ECG SHIRT

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Team 14

Abstract

The primary purpose of this project is to provide heart patients with a way to monitor their health while going about regular daily activities.

Finding a way to detect heart attacks faster and more effectively would significantly reduce the number of cardiovascular problems and deaths that occur each year. This project focuses on making a portable, wearable ECG (Electrocardiogram) that can detect heart irregularities.

The result of the project is a 3-lead ECG that has been integrated into a t-shirt for convenience. It is completely portable and takes ECG readings in real time, it then communicates the results to our mobile application via Bluetooth where the signal is displayed. Our machine learning model analyzes the signal and checks for signs of heart disease. The user app then updates with the machine learning model output thus displaying the user’s current health status.

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1. Introduction

Cardiovascular disease is currently the leading cause of death in the world, with myocardial infarctions being one of the most common types of this disease. Myocardial infarctions are often treatable when diagnosed quickly; however, symptoms of a myocardial infarction are not always detectable and thus, treatment may be delayed. Around 17.9 million people around the world die from heart attacks each year and over 1/3 of those who experience a heart attack do not experience the most common warning signs.[1] The first test done to diagnose any past or present myocardial infarctions is an Electrocardiogram, or ECG. The ECG can often detect a heart attack earlier than blood tests for heart damage, which can take 4+ hours to indicate damage to the heart. The increased accessibility of ECGs to the public can increase the detection of heart attacks and decrease the fatality of these events.[2]

We have designed a low-cost portable ECG that contains 3 leads (4 electrodes) in the ECG and transmits data to a mobile app which warns the user of an abnormal cardiovascular behavior that might result in a myocardial infarction. This portable ECG can be worn at any time and is developed in such a way that it can be attached to t-shirts. The high-level design of the project can be seen in Figure 1. The device is used by placing four electrodes on the user's body (1 above the heart, 1 across from it, 1 on left under the rib cage, and 1 on right under the rib cage).[3] The readings from the electrodes are processed by our PCB which includes the microcontroller and transmitted to a mobile device through Bluetooth. The mobile application informs the user whether their heartbeat readings are normal, or they are at risk of a heart attack, after the heartbeat readings have been analyzed by our machine learning model. The goal for this ECG device is to make heart monitoring more easily accessible to public and integrate its use in everyday activities.

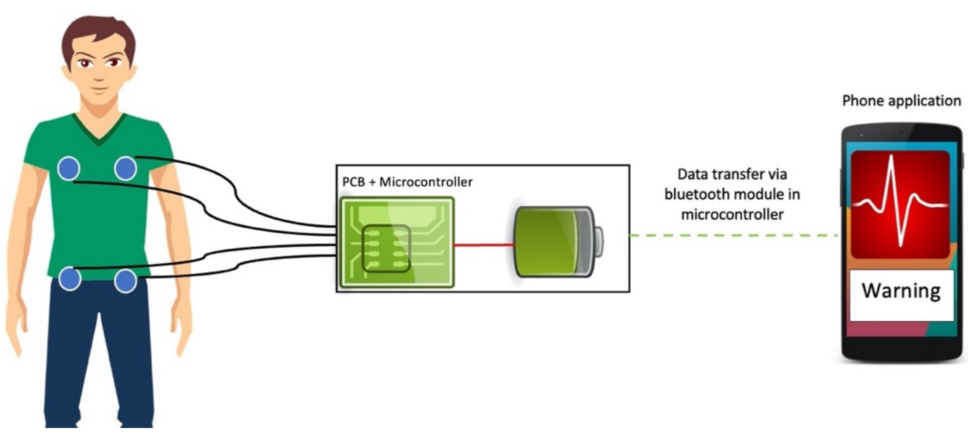

Figure 1. High level physical design of the ECG device

This ECG is divided into three main subsystems:

The **power subsystem** is the system that supplies power for our data subsystem, which is our on-board circuit. It is composed of a 3.7 V lithium-ion battery that is being charged by a Micro-Lipo charger which gets its power supply through a MicroUSB jack. We pass the voltage from the battery through a voltage regulator, to create a stable power supply of 3.3 V for powering the two heart rate monitors. The microcontroller is powered directly through the battery. The battery lasts for at least 72 hours continuously for when the ECG is powered on, making the portability of the ECG efficient.

The **data subsystem** acts as our electrode reading acquisition subsystem. It is composed of 3 leads, 4 electrodes which will read heartbeat rhythms from the user's right arm, left arm, right leg, and left leg. These heartbeat rhythms are passed through two analog heart rate monitor frontends. Initially, the outputs of the heart rate monitors were supposed to be passed through a 16-bit ADC for further signal clarification, however, the testing was done through microcontroller's in-built 12-bit ADC which gave comparable results and due to time constraints, we were unable to incorporate the ADC in our final PCB design. Therefore, in our final design, the outputs of the heart rate monitors are passed to our microcontroller directly which wirelessly transmits the data to a mobile device utilizing the Bluetooth module in the microcontroller and the Bluetooth module in the mobile phone.

Lastly, the **application subsystem** is composed of the phone's Bluetooth module, the machine learning model, and the frontend application. It displays the ECG signals coming in via Bluetooth from the data subsystem through a graphical visualizer application. The machine learning model in the application subsystem takes in pre-recorded ECG signal dataset, it further filters the signals and through its training, identifies the PQRST points in the heartbeats. The model then passes the heartbeat through PQRST wave checks designed by us and a check for ST elevation, through which it determines whether the heartbeat is a healthy heartbeat or indicates a risk of heart attack. The result of the analysis of the ML model is displayed as "Normal" or "Warning" on the frontend application we designed.

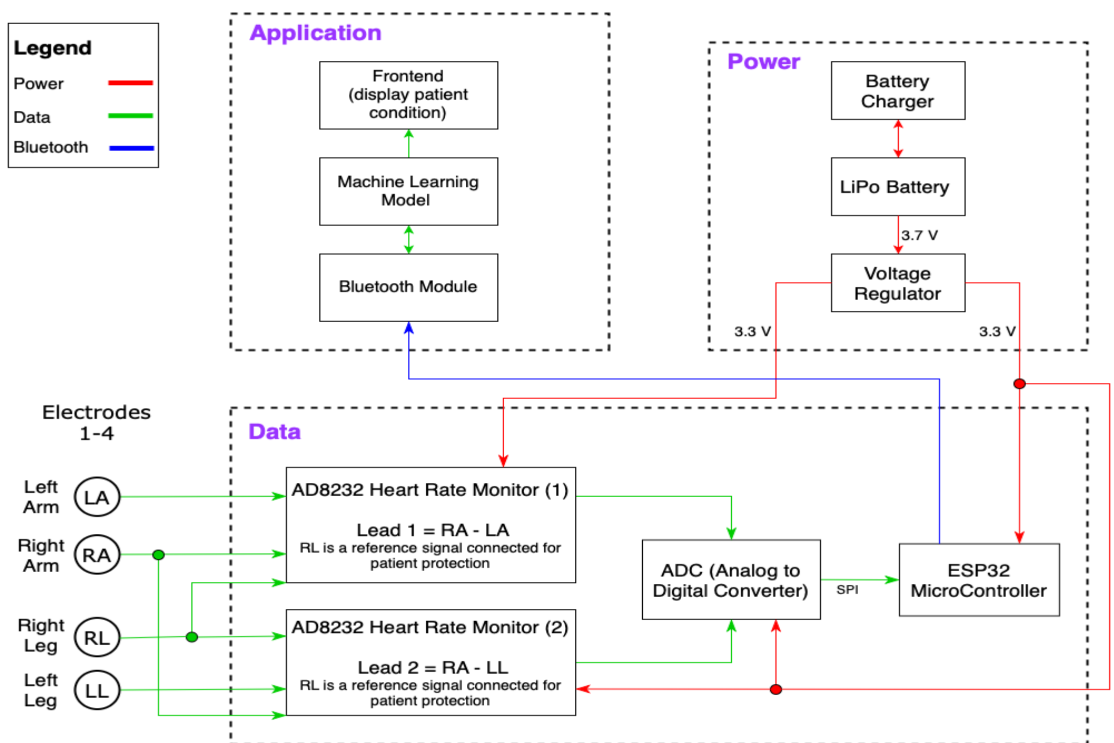

Figure 2. Block Diagram of the ECG device

2. Design Procedures and Details

2.1 Power Subsystem

One of the main requirements for our ECG shirt was that it was completely portable. We had to keep this goal in mind when designing the power system and so we decided that we would make the ECG battery operated. We considered a variety of rechargeable batteries and eventually decided on a Lithium-Ion battery because it's lightweight, compact, and has a high energy density. We chose a Lithium-Ion Battery with 3.7 V and 2000 mAh which would meet the demand of the parts chosen for the data subsystem which required a supply of 3.3 V ± 50 mV and at least 1400 mAh. It was also decided that the battery voltage will first go through a voltage regulator and then through the voltage regulator the power will be supplied to the two heart rate monitors in the data subsystem to stabilize the voltage coming in from the battery and keep it within the acceptable range for the parts in the data subsystem. We incorporated a low voltage dropout regulator in our design that had an input voltage range of 3 V to 40 V, and a fixed output range of 3.3 V or 5 V depending on the input voltage with a good accuracy range of ±0.85%, which perfectly met our needs for supplying the parts with a 3.3V power supply.

To complete the power system, we selected a battery charger that can be charged through a micro-USB port to make our project more user friendly and increase the product life. We chose the charger keeping in mind its small size which could lead to an easy integration into our portable design and the fact that it was ready to use with our chosen LiIon battery which came built in with a JST wire.

The power subsystem is important to our design since our data acquisition process through the ECG leads is dependent upon constant and correct power supply to the circuit. For this reason, we had to choose our parts carefully and approximate how much current would be drawn by each component on our PCB.

Table 1 Approximate current drawn by each component in the Data subsystem

Component	Power Bus	Approximate Current (mA)
Microcontroller	Battery	~50
Heart Rate Monitor (1)	Voltage Regulator	~230
Heart Rate Monitor (2)	Voltage Regulator	~230

2.2 Data Subsystem

2.2.1 Microcontroller

Picking the microcontroller was arguably the most difficult part of our component selection. The main requirement we had was that the microcontroller had the ability to communicate via Bluetooth. We initially chose to use the ESP-32-WROOM which supports both mobile Bluetooth and BLE (Bluetooth low energy). However, during the design review we were told that using Bluetooth on the WROOM could be challenging. We did some research and managed to find another microcontroller called the ESP-

32-C3. This microcontroller did not support mobile Bluetooth, but it did support BLE. We went ahead and selected the ESP-32-C3 microcontroller, and we created our PCB according to this microcontroller.

When we were in the lab doing breadboard testing, we ran into several issues with this microcontroller. For one, when testing we realized that this microcontroller only had one channel that could be used to display the heart rate monitor signal. When we were trying to connect two heart rate monitors the code would fail to upload to our microcontroller, this is because one channel was picking up no signal. Another issue was that this microcontroller supported BLE but not mobile Bluetooth. Our phone was able to connect to the microcontroller and receive values, but it couldn't display the ECG signal graph on the phone due to BLE restrictions. The connection to BLE was also weak and it would often lose connection from the phone easily. At this point, we were stuck and decided that using this microcontroller would not work out for our project.

We then decided to attempt using the ESP-32-WROOM 32 because it had mobile Bluetooth module and supported speeds up to 1590 Kbps. After looking at the datasheet we realized that it had enough channels to display the signal from both heart rate monitors. We tried doing this and it managed to connect to both monitors successfully. We then worked through the week and managed to get Bluetooth working as well. This Bluetooth module had much better speed and was working at a speed greater than 1000 Kbps. At this point, our project hardware was fully working on the breadboard and so we placed another PCB order with the new microcontroller specifications.[4]

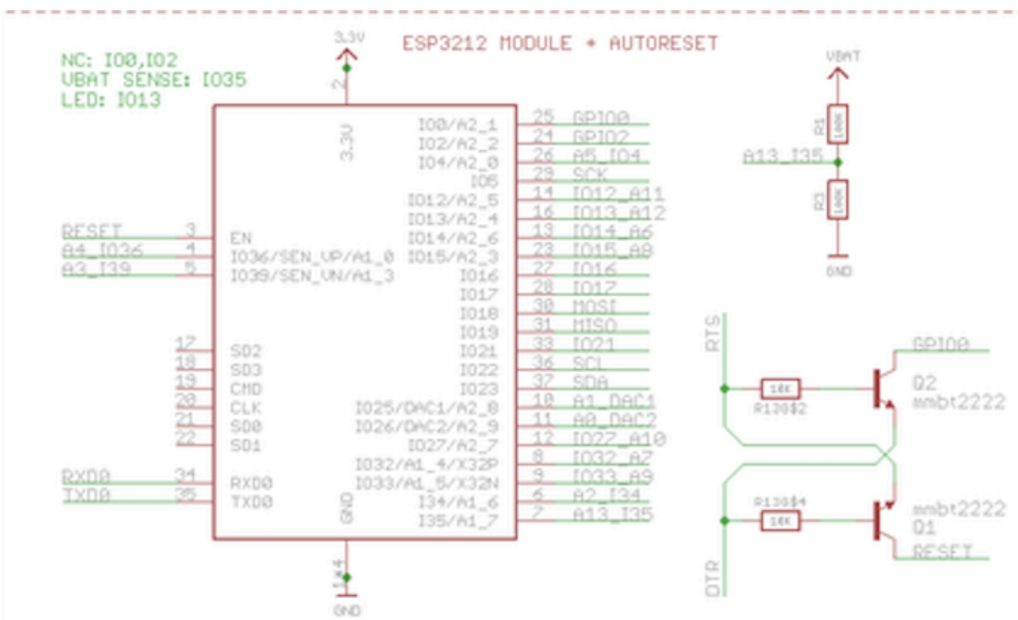

Figure 3. Schematic of the microcontroller ESP32-Wroom-32

2.2.2 Heart Rate Monitor

For our device, we needed a system to filter the signals being picked up from the user by the 4 electrodes placed on their body. We chose the SparkFun Single Lead Heart Rate Monitor -

AD8232 for the initial processing of the analogue signal being picked up from the textile electrodes. We chose the heart rate monitor since the AD8232 chip is composed of op-amps which allowed us to amplify the analog signals and implement a high pass and a low pass filter through a single chip granting us a band pass filter functionality to achieve our desired cutoff frequencies of 0.5 Hz and 40 Hz. The chip is also commonly used for small biopotential signal in presence of noisy conditions, which is exactly what our textile electrodes were picking up as the heartbeats were the small biopotential signals and their noisy conditions were caused by respiration and other physical bodily movements. We also decided to choose 2 heart rate monitors for our design, since each monitor is used for 1 lead. The first heart rate monitor outputs Lead I (Right Arm, Left Arm, Right Leg) and the second heart rate monitor outputs Lead II (Right Arm, Left Leg, Right Leg). This was done to achieve the 3-lead functionality of our project, since at least two leads needed to be physically picked up from the user's body through electrodes to be able to calculate the third lead in software by just subtracting Lead 1 from Lead 2. Lastly, the heart rate monitor had efficient communication with the microcontroller as well,

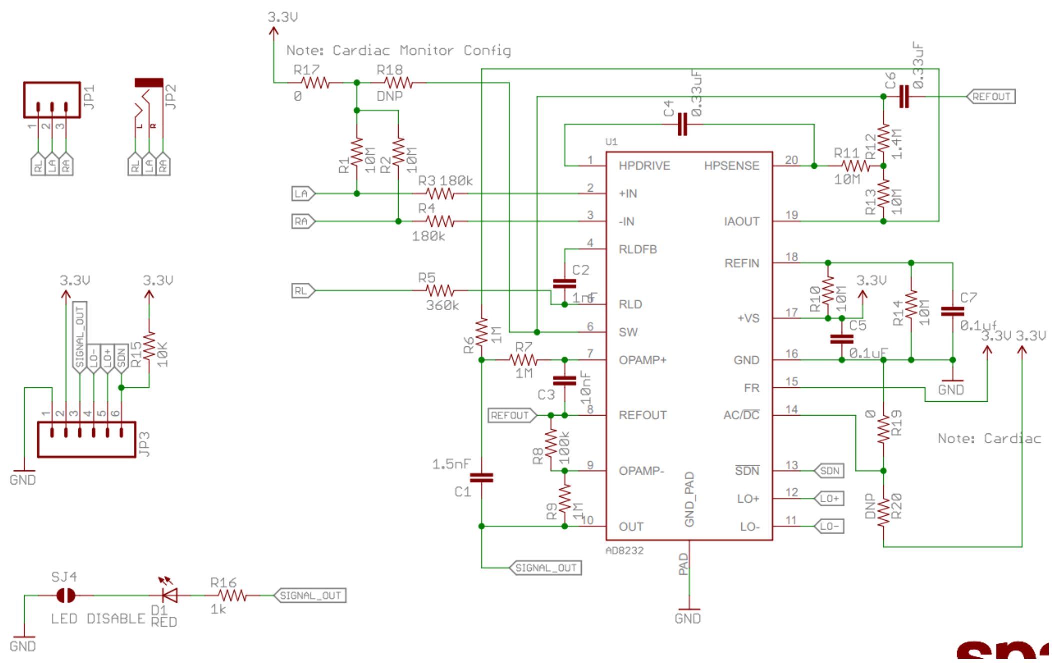

Figure 4. Schematic of the heart rate monitor AD8232

because of its analogue signal output and the microcontroller's in-built ADC and enough I/O channels to process outputs from both the heart rate monitors.

2.3 Application Subsystem

The software component of our project makes up the bulk of the application subsystem. The application subsystem primarily consists of our machine learning model and a frontend phone application. The machine learning model was a major part of our project because it set our project apart from other portable ECG's available in the market. We use our software component to make up for the fact that we built a 3-lead ECG rather than a 12-lead ECG. We built a machine learning model that analyzes an ECG signal over 10 seconds and performs different calculations on the PQRST segments of each wave. You can see what this wave looks like in Figure 5 below, these segments are critical in identifying a myocardial infraction. Dr. Erickson provided us with the appropriate datasets of patients with myocardial infraction to train our model on. By looking at the lengths and intervals of different parts of the ECG wave and by analyzing the ST depression/elevation we aimed to make up for the fact that our ECG is not 12-leads.

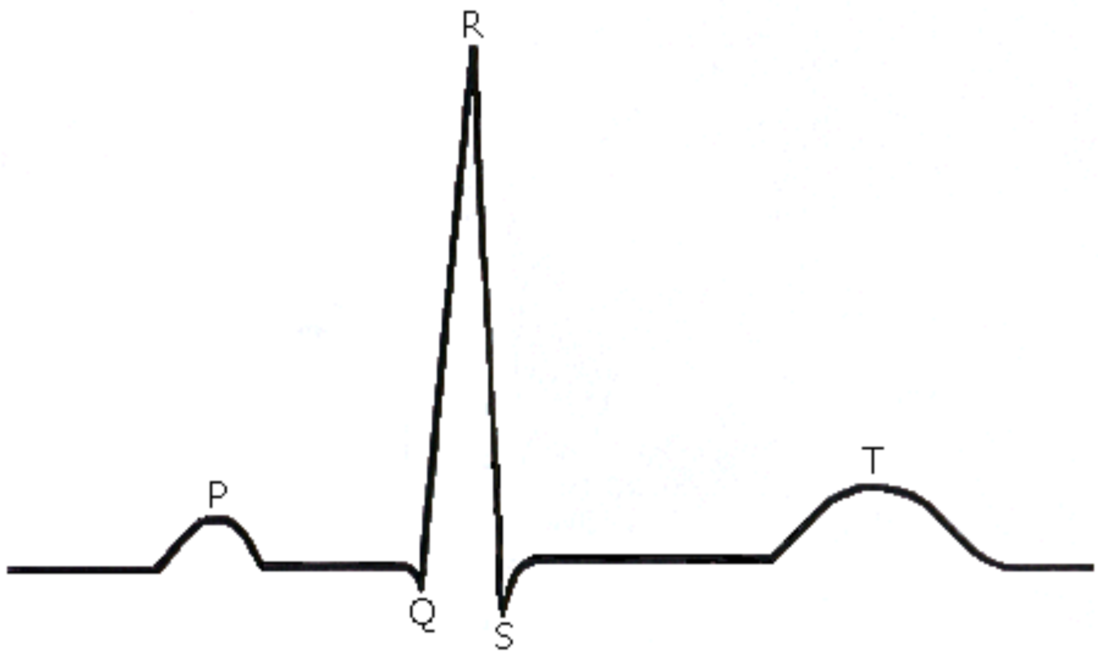

Figure 5. A heartbeat wave example with PQRST points of the heartbeat labeled

Ideally, a heart attack is identified by an ST depression/elevation which is visible by looking at all 12 leads from an ECG reading.[5] This is because depending on what area of the heart the heart attack occurred in it will get detected by one or more leads. This poses a problem for our device; we are using 3 leads that look at the readings from the frontal view of the heart. This means that if the heart attack were to occur at the back of the heart our ECG would not identify an ST depression/elevation. To defeat this problem our machine learning model is trained to not only search for an ST depression/elevation, but also look at the other parts of the ECG wave and ensure they are within normal range. Table 2 below shows a summary of all the calculations our machine learning model performs on the ECG signal.[6]

Table 2 PQRST wave acceptable ranges and ST elevation/depression acceptable ranges for a healthy heartbeat [6]

ECG	Description	Range for healthy person
QRS Complex	Indicates the atrial systole, atrial diastole, and ventricular excitation respectively	0.08-0.12 sec
P-R interval	Indicates the electrical signal generated by the sinus node is normal and travelling in a normal fashion in the heart.	0.12-0.22 sec
Q-T interval	Indicates the flow of electrical impulse and blood from the atrial chambers to ventricles	0.35-0.43 sec
P-wave	Indicates the rate of atrial excitation	< 0.12 sec
ST elevation	Indicates heart attack	−1.0 to 1.0 mm

By looking at these are other segments and intervals, our machine learning model has a higher chance of detecting a potential heart attack. If someone is experiencing a heart attack and there is an ST elevation/depression that cannot be seen by our ECG, the machine learning model will be able to find other factors that look abnormal in the leads that we have readings for.

Shown in Figure 6 is the patient evaluation on patient #308.[7] As we can see, the patient is experiencing "q wave and ST segment elevation in v2" and "ST segments are depressed in i". It's important to note the "v2" and "i" correspond to lead numbers. Our device measures lead I, II, III.

308	640.0	79.0	0	162.0	64.0	5.0	1.0	AT-6 C 5.5	1986-09-13 10:20:48	sinus rhythm. borderline left axis deviation. q wave and st segment elevation in v2, cannot rule out anteroseptal myocardial damage. st segments are depressed in i, avl, v5,6. t waves are low or flat in these leads. this may be due to lv strain or ischaem

Figure 6. Annotated patient record of a patient experiencing a myocardial infarction

Steps taken by the machine learning model:

1) First, we plot the ECG signal over 10 seconds.

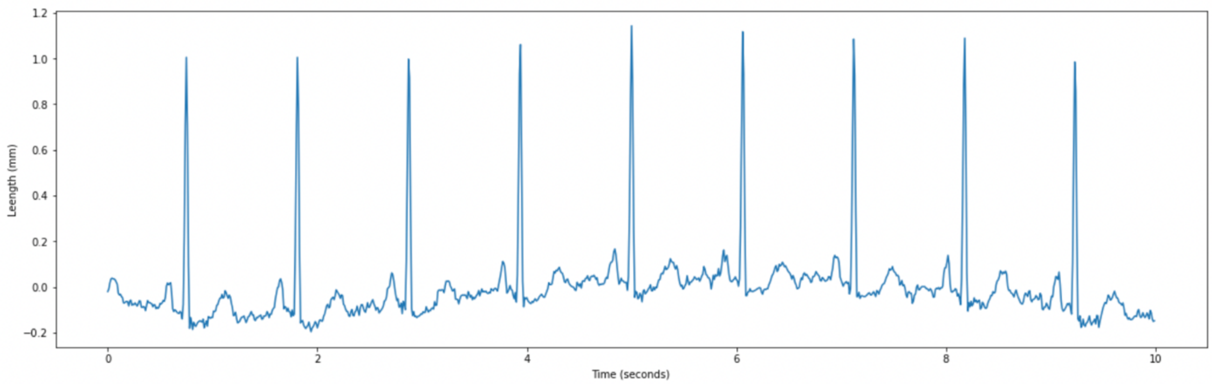

Figure 7. ECG signal of patient recorded over 10 seconds

2) After amplification and filtration, we take an average of these points over 10 seconds and plot a single wave. Then we identify the P, Q, R, S, T points between the maximum-minimum points. This looks at the beginning of the wave, peak, and end of each significant point.

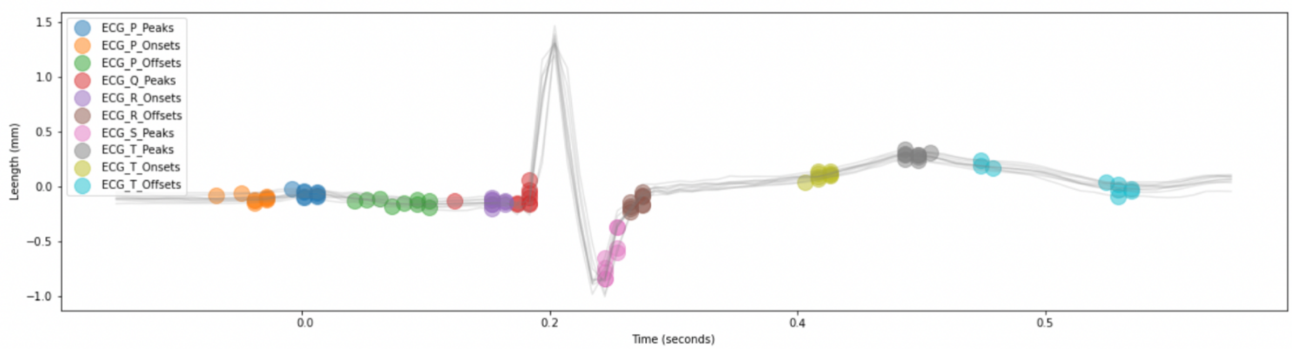

Figure 8. Average single heartbeat wave of patient with identified PQRST points

3) Finally, we use these point markers to perform the calculations described in Figure 9. We check to see if these boundaries are within normal ranges. Here is the output of our ML model for patient 308:

```
PR wave evaluation:  0.19 True
QRS wave evaluation:  0.11 True
QT wave evaluation:  0.46 False
P wave evaluation:  0.12 True
PQRST feedback: Needs further assesment
ST Elevation evaluation:  1.0025555555555554
ST feedback: elevation/depression present
Patient Evaluation: WARNING!
```

Figure 9. Example analysis result of a patient experiencing myocardial infarction

Note: True corresponds to “within normal range” and False corresponds to “out of normal range”
Here we can see that although many checks pass within normal range our ML model detects the “QT

wave evaluation” as being abnormally high and the slight ST elevation is present as well. This is consistent with the patient evaluation from above which described “q wave and ST segment elevation”.[8]

2.4 Physical Design

The main goal to keep in mind for the project’s physical design was that the project must be portable and user friendly. Portability was achieved firstly by making our power subsystem battery operated. The inclusion of a battery charger in there also ensured longevity of the project. Secondly, we wanted the project designed in such a way that it could be integrated into a t-shirt. One of the challenges that came with that was the restriction on the size of the PCB. We wanted the PCB to be as compact as possible, so that it can be stitched onto a t-shirt but would still ensure user comfort. Keeping this in mind, we developed our PCB of size 124.71 mm x 50.55 mm. This was one of the more compact sizes we could come up with, restricted by the sizes of our other components.

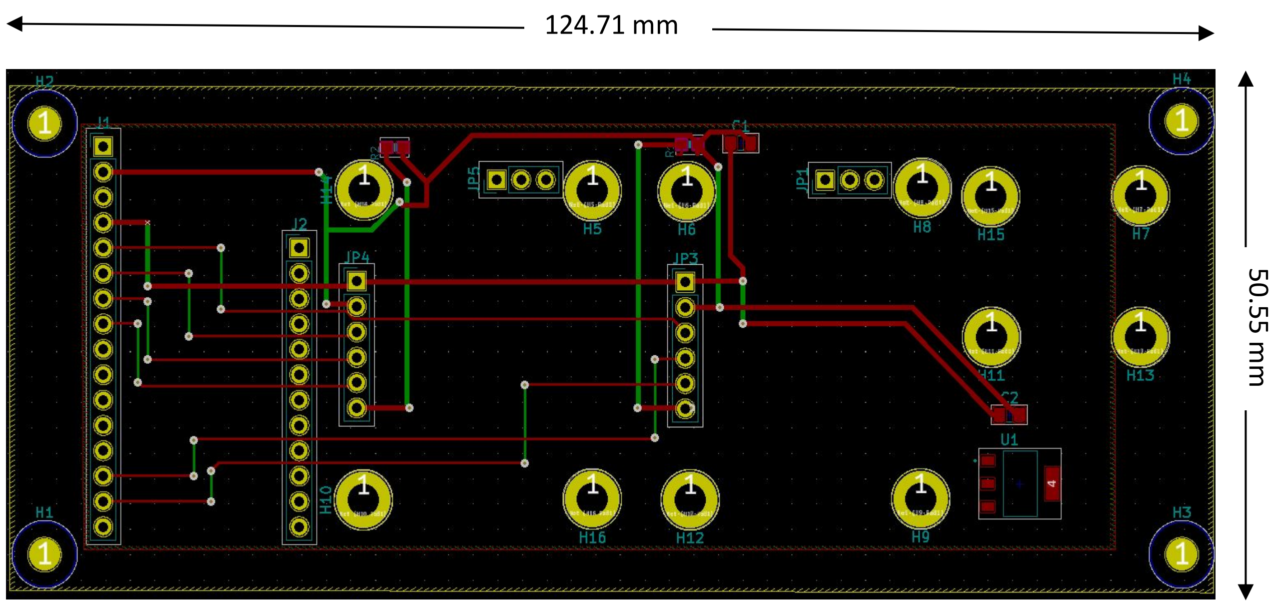

Figure 10. PCB board design with dimensions

We also chose textile electrodes as the electrodes we would use to pick up the heartbeat signals from the user, although we were unable to stitch them onto the t-shirt, they are compatible with textile and thus have the capability of being integrated into a t-shirt. For the PCB itself, we decided to attach the PCB on the sleeve of our t-shirt, keeping in mind where it would be most comfortable for the user to wear it. To enclose our PCB, we chose a stretchy-soft material, a wool and polyester mix, which would easily enclose the whole PCB and would not scratch on user’s skin. We attached the battery on the backside of the PCB to keep the size compact. We then provided three outlets in our cloth enclosure; two of them were for the wires from the electrodes to the heart rate monitor, and one of them was a safety outlet to deal with any problems on board with the circuit or the battery. The outlets were made facing inward towards the shoulder patch of the t-shirt so that none of the wires are dangled outside the t-shirt and the user can have easy access to them. The T-shirt design can be seen in Appendix B.

3. Design Verification

3.1 Power Subsystem

We described many verifications for our power subsystem to ensure safety and consistency in our project. The verifications included checking that the right amount of power was being constantly supplied to each component and that the battery life was sufficient for our portable ECG. The power system was fully functional for our final demonstration, and it passed all requirements highlighted in Appendix A.

We checked the battery life by leaving our system plugged in and powered on. The battery lasted around 74 hours which is what we had in mind for the project.

The most important verification was to make sure we were able to supply our entire system with a constant supply of 3.3 V ± 50 mV. We did this using our 3.7 V battery and a 3.3 V voltage regulator. We checked the voltage across our components with the voltage probe and verified the values across our microcontroller and heart rate monitors. The power being supplied was 3.28 V ± 50 mV.

3.2 Data Subsystem

3.2.1 Signal Filtering

One of the main requirements of our data subsystem was to get a clear ECG signal from the user. To achieve this, we chose the two heart rate monitor frontends to extract, amplify, and filter the small biopotential signals and output amplified, noise reduced analog signals. The analogue signals taken from these heart rate monitors were passed into our microcontroller which had an in-built ADC that gave us a 12-bit clear signal. In addition to all of this, we implemented a bandpass filter when coding our microcontroller to achieve one of our high-level requirements which mentioned that we wanted the signals to be filtered with the cutoff frequencies of 0.5 Hz and 40 Hz. This band pass filter was applied on the signals being outputted by the microcontroller's ADC, and it was applied on the signals before they were transferred to the mobile application via Bluetooth. The filtration process had a very significant impact on the ECG signals being recorded.

Initially, without the filter, we had an extremely noise signal, with the signals exceeding amplitude limits. It was impossible to figure out a heartbeat reading from these signals as seen in Figure 11.

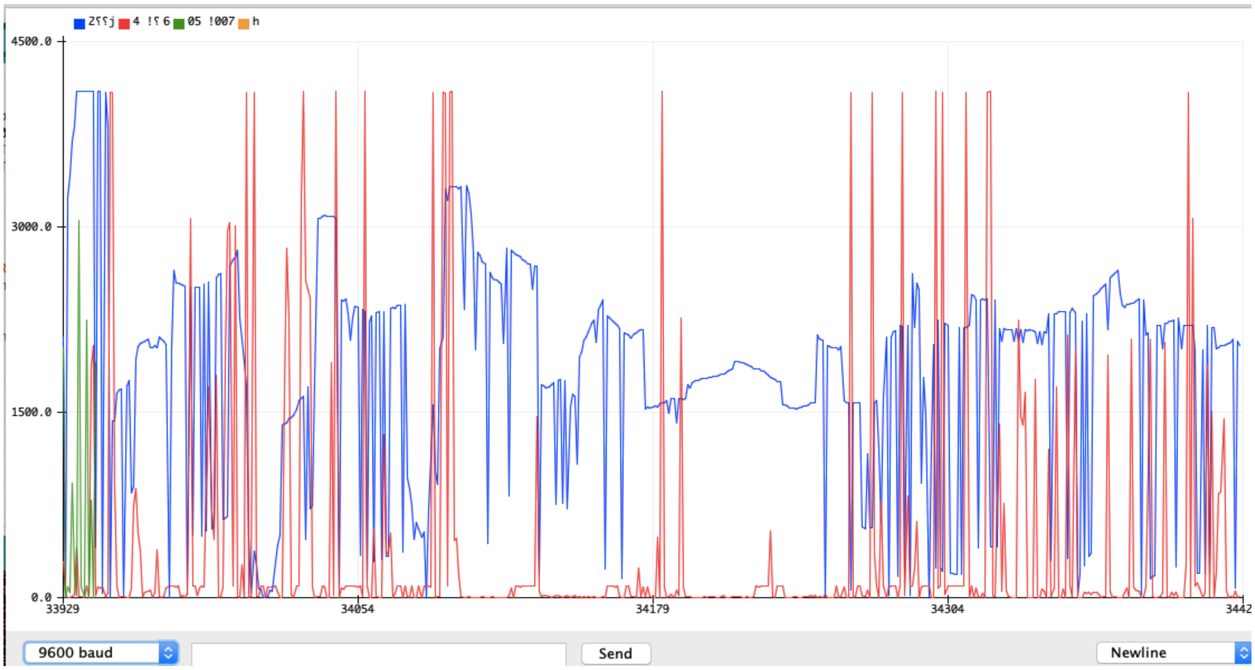

Figure 11. Noisy ECG signal before filtration

With time as the X-axis and signal amplitude in mm as the Y-axis, the signals had heartbeat rhythms in them, however, they were almost undisguisable from the noise and could not be used for any kind of monitoring or analysis. After the implementation of the filter, the ECG signals from the user cleared up significantly as seen in Figure 12. The PQRST points of these signals were clearly visible, and this signal quality could be used for heartbeat analysis by our ML model also.

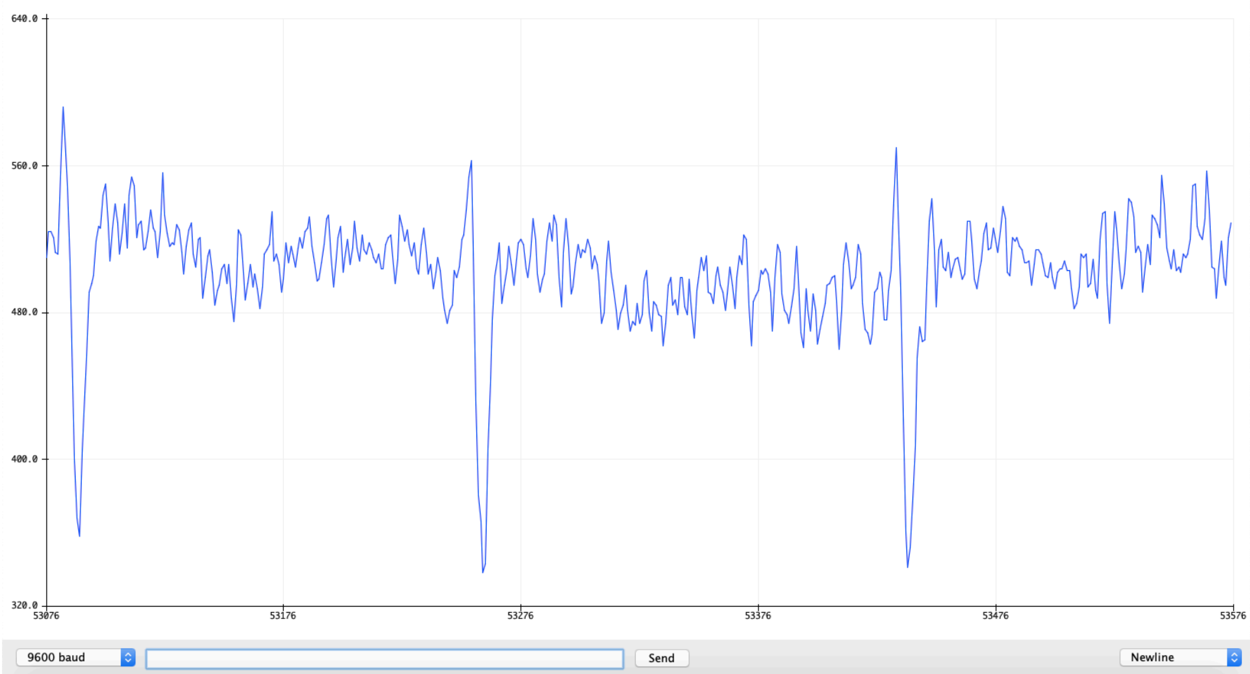

Figure 12. Clear ECG signal after filtration

3.2.2 Bluetooth Module

The ECG's portability was dependent on wireless communication as well, making our Bluetooth interface an important aspect of our project. One of our high-level requirements was that the microcontroller can transmit the ECG signals being picked up by the user to our mobile application using its own Bluetooth module and the mobile's Bluetooth module at a speed of 1000 Kbps. This requirement was achieved by coding the microcontroller's Bluetooth module to be able look for devices to pair in the vicinity, connect to a Bluetooth device, and enable sending data over to the connected device. We performed testing for our Bluetooth module by verifying that the data is being sent over to the phone by keeping a track of the serial monitor of Arduino IDE as seen Figure 13.

We sent over pre-decided data to our mobile application after connecting to the microcontroller's Bluetooth and matched if the data being sent over to the mobile application was the same as the data we were generating to get sent over. The matches were successful and timestamp feature in Arduino serial plotter helped us determine that the speed of transmission was greater than 1000 Kbps.

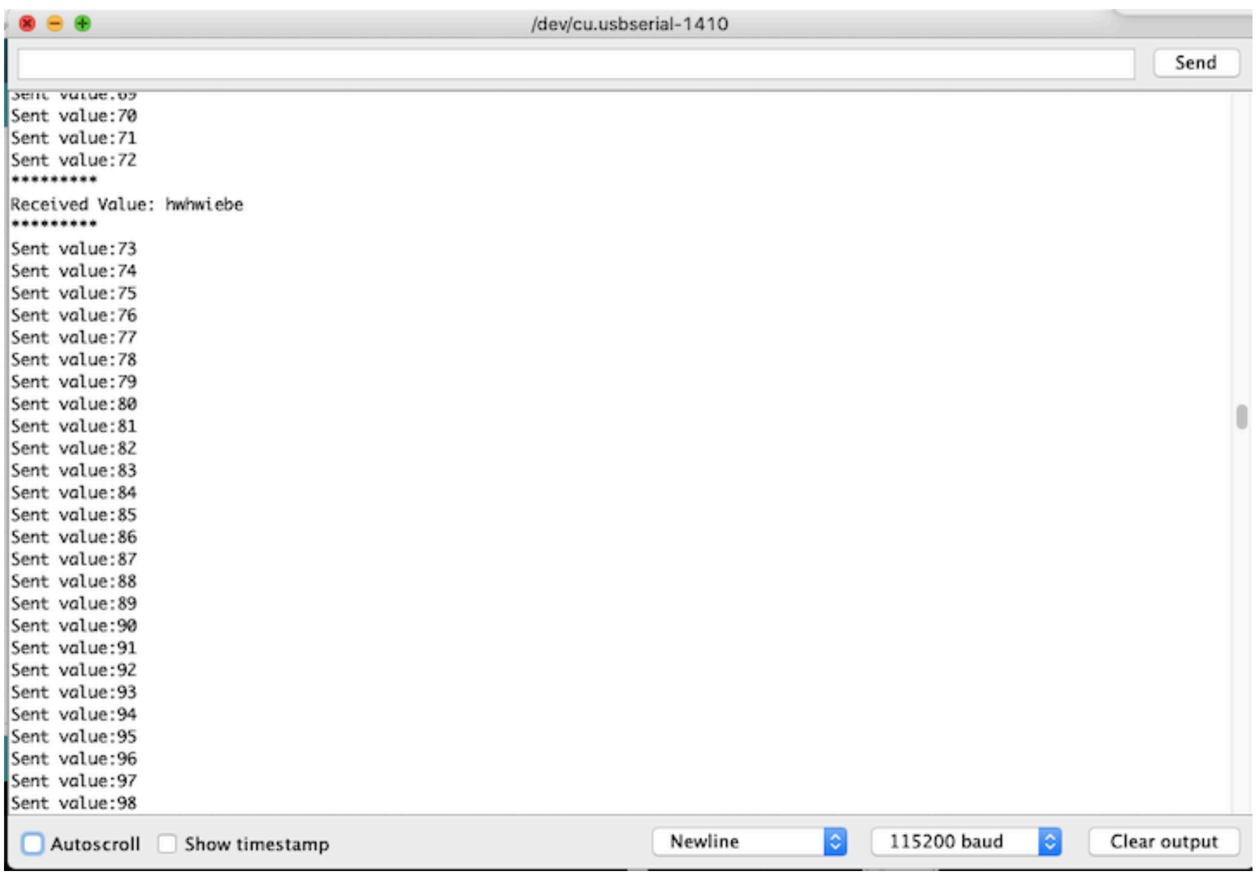

Figure 13. Serial monitor displaying the pre-determined data being sent over by the microcontroller to the mobile application via Bluetooth

3.3 Application Subsystem

The verification table shown in Appendix A highlights which requirements were fulfilled. The first requirement was that our machine learning model would run in under 180 seconds. The figure below is a screenshot of the runtime analysis when we run the full model.

```
PR wave evaluation:  0.19 True
QRS wave evaluation:  0.11 True
QT wave evaluation:  0.46 False
P wave evaluation:  0.12 True
PQRST feedback: Needs further assesment
ST Elevation evaluation:  1.0025555555555554
ST feedback: elevation/depression present
Patient Evaluation: WARNING!
CPU times: user 2.13 ms, sys: 550 µs, total: 2.68 ms
Wall time: 2.24 ms
```

Figure 14. Example analysis by the ML model of a patient with runtime

As shown above, the total CPU time is 2.68 ms and the Wall time is 2.24 ms. The ML model runs very fast and exceeded the expectations in terms of speed (much less than 180 seconds).

Additionally, the ML model was able to successfully analyze all datasets provided to us by Dr. Erickson. This was verified by cross-checking the output of our model with the actual patient evaluations provided to us. Although the time crunch didn't allow us to automate the frontend-backend connection fully, our frontend was able to update almost immediately with the output from the Jupyter notebook. By measuring the time and seeing it was instantaneous, we verified that this happens in under 30 seconds. Our frontend runs the Jupyter notebook, takes the final output of the patient and then displays it on the frontend as shown below in Figure 15.

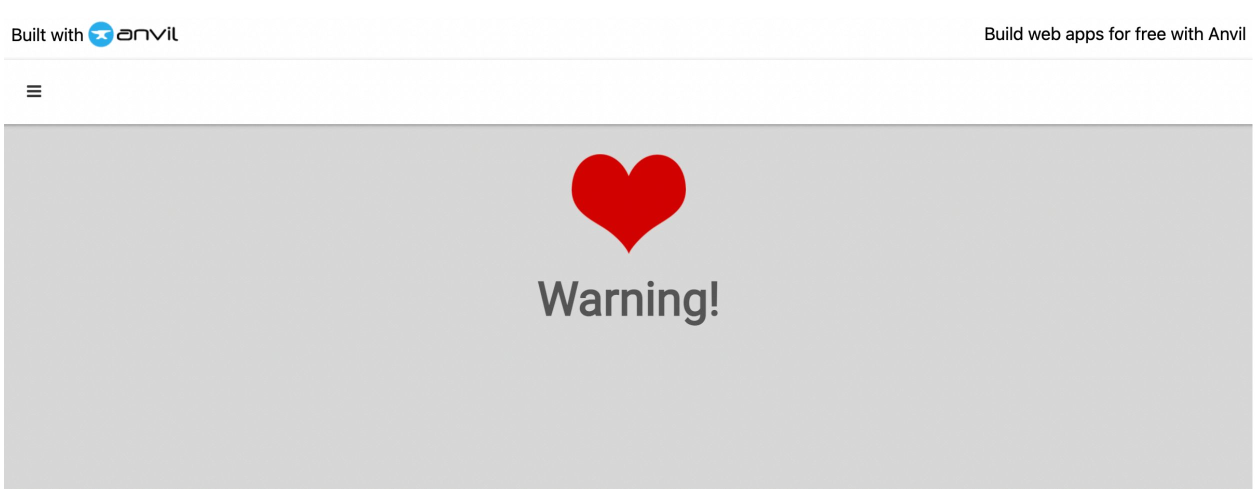

Figure 15. Frontend application displaying ML model result

4. Costs and Schedule

4.1 Parts

The costs of this project were very carefully considered. We wanted to make this project as cost effective as possible, keeping in mind a future goal of this project which is to make it an easily accessible product for the pubic.

Table 3 Parts used for the project and their costs

Part	Manufacturer	Qty	Retail Cost ($)	Bulk Cost ($)	Actual Cost ($)
Lithium-Ion Battery - 3.7v	AdaFruit	1	12.50	11.25	12.50
ESP32 Development Board	AdaFruit	1	20.95	16.76	20.95
SparkFun Heart Rate Monitor - AD8232	SparkFun	2	19.95	16.96	39.90
Micro-Lipo Charger with MicroUSB Jack	AdaFruit	1	6.95	5.56	6.95
Voltage Regulator - LT1117IST	Mouser	1	6.49	3.85	6.49
Female Headers	Harwin	10	1.15	0.524	9.26
Male Headers	TE Connectivity	10	0.42	0.168	3.52
PCB	PCB Way	1	30.14	25.18	30.14
ECG Snap Electrodes (bag of 50)	3M	1	18.51	18.51	18.51
Total Cost					**148.22**

4.2 Labor

The average hourly wage for a Computer Engineer is $57.48/hr. Based on the hourly wage, the time dedicated to this project, and the overhead costs, the total labor cost for this project is $86,220.

Cost per hour = $57.48 (average hourly pay for a software engineer)
Hours per week = 8 hours
Total Weeks = 10 weeks

Cost per person = 57.48 ($/hour) * 2.5 * 8 (hours/week) * 10 (weeks) = $11,496
For all team members (3 people) = $34,488
Total cost (including the overhead cost) = $34,488 * 2.5 = $86,220

4.3 Schedule

Table 4. Schedule for the semester

Week	Pakhi	Pooja	Ruthvik
10/4	Design Review	Design Review	PCB Design/Ordering Parts
10/11	Solder PCB	Solder PCB	Solder PCB
10/18	Test data subsystem	Test data subsystem	Machine learning model development/
10/25	Test data subsystem	Test data subsystem	Machine learning model development
11/01	Test data subsystem, Design frontend for mobile application and test ML model	Test data subsystem, Design frontend for mobile application and test ML model	Test data subsystem, Design frontend for mobile application and test ML model
11/08	Test application subsystem and data subsystem communication over Bluetooth	Test application subsystem and data subsystem communication over Bluetooth	Test application subsystem and data subsystem communication over Bluetooth
11/15	Design new PCB and order new parts	Design new PCB and order new parts	Design new PCB and order new parts
11/22	**Final system testing for final demo**		
11/29	Final presentation	Final presentation	Final presentation
12/06	Final paper	Final paper	Final paper

5. Conclusion

Over the course of the semester, we faced multiple challenges which forced us to adapt and overcome. From designing PCBs to cleansing raw sensor data for an ML algorithm, there were many tasks that we were inexperienced in and had to find ways through. Our project was a success and almost everything that had been outlined as a goal for the project was met. At the end of the semester, we had our portable 3 Lead ECG with an ML model and frontend application. Most weekly goals were met until the last month; at which point the path we took ended with us not automating the data formatting process which would have allowed our ML model to analyze the user's heartbeat signals in real time. We also put analytical writing and documenting scientific work in the lab into practice. The course of the project overall not only honed our technical skills but also made us more experienced in teamwork, adaptability, and time management.

5.1 Accomplishments

Our ECG system uses 4 electrodes to generate two leads and uses both the leads to generate a third lead in the software. This 3 Lead ECG system is integrated into a T-Shirt and comes with a rechargeable and easily replaceable battery. It is a portable system and ensures user comfort. Bluetooth transmission is used to communicate the heartbeat signal data to a mobile application. Our trained ML model takes less than 180 seconds to give a warning to the user whether they are at risk of a heart attack or not. We have a frontend application that takes the output of the ML model and displays it in a user-friendly format. Lastly, the project is cost effective and has great potential for future technical and entrepreneurial developments.

5.2 Ethical considerations

This is a prototype and cannot be marketed in any form in the United States of America until it receives appropriate FDA approval.

The shirt is not waterproof but can withstand an external splash as long as armband components (PCB & Heart Rate monitors) are dry. We need to make sure that the user is aware to keep the shirt dry when PCB and wiring is in the shirt.

The ECG Shirt is not strong enough to shock the user as a minimum of 50 V is required to cause any damage to a human body for shock; however, our right leg driver circuit and the component voltages keep the voltage flowing around in the circuit at a maximum of 3.3 V..

There may be minor discomfort like taking a bandage off when removing the electrodes which can rip off body hair under the electrode, however we have tried to minimize this discomfort with the use of textile electrodes.[9]

5.3 Future work

We met most of our goals in terms of prototype design and execution. If time would have permitted, we would have ensured that the data being collected from the ECG Shirt was stored in the right format for the ML model to perform a real time analysis on the heartbeat read on the shirt. However, we were unable to execute this implementation in time. Given more time, this is the first thing to address. In the current state, the data must be manually fed into the ML model for analysis.

To improve the quality of the heartbeat analysis and the precision of the heartbeat measured, we could use data channels with higher precision. Further, more data can be collected by adding more leads. Different leads capture the pulse from different points on the body, essentially recording different views of the heart. With more leads, our ML model can be used to better detect heart attacks as we would be observing more pulse readings of the organ. Therefore, a 12-lead expansion of this project would be a future goal for us.

Noise reduction has been addressed in multiple components in the hardware and software. To add to this, further design choices must be made in terms of PCB design and disturbance caused by shirt movement. While compression vests solve this problem, we want our shirt to be comfortable.

There could be substantial improvements made to shirt design. Wires can be embedded in the shirt instead of being taped to the inside and the PCB can be sealed in a Velcro compartment on the armband instead of being sewn into place on the sleeve. It is essential that these design choices are made keeping in mind that the life cycle of the shirt is limited by the number of washes and the equipment must be sealed in a safe and sustainable method while retaining comfort. On top of this, textile electrodes can be implemented to add to comfort.

The system could be adapted to different use cases by changing the ML model being used. It could be used in emergency situations in remote situations or by athletes to track performance. While there is a tremendous potential for entrepreneurial ventures, the product would have to be built to required standards for necessary approvals such as FDA approval in the USA.

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Appendix A Requirement and Verification Table

Table 5 Requirements and Verifications

Power Subsystem		
Requirements	Verification	Verified?
The battery charger will charge up the LiPo to 3.70V±50mV when supplied with an input voltage of 3.75-6V.	a) Discharge and recharge the battery using an input voltage of 6V without limiting current. b) Once the battery is fully charged check that it is between 4.2-4.5V.	Yes
Rechargeable battery with a battery capacity of at least 72 hours.	a) Discharge the battery completely to 2.75V±50mV and then charge it completely to 4.2-4.5V±50mV. Check that the battery voltage is 3.7V±50mV. b) Charge the battery completely to 4.2-4.5V±50mV. Let the battery discharge for 72 hours and check to make sure the voltage remains at 4.2-4.5V±50mV.	Yes
Provides 3.3V±50mV from a 3.7-4.5V±50mV source.	a) Measure the output voltage using an oscilloscope and ensure that it is within 50mV of 3.3V.	Yes

Data Subsystem		
The input signals are filtered with the cutoff frequency of 0.5 Hz and 40 Hz.	Check the output signal and check to see if it is clearer (we can tell it is clearer by noticing the PQRST points): 1) Connect the heart rate monitor to an Arduino, pick up ECG signal by placing electrodes on one of the team members. 2) Use Arduino Serial Plotter to display the ECG Signal 3) Check the passband levels by checking the point where output to input ratio is 0.707 and ensure that those align with our cutoff frequencies.	Yes
Microcontroller receives data over SPI at a frequency of at least 100 Hz.	a) Send a sample ECG signal (of known size) from the ADC to the microcontroller. b) The microcontroller supports fast SPI connections with an external SD card. We will use the SPI flash lines of the microcontroller to store the sample ECG signal on the external SD Card. c) Plug the SD card into a computer and verify that all the sample data was received by the microcontroller. d) Use the timestamps of the data arrival to check the frequency of data transmission. Ensure it is at least 100 Hz.	No, didn't implement external ADC

Microcontroller can transmit data through Bluetooth at a speed of at least 100 Mbps.	a) Send a sample ECG signal data of known size through Bluetooth b) Once the data arrives on the mobile application check the timestamp of arrival to ensure the speed is at least 100 Mbps.	Yes
	Application Subsystem	
Machine learning model analysis time is within 180 seconds.	a) Run the machine learning algorithm on a 3-lead sample set. b) Each lead should capture data for at least 10 seconds. c) Measure to check that the algorithm analysis is below 180 seconds.	Yes
Data is received by the phone's Bluetooth module via the microcontroller's Bluetooth module at a rate of at least 100 Hz.	Send a sample set of data via Bluetooth and measure the rate at which it's received by the phone.	Yes
Frontend interface updates with the output of the machine learning model in at most 30 seconds.	Send randomized output to the frontend server and ensure it updates in at least 30 seconds.	Yes

Appendix B Physical Design: T-Shirt Integration

Figure 16. T-Shirt with PCB front view

Figure 17. T-shirt with sewn on PCB on the sleeve and the outlets for the electrode wires; inside view