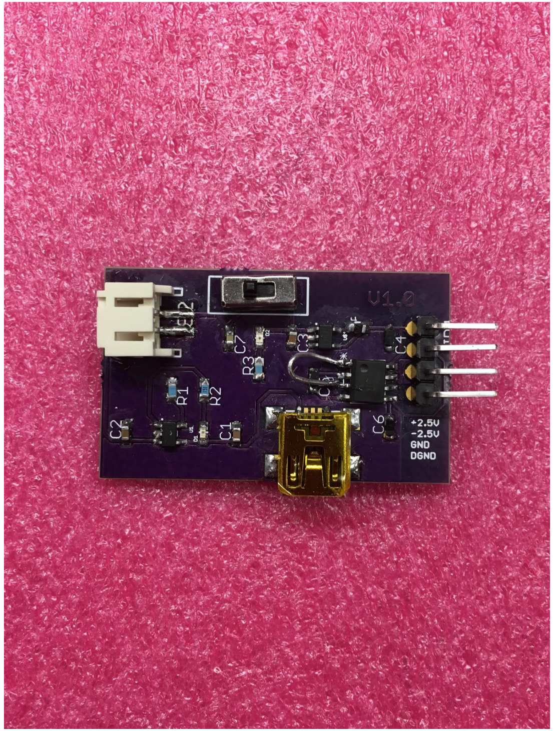
Topic	Primary Focus	Secondary Focus
Analog Signal Processing	Ulbert Botero	Ryan Shifman
Digital Signal Processing	Ulbert Botero	Alex Consunji
Embedded Processing	Alex Consunji	Ulbert Botero
Application/Server Development	Karson Kimbrel	Alex Consunji
Power Management	Ryan Shifman	Ulbert Botero
PCB Design	Ryan Shifman	Ulbert Botero
Wireless Transmission/Comms.	Alex Consunji	Karson Kimbrel

Sensors

- The sensors are comprised of 3 interconnected PCBs that wrap around the wrist. Other attachments include Li-Ion battery pack and medical grade wet electrodes.
- Power board - contains the battery connector, charging circuitry, mini-USB port for charging, buck regulator, and charge pump voltage inverter
- Analog front end board - holds the analog filters and pins for the signal acquisition and reference electrodes
- Digital board - MSP430G2553 microcontroller, analog to digital converter, time stamp, and interfaced HM-11 bluetooth module for wireless transmission

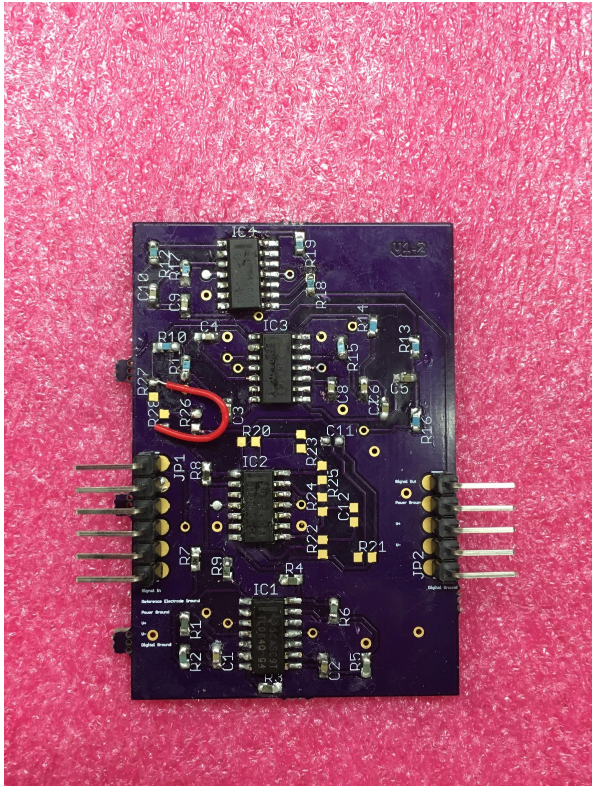


Power Board



- JST connector for 3.7 V 150 mAh Li-Ion battery - high energy density, small size and profile, no memory effect
- MCP73831 Li-Ion charge controller - charging current regulated to 100 mA by an external resistor to prevent overheating
- Mini-USB port for battery charging
- Green On/Off LED
- TPS62205 buck converter - step down voltage level from 3.7 V to 2.5 V with a max current output of 300 mA
- LM2663 switched capacitor voltage inverter - inverts inputs voltage from the buck converter to -2.5 V to power the negative supply rail of the TL084 dual supply op amp used in the analog board. The LM2663 outputs a max of 200 mA
- Simulated power calculations show the AFE draws 50 mA per sensor, total current draw of each sensor is tested to be 150 mA

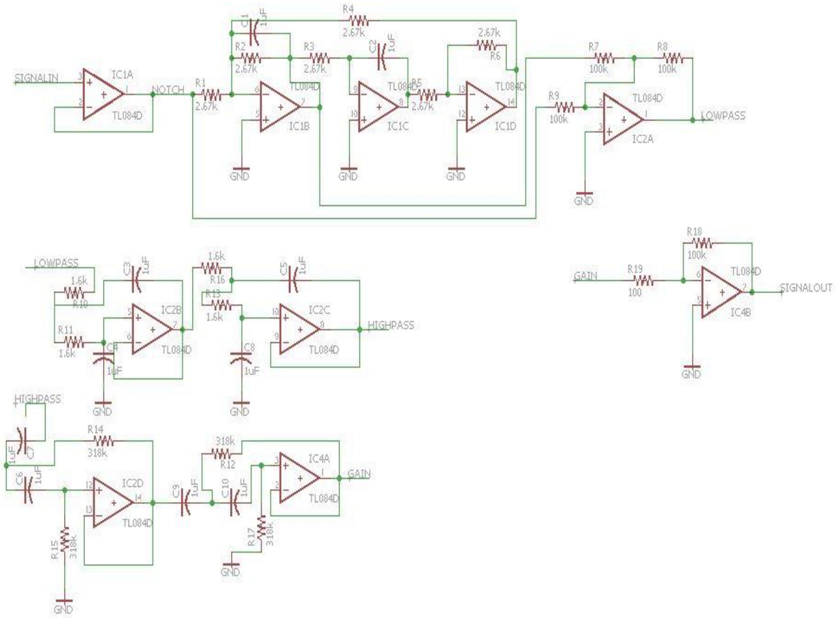
Analog Board



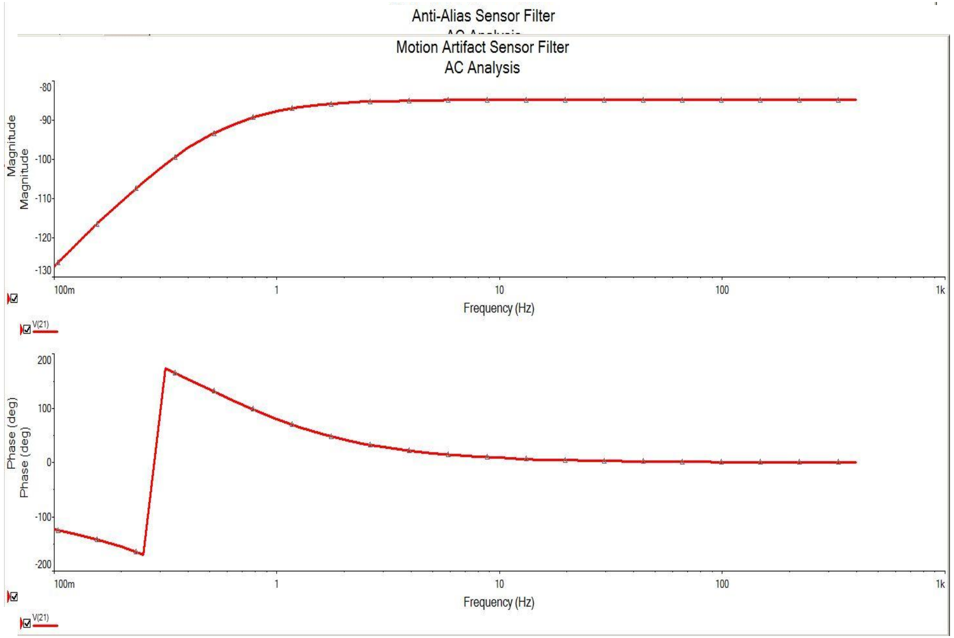
- Input buffer to take advantage of the op-amp's low output impedance to minimize unwanted noise from electrode impedance mismatching.
- TL084 dual supply op amp for active filtering
- 60Hz Tow-Thomas Biquad topology notch filter
- Sallen-Key topology lowpass and highpass filters for small Q application and simplicity in minimizing component spread.
- 4th order Motion artifact filter 80 dB/decade
- .5 Hz Motion artifact filter -3 dB frequency
- 4th order Antialias filter 80 dB/decade
- 100 Hz Antialias filter -3 dB frequency
- Non-inverting Gain Stage of 1000
- Summing amplifier to center signal around 800 mV

Analog Filter Schematics & Responses

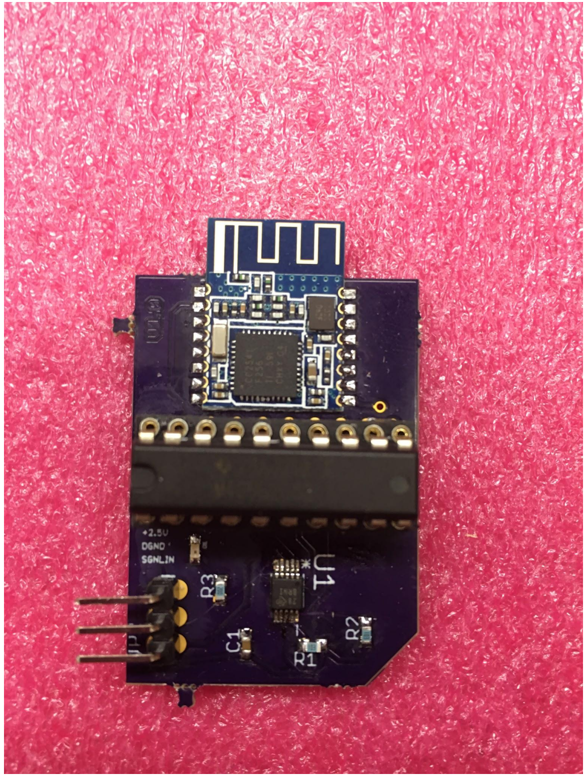
Analog Front End Schematic



Magnitude & Phase Response



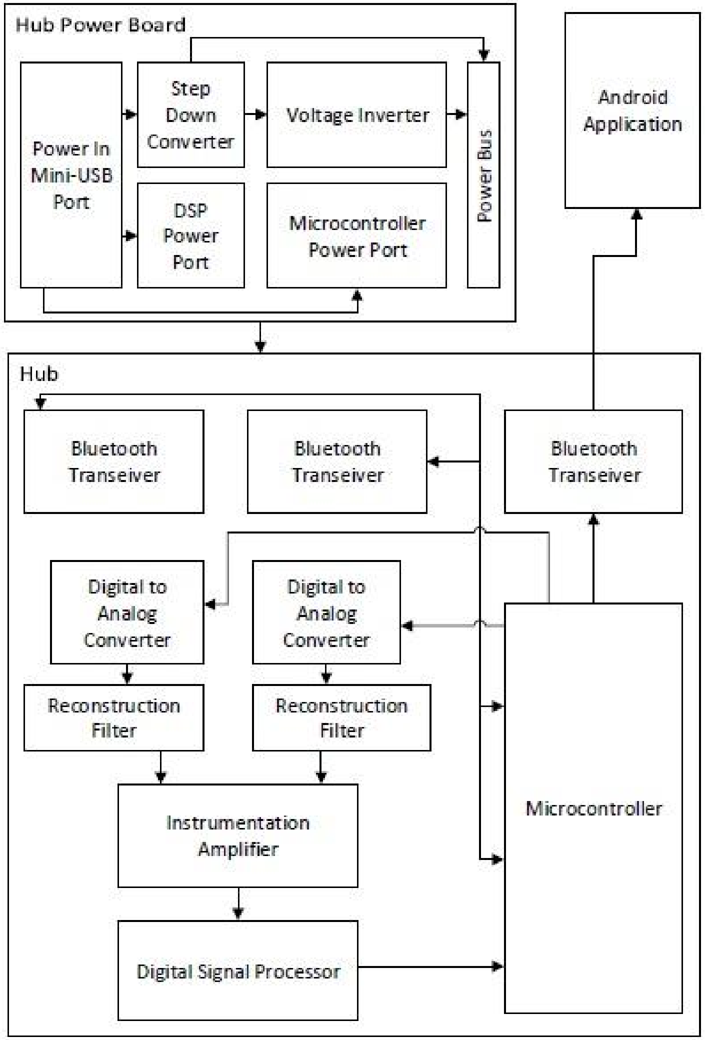
Digital Board



- MSP430G2553 Microcontroller Unit
- ADS1114 16-Bit Analog to Digital Converter controlled via I2C lines from the MCU
- Orange Transmission LED
- HM-11 Bluetooth LE module

Hub

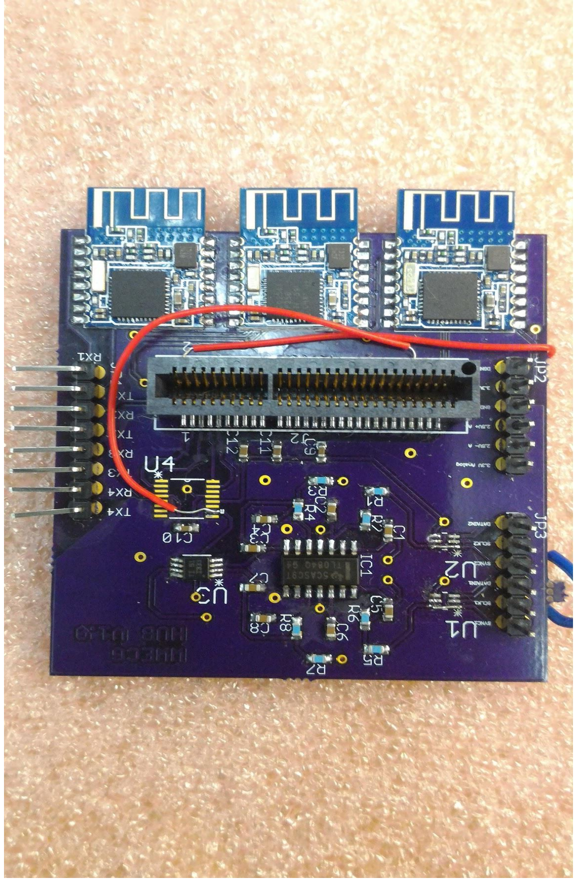
- The Hub is the center for processing data obtained from the wrist sensors.
- 3 Bluetooth Transceivers - receive data from the sensors and send processed data to the Android application
- Arduino - interact with Bluetooth transceivers
- 2 Digital to Analog Converters - convert each digital signal to analog
- 2 Reconstruction Filters - smooth out the signal after zero order hold reconstruction
- Instrumentation Amplifier - eliminates common mode noise
- Digital Signal Processor - implement algorithms to detect QRS complex, calculate heart rate, and detect arrhythmia

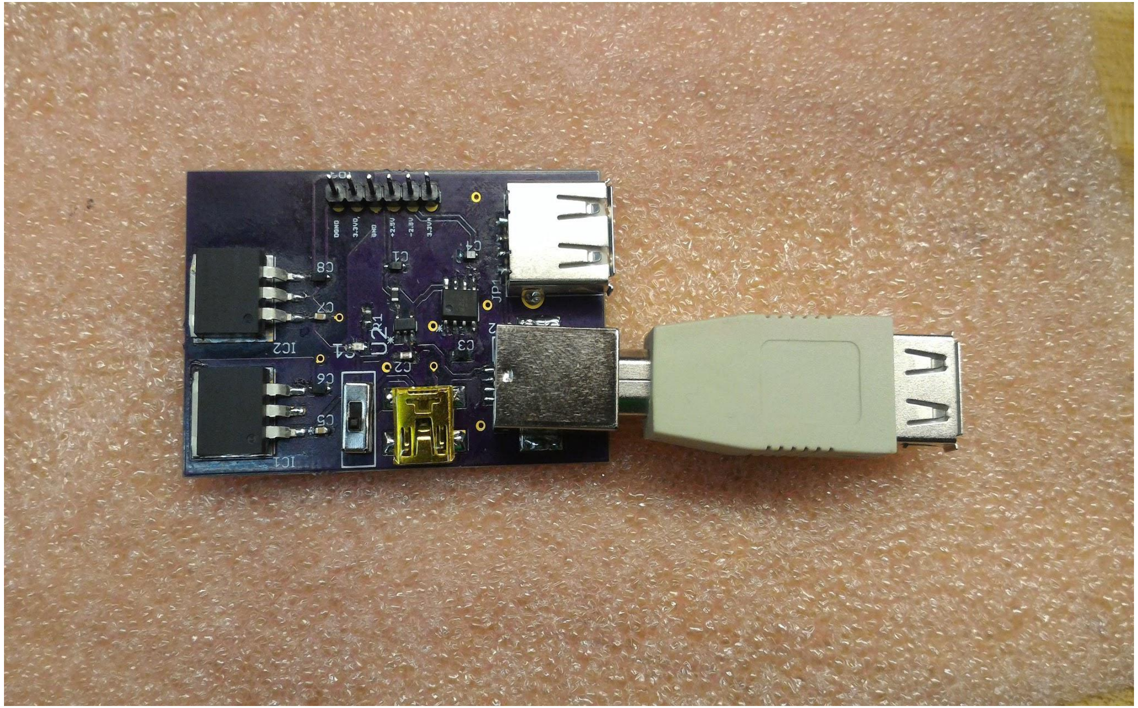


Power - Hub

- The Hub Power Board features a USB Mini port for to power it from a 5 Volt USB port and two USB-A ports to power DSP and MCU boards.
- TPS62205 Buck Converter - powers positive rails of TL084 op amp and INA 333 Instrumentation amplifier
- LM2663 Switched capacitor voltage inverter - powers the negative supply rails of the TL084 and INA 333.
- LM2937 LDO voltage regulator - powers Bluetooth modules on the Hub

Hub and Power Boards

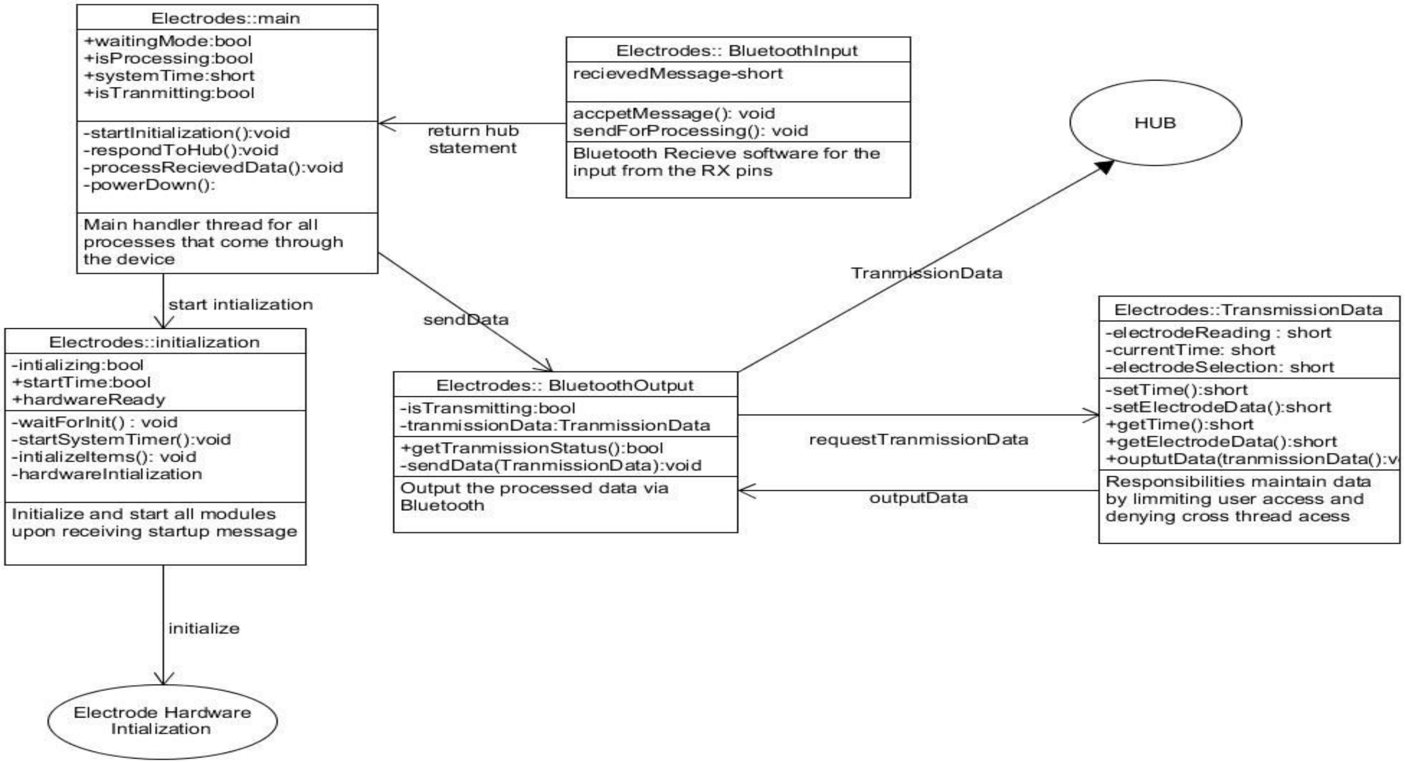




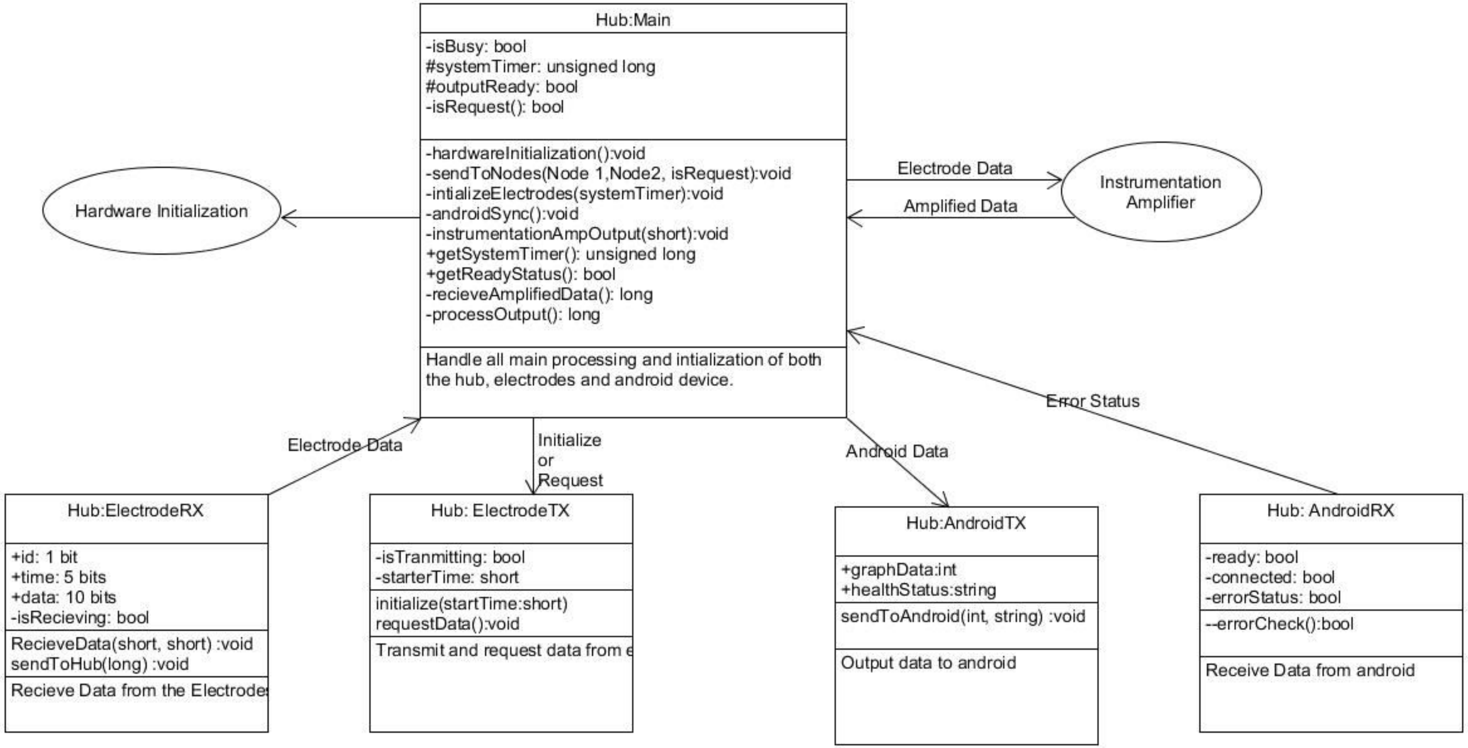
Embedded Processing

- Overview
  - Process all data received from each wrist sensor then transmit to hub where it will be filtered and outputted to Android device for data visualization.
- Steps
  - Send synchronized startup signal from hub to both sensors in order to begin collecting data
  - Collect data from wrist mounted sensors and convert using ADC where it will be outputted via BLE to hub
  - Received data is then processed via hardware then inputted to hub where it will be transmitted to the Android device via BLE.

Embedded Software Sensor UML



Embedded Software Hub UML



Microcontrollers Selections

- Sensors use MSP430G2553
    - 1 UARTS
    - 1 I2C line for 16 BIT ADC
    - Programmed and with Energia via USB
    - 16 bit RISC Architecture
    - 16 MHz Clock
- Hub use ATMega2560
    - 4 UARTS
    - 1 I2C line for both DAC
    - 16MHz Clock
    - 256KB of flash memory

Wireless Transmission Bluetooth LE Overview

- TI CC2541 Bluetooth LE
- Pros
  - Low Energy consumption
  - Easily Compatible with Android (4.3 or later)
  - Relatively fast data transmission
  - Built in encryption with password protection
- Cons
  - 20 byte limit per transmission
  - Connectivity problems
  - Possible Bottlenecking

Wireless Transmission Bluetooth LE Sensor

- Overview
  - Setup
    - AT Commands sent via serial UART to setup mode as slave, baud rate and transmit and receive functionality
  - Use
    - Receive data for synchronization from the hub on MSP430
    - Output data back to hub via transmit UART from MSP430 until off command is received
    - Receive data for device turn off

Wireless Transmission Bluetooth LE Hub

- Overview
  - Setup
    - AT Commands sent via serial UART to setup mode, baud rate and transmit and receive functionality
    - Set first HM-11 module as Master for both wrist sensors and second Hm-11 as slave for Android device
  - Use
    - Send data for synchronization from the hub on ATMega2560
    - Transceive data between sensors and hub using ATMega2560 and master module mounted on hub
    - Transceive data between Android device and hub
    - Send off command when powering off

Digital Signal Processing

- Implemented via Texas Instruments TMS320C5535 Fixed Point DSP
  - Chosen due to its high performance and low power consumption.
  - Additionally, chosen due to the flexibility implementing the DSP algorithms via software in C offers versus implementing via hardware on an FPGA.
- Consists of additional digital filtering(Notch, Lowpass, and Highpass) to further clean signal to have as pure of a signal to transmit to the phone application for display as possible.
- Additionally, this makes less analog filters needed on sensors to clean initial signal.
- Use on chip Analog to Digital converters to convert and process final signal from Instrumentation Amplifier
- The Digital Signal Processor will implement the QRS Complex Detection algorithm, Heart Rate Calculation, and Arrhythmia Detection Algorithm.
- FIR filters chosen over IIR filters due to their inherent stability and ease in implementing in the digital signal processor.
- Heart Rate Calculation uses the R peaks gathered from the QRS Complex detector and calculates the heart rate based on the number that occur in a 6 second interval.

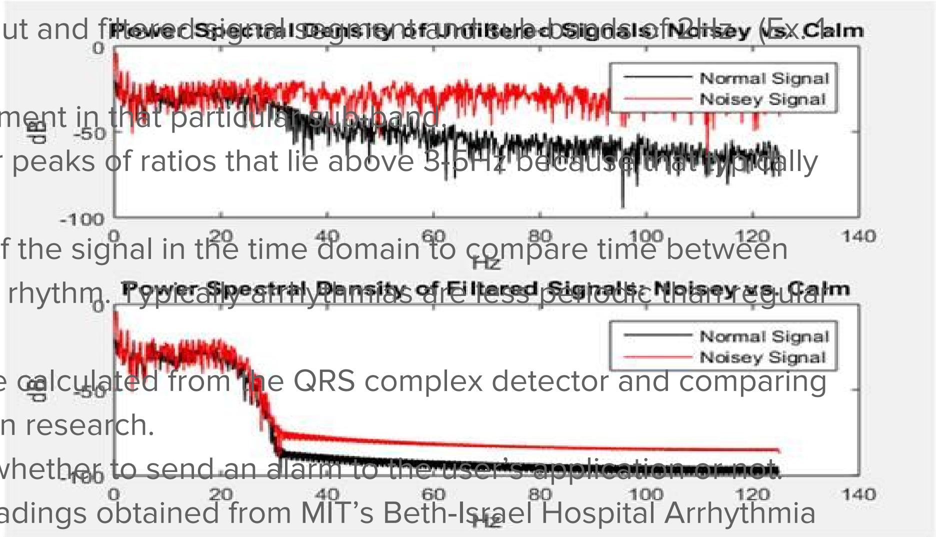
QRS Complex Detection Algorithm

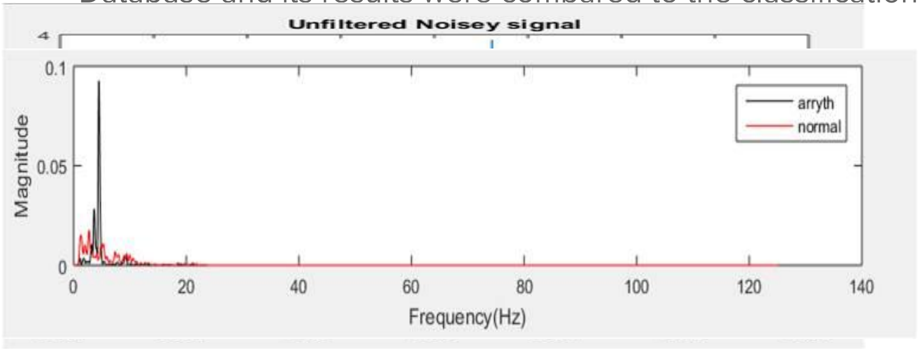
- Based on Pan & Tompkins Algorithm
- Pre-Processing:
  - Digital Bandpass Filtering BW: 5-24Hz
  - Signal Differentiated
  - Absolute Value of Signal
  - Moving Average of Signal over 80ms Window.
- Algorithm:
  - Find peaks of Pre-Processed Signal
  - Compare peak timing relative to past or future peaks. If successive peak occurs in less than 196ms ignore that peak. Otherwise classify as R peak.
  - Now refer back to raw signal and determine if it is a peak in the raw signal or a baseline shift instead.
  - If classified as a peak in the raw signal then compare to the calculated QRS peak threshold, Classify as QRS peak for values greater than the threshold.
  - Classify a peak as a QRS complex if no other QRS has been classified within 1.5 R-to-R intervals, but a peak greater than half the detection threshold followed the previous QRS detection by at least 360ms.
  - Otherwise classify as noise.

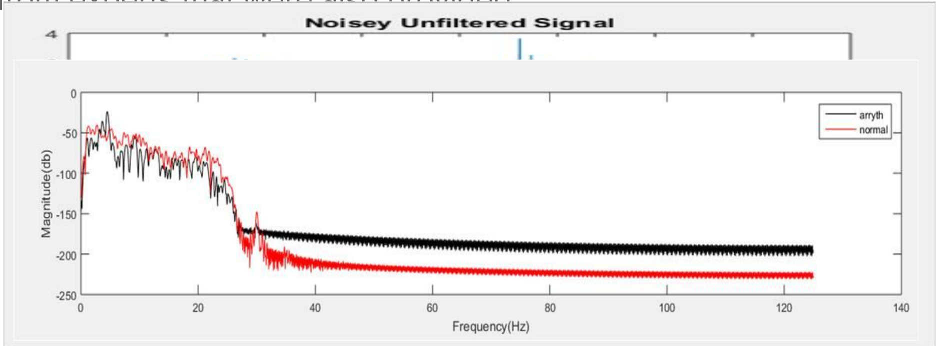
Arrhythmia Detection Algorithm

- Compute the Power Spectral Density of the entire filtered input and filtered signal segment and sub-bands of 2Hz. (Ex 1-3Hz, 2-4Hz, 3-5Hz...18-20Hz)
- Compute the ratio of PSD in sub-bands versus the entire segment in that particular sub-band
- After ratios have been computed the algorithm then looks for peaks of ratios that lie above 3-5Hz because that typically results in an Arrhythmia.
- Additionally, part of the algorithm analyzes the morphology of the signal in the time domain to compare time between successive peaks in time domain versus known regular heart rhythm. Typically arrhythmias are less periodic than regular sinus rhythm.
- Last weighted metric for detection is based on the Heart Rate calculated from the QRS complex detector and comparing with characteristic heart rates of different arrhythmia based on research.
- All these metrics are weighted and the result will determine whether to send an alarm to the user's application or not.
- Initial testing for algorithm was done on Matlab using ECG readings obtained from MIT's Beth-Israel Hospital Arrhythmia Database and its results were compared to the classification from experts that were also provided.

- Based on Algorithm prototyped in Matlab. Now implementing on actual DSP.
- Signal will be processed in 5 second segments and return an alarm if an Arrhythmia is detected for this time frame.
- Filter Raw Signal with High Order Lowpass FIR filter with -3db point of .5Hz and Highpass FIR Filter with -3 db point at 25Hz.
  - This is because most of the information that distinguishes normal heart rhythm from an Arrhythmia is contained in this bandwidth.
  - Further cleans the signal to remove any noise.



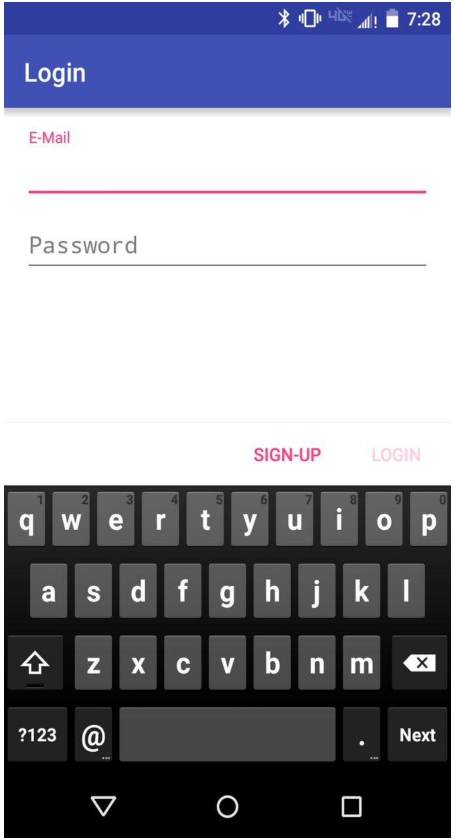


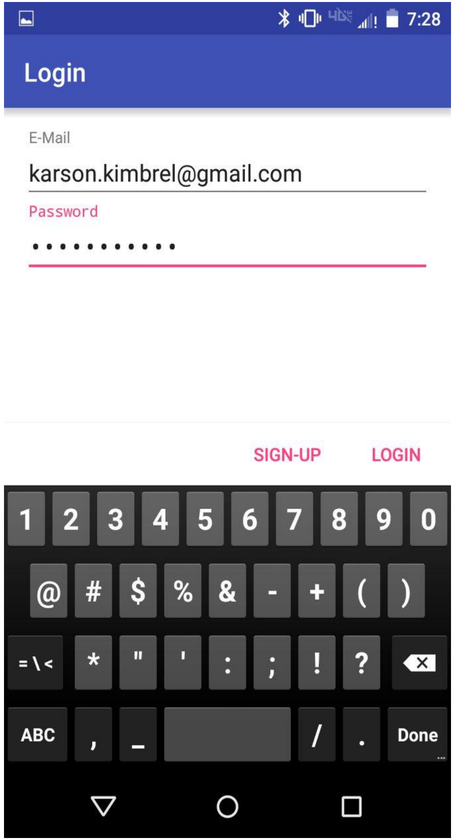


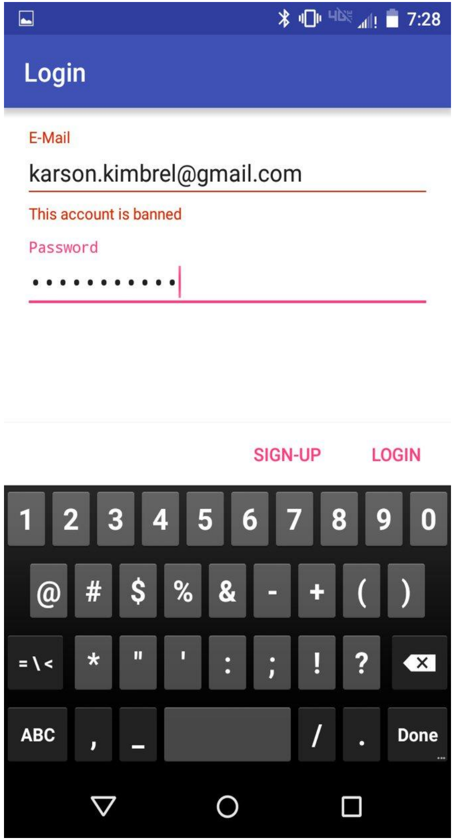
Android Application

- The app facilitates the ability to view and record local live WWECG Sessions and the ability to review previously recorded WWECG Sessions
- Supports Android 5.0+
  - Chosen because of Android's improved support of BLE
- Google's Material Design Guidelines
- WWECG Sessions are not stored on the Android device for very long (once they are uploaded or no longer needed, they are deleted)
  - Risk of WWECG Sessions leaking from the app is severely reduced
- The app was designed for both the general public and doctors
  - Doctors can create new randomly generated patient ids to record sessions with
  - This is done so that the system does not need to be HIPPA compliant

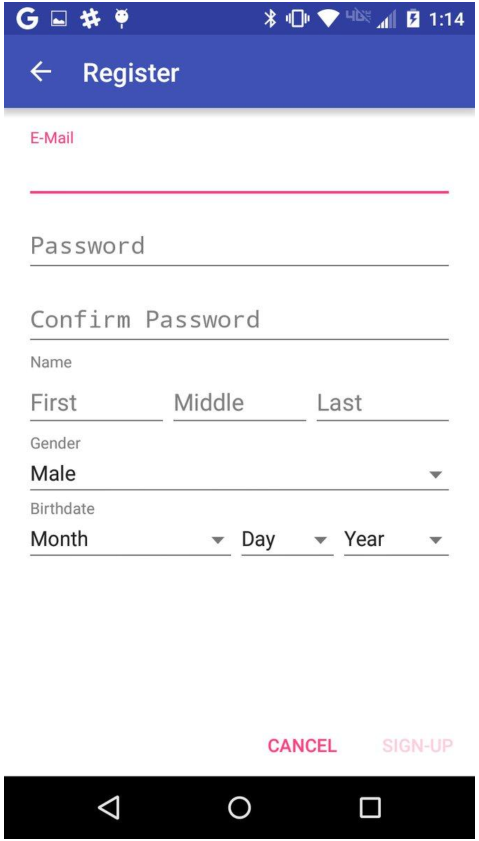
Screenshots - Login Screen

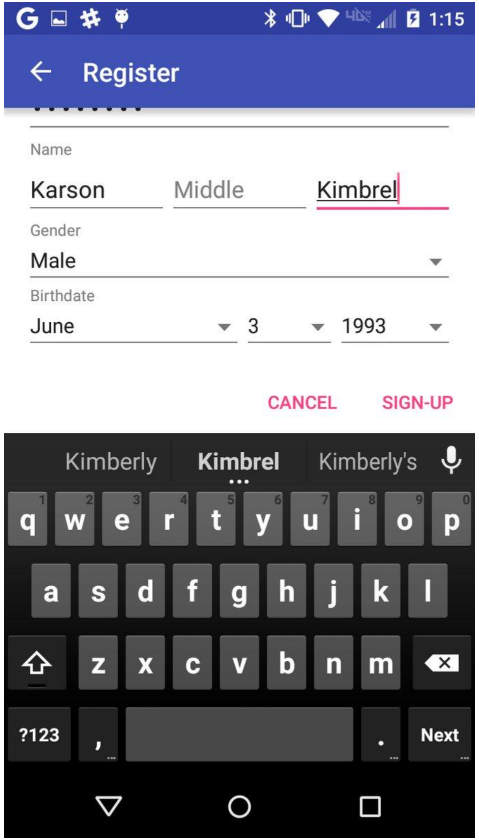


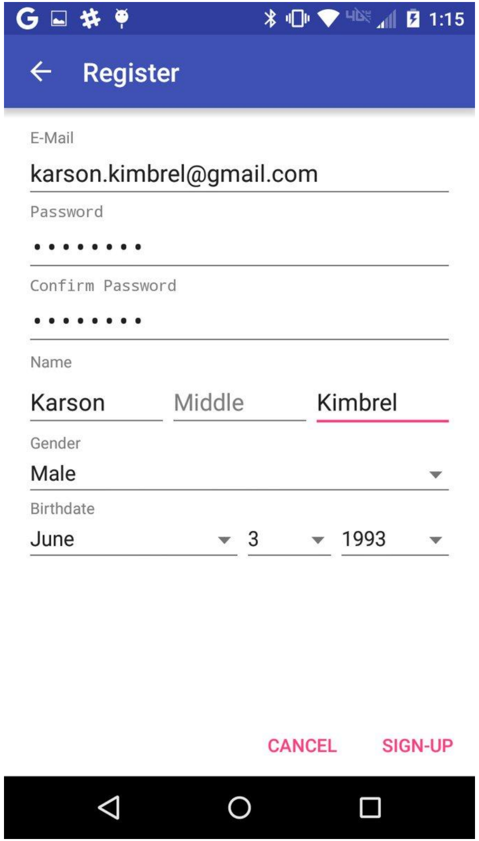




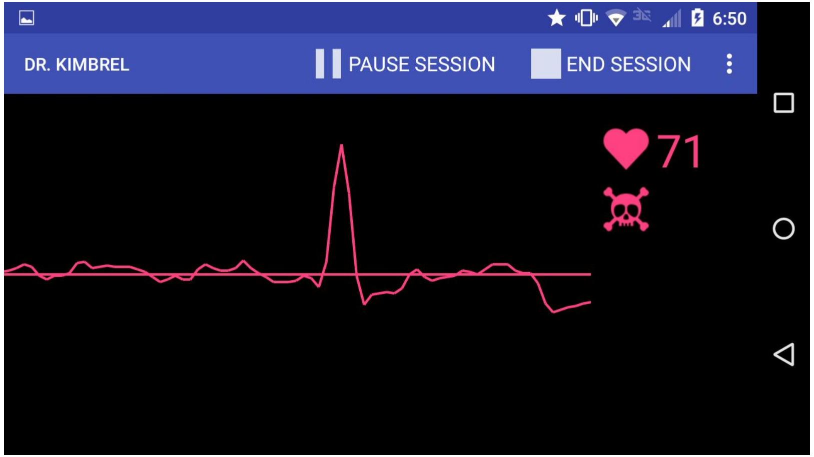
Screenshots - Register Screen



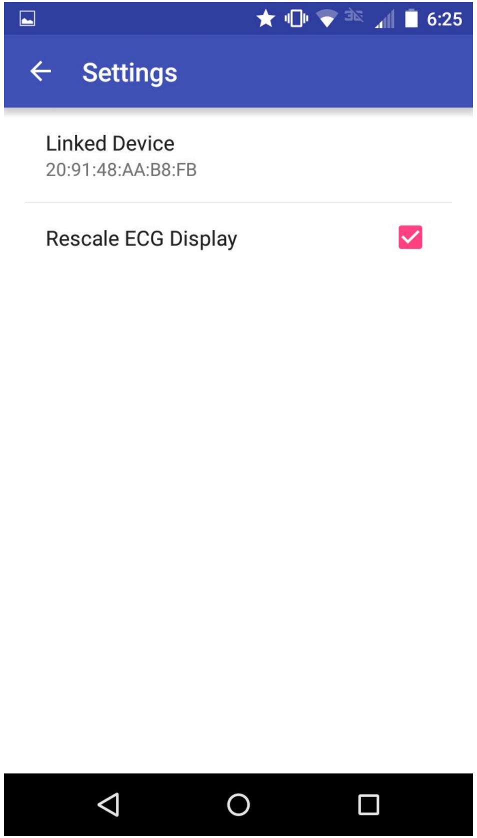




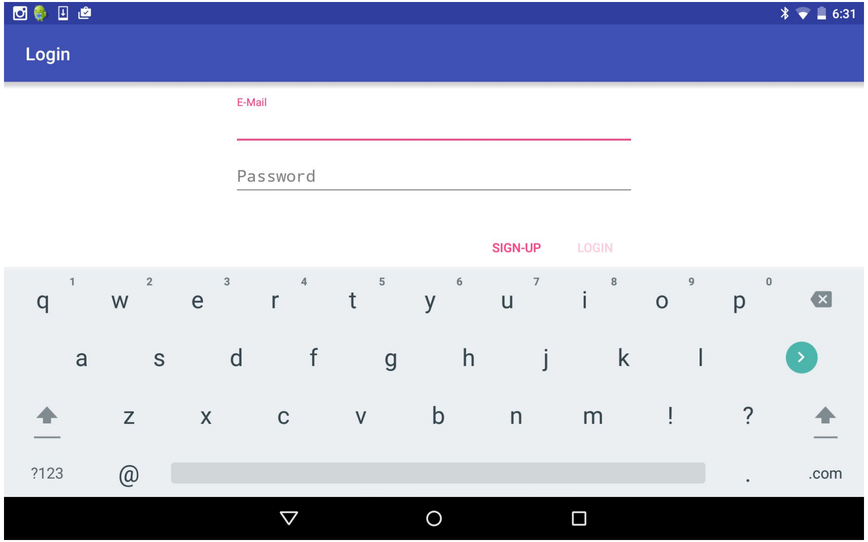
Screenshots - Main Screen

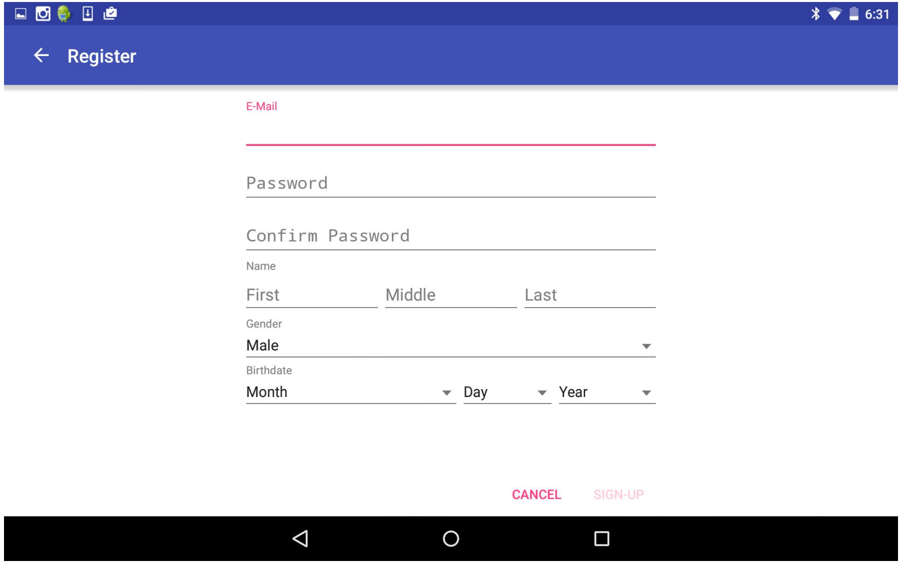


Screenshots - Settings Screens

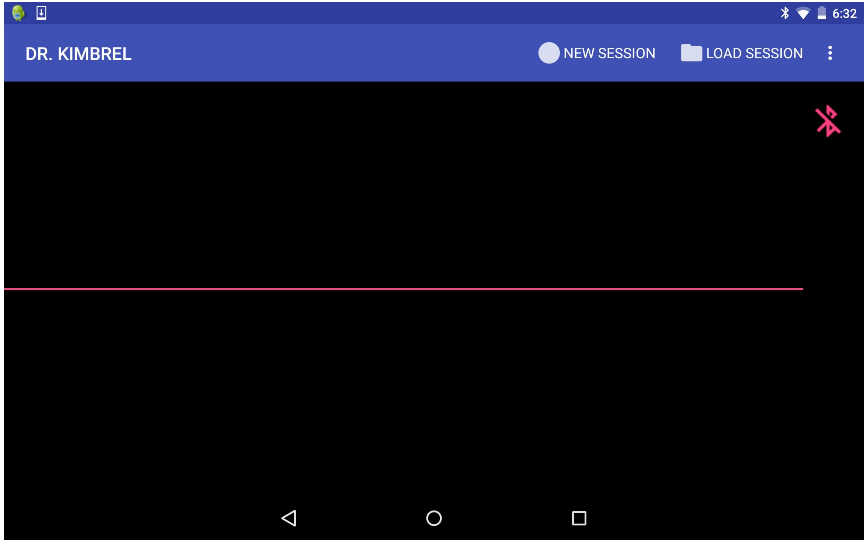


Screenshots - Tablet Login and Registration Screens





Screenshots - Tablet Main Screen



Server and Database Overview

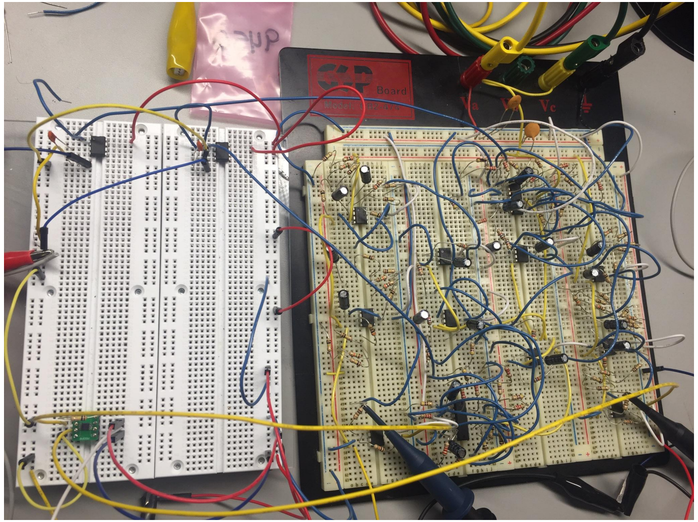
- LAMP stack on a Google Cloud Compute Engine instance
  - Linux, Apache, MySQL, and PHP
- Some endpoints or features of endpoints are only useable by doctor accounts

Endpoint	**Description**
/data/privacy	Provides the WWECG Service Privacy Policy
/data/tos	Provides the WWECG Service Terms of Service
/ecg/file	Provides a specified file
/ecg/files	Lists files for a specified user
/ecg/newpatient	Creates a new patient account
/ecg/patients	Lists the patients for a doctor
/ecg/upload	Uploads a new WWECG Session
/user/whoami	Identifies the user who is currently authenticated

Server and Database Security

- OAuth2 authentication schema
  - Supports grants for client credentials, user password, and refresh tokens
  - Utilizes an implicit global permission scope
  - Supports the addition of third or second party apps
- All WWECG sessions are encrypted with AES-256
- Passwords are run through PBKDF2
  - A password safe Key Derivation Function
  - If the database is leaked, the original passwords cannot be easily determined

Testing Progress



Breadboard prototype of sensor AFE

Signal outputted from purely analog hardware

Tested prototype of sensor's Analog Front End by connecting sensors directly to Instrumentation Amp. to confirm proper signal acquisition and conditioning prior to analog to digital conversion and wireless transmission to hub.

Example ECG Wave


DR. KIMBREL
PAUSE SESSION
END SESSION
124

Costs

Item	Cost
Electrodes	$54.00
DSP Dev Board	$106.00
HM-11 Bluetooth Module	$61.55
ECG-PRO-3-WAY-CABLE	$37.50
Power Board	$7.75
AFE Boards	$45.50
JST connector	$3.80
SPDT switch	$7.60
Mini-USB port	$2.46
Current meter	$6.00
SMT Polarized Caps	$3.32
MSP432 Dev Board	$20.00
Connector DSP PCB	$17.05
ADC breakout board	$2.20
Hub PCB	$25.15
Jumpers	$22.00
Right angle pin header	$11.40
Power Hub PCB	$16.00
MCP4725 Breakouts	$27.00
Arduino Mega	$21.00
Total	$497.28

Questions?