ECE445

Fall 2025

Senior Design Lab

Final Report

Insight: Cardiovascular Screening Device

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December 10, 2025

Abstract

We built a low-cost at-home cardiovascular screening device that collects ECG, PPG, and motion data to check for three common conditions: atrial fibrillation, hypertension, and sinus bradycardia. Our system uses an ESP32 to sample all sensors, send the data to a PC, and keep the signals aligned for analysis. On the software side, a Python pipeline extracts features like heart rate, RR, and pulse transit time to run simple rule-based checks and display the results in real time. During testing, we were able to capture clean ECG and PPG signals with noise under 1 mV, maintain sensor synchronization within a few milliseconds, and keep the overall processing delay well under one second. Across repeated trials, the device produced consistent classification results and met the accuracy goals we set at the start of the project. This shows that basic cardiovascular screening can be done at home using inexpensive hardware.

Contents

1. Introduction

Cardiovascular diseases are some of the most common and preventable health issues, yet early screening typically requires clinical equipment, trained personnel, and in-person appointments. This creates a gap for individuals who could benefit from quick, accessible checks for conditions such as arrhythmias, hypertension, and sinus bradycardia. Our project addresses this engineering challenge by developing a low-cost, at-home screening device that measures ECG, PPG, and motion signals via accelerometer, processes them in real time, and identifies basic risk patterns using simple rule-based diagnostics.

The system is built around a custom data acquisition board with an ESP32-C3 microcontroller, dedicated ECG and PPG front ends, and a 3-axis accelerometer. The board collects synchronized physiological signals and streams them to a PC, where our Python-based software pipeline performs filtering, feature extraction, and classification. The goal is not to replace medical diagnostics, but to give users an immediate, easy-to-interpret indication of whether their measurements show abnormal patterns worth discussing with a clinician.

The remainder of this report describes the design and evaluation of the system. Section 2 details the hardware and software architecture, including the PCB, sensors, microcontroller interfaces, and the processing pipeline. Section 3 presents the verification procedures used to validate power stability, sensor performance, communication reliability, and diagnostic consistency. Section 4 summarizes the parts, labor, and project schedule. Section 5 concludes with our main results, namely that the system consistently captured clean physiological signals, maintained synchronization, and produced stable classification outcomes, and discusses remaining uncertainties, ethical considerations, and future improvements.

1.1 Product Images

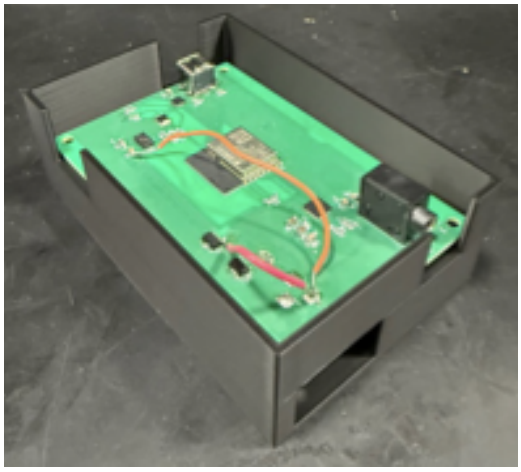

Figure 1.1.1: Final Project Image

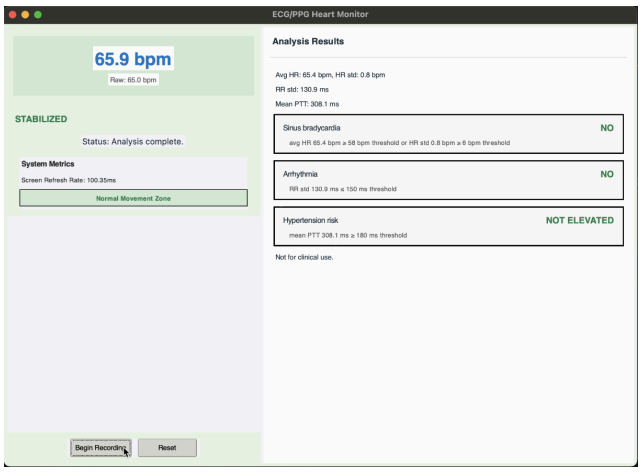

Figure 1.1.2: Final Project Web Interface

2. Design

The overall system is composed of two major functional components: a Data Acquisition System (DAC) implemented on a custom PCB with embedded firmware, and a Disease Detection System running in software. Together, these systems collect physiological signals, preprocess them, extract biomedical features, classify potential cardiovascular abnormalities, and present diagnostic results to the user.

2.1 System Overview

The Data Acquisition System collects ECG, PPG, and accelerometer data using sensors mounted on a custom PCB. An ESP32-C3 microcontroller samples the sensors, applies basic preprocessing, timestamps the data, and sends the combined data stream to a host computer through USB. The PCB includes power regulation for the 3.3 V and 1.8 V rails required by the sensors and the analog front end, as well as a communication interface through a USBC port.

The Disease Detection System runs on a PC and receives the incoming sensor data. It processes the data using a defined software pipeline that performs cleaning, synchronization, normalization, and feature extraction. The extracted features are used by three diagnostic detectors: arrhythmia, hypertension, and sinus bradycardia. The system outputs the diagnostic results through a local API, which are displayed on a web-based dashboard.

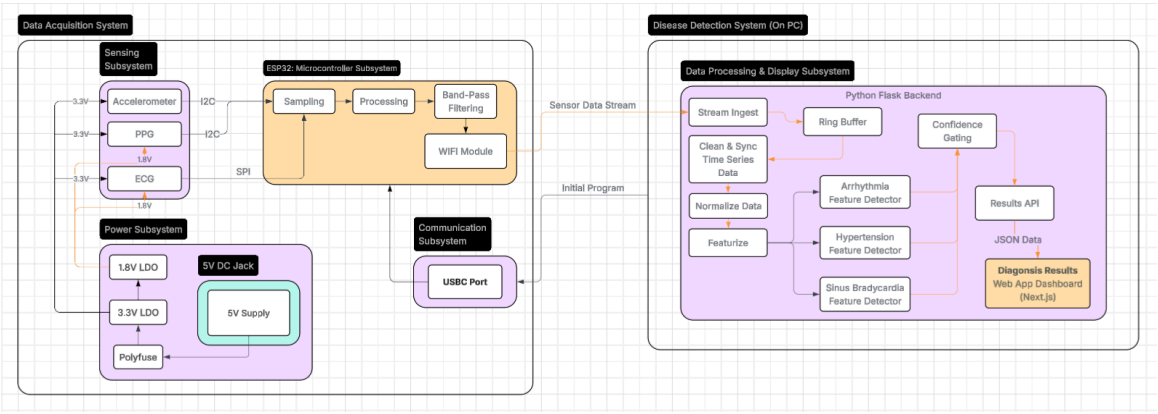

Figure 2.1: System Level Block Diagram

2.2 PCB Design: Data Acquisition System

The PCB was designed in KiCad as a compact mixed-signal biomedical data acquisition platform. It combines power regulation, digital processing, and communication into a single board while maintaining low noise, electrical safety, and reliable signal routing. More specifically, the board acts as a data acquisition system that measures and samples ECG, PPG, and 3-axis acceleration and streams the data to an ESP32-C3 microcontroller for processing and wireless transmission. The board is organized into four hardware subsystems: the power subsystem, sensing subsystem, microcontroller subsystem, and communication subsystem.

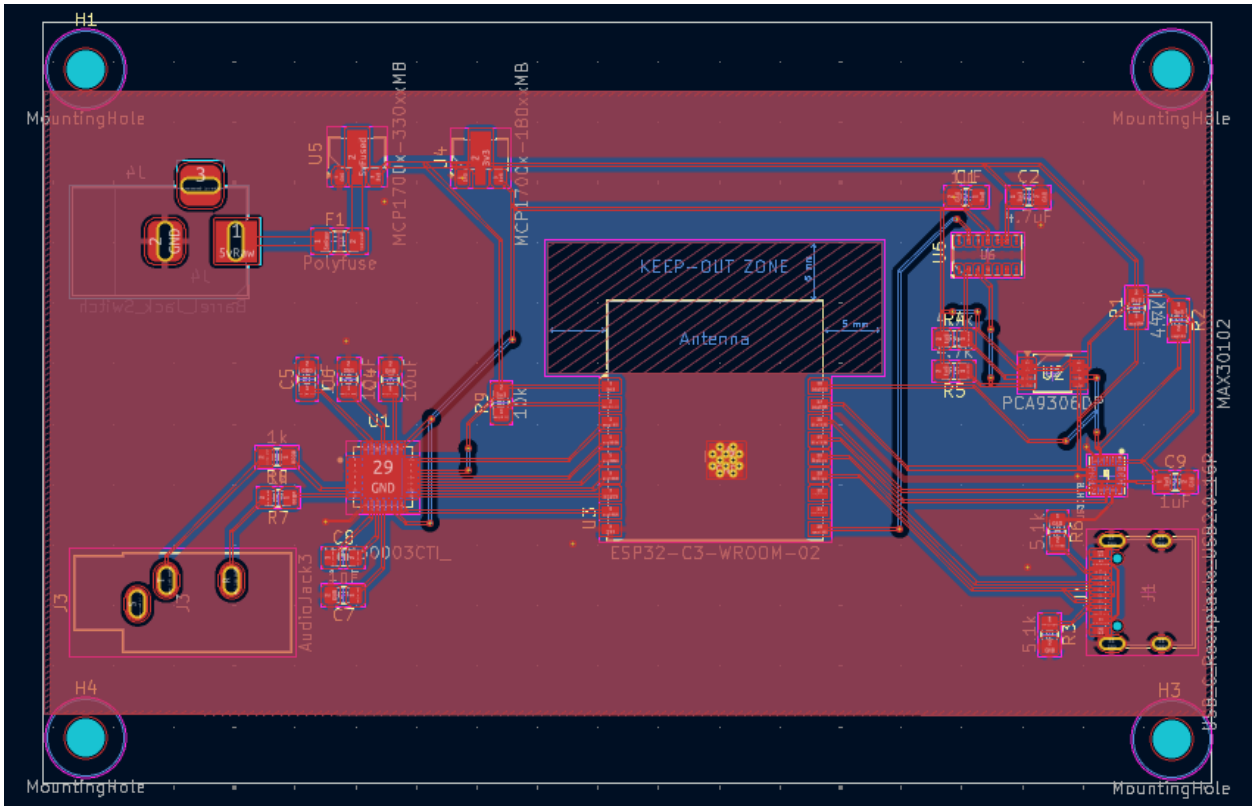

Figure 2.2: KiCad PCB Layout

2.2.1 Power Subsystem

The power subsystem provides stable voltage rails for all sensors and digital components while protecting the board from electrical faults. Power enters the board from a 5V barrel jack. Immediately after the input, a resettable polyfuse protects against accidental shorts and prevents excessive current draw from external power sources.

Two low-dropout regulators generate the necessary supply rails. The MCP1700-3.3 provides the 3.3 V rail used by the ESP32-C3, LIS3DHTR accelerometer, and the LED driver of the MAX30102 PPG sensor. The MCP1700-1.8 generates the 1.8 V rail used by the MAX30003 ECG analog front end and the digital logic domain of the MAX30102. These regulators were selected for their low noise, low quiescent current, and guaranteed stability with small output capacitors, which reduces board area while maintaining power security. In addition, local bypass capacitors were placed along both the 1.8V & 3.3V rails from the respective regulators' output to ensure loop stability and minimize transient noise.

To reduce coupling between the digital components and the highly sensitive ECG circuitry, the PCB separates analog and digital power domains. The MAX30003 is powered from a dedicated analog region of the 1.8 V rail with its own analog ground area. This region connects to the main digital ground at a single star point to prevent ground-loop noise from propagating into the front end. By contrast, digital components such as the ESP32-C3 use a continuous digital ground plane. This power-domain isolation significantly reduces RF interference and switching noise from corrupting the ECG signal.

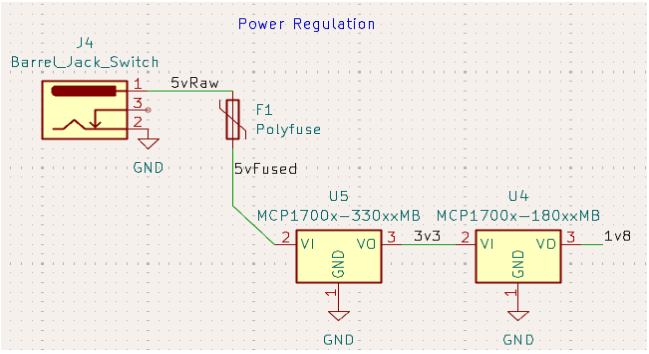

Figure 2.2.1: KiCad Power Regulation Schematic

2.2.2 Sensing Subsystem

The sensing subsystem contains all components and sensors responsible for acquiring physiological and inertial signals required by the data acquisition system. This subsystem integrates three sensor ICs: the MAX30003 ECG analog sensor, the MAX30102 PPG optical sensor, and the LIS3DHTR 3-axis accelerometer. Each device has its own electrical requirements, routing guidelines, and decoupling methods to keep an accurate biosignal reading. The sensors are connected to the ESP32-C3 microcontroller through the SPI & I²C protocols, and each device provides dedicated interrupt addresses/lines for event-driven sampling.

2.2.2.1 ECG Front End(MAX30003)

The ECG subsystem uses the MAX30003, a low-noise analog front end designed for single-lead ECG acquisition. The ECG inputs pass through 1 kΩ series resistors that provide input protection and limit fault current, followed by AC-coupling capacitors that form a low-pass filter and stabilize the internal bias network. These components follow the manufacturer's recommended analog front-end structure to maintain signal integrity. The 3-pole audio jack used for electrode connection is referenced to the analog ground region to isolate the ECG return path from digital ground currents. The MAX30003's analog supply pins use the 1.8 V rail, with local decoupling capacitors located within a few millimeters of each power pin. The device communicates with the ESP32-C3 through an SPI interface and uses an interrupt pin to signal when new ECG samples are available.

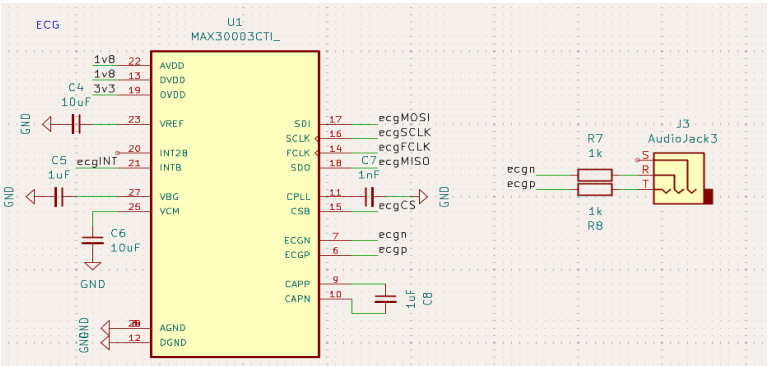

Figure 2.2.2.1: KiCad ECG(MAX30003) Schematic Connections

2.2.2.2 PPG Sensor & Level Shifter(MAX30102 + PCA9306)

This subsystem section is built around the MAX30102 optical biosensor, which integrates red and IR LEDs, photodiodes, and an internal transimpedance amplifier for capturing blood-volume changes in the fingertip. Because the MAX30102 uses 1.8 V logic for its I²C interface, a PCA9306 bidirectional level shifter translates signals (specifically SDA & SCL lines) between the 3.3 V ESP32-C3 I²C bus and the sensor. This ensures reliable communication without violating the sensor's voltage tolerances. The LED driver within the MAX30102 produces short bursts of high current, so the PCB includes local bypass capacitors positioned adjacent to the VLED and VDD pins to prevent LED switching noise from propagating into the rest of the system.

The sensor is placed along the board's perimeter so that it can later align with a finger optical window in future enclosure revisions. The MAX30102 generates an interrupt to indicate when its FIFO contains new samples, allowing the microcontroller to read data without constant polling. Routing between the MAX30102, the level shifter, and the ESP32-C3 is kept short to maintain signal integrity and reduce I²C line capacitance.

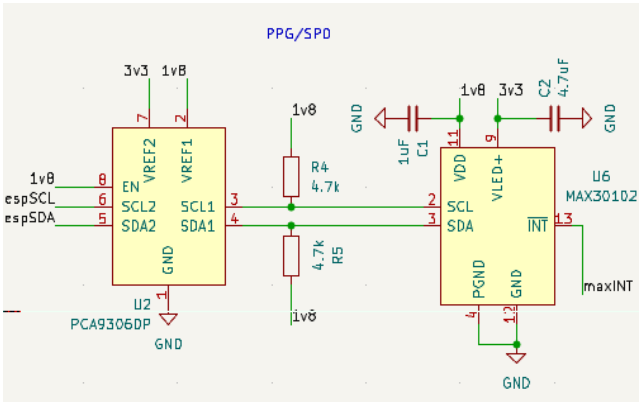

Figure 2.2.2.2: KiCad ECG(MAX30003) Schematic

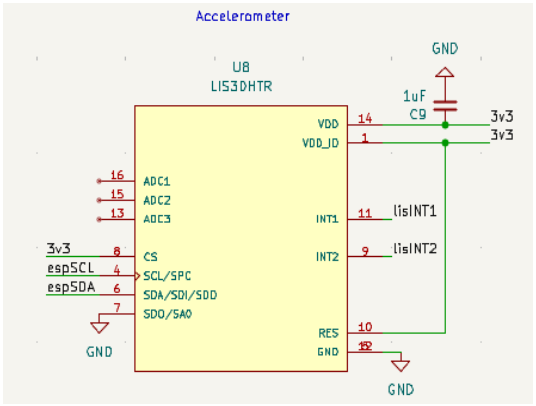

Figure 2.2.2.3: KiCad Accelerometer(LIS3DHTR) Schematic

2.2.2.3 Accelerometer(LIS3DHTR)

The LIS3DHTR accelerometer provides 3-axis motion data used for activity detection and for mitigating motion artifacts in ECG and PPG measurements. The device operates entirely from the 3.3 V rail and requires only a single bypass capacitor to stabilize its supply. It communicates with the ESP32-C3 over I²C, sharing the same bus as the MAX30102 but using separate interrupt pins to report events such as activity detection or data.

The accelerometer is located near the center of the PCB to more accurately represent device motion when handled. Its placement avoids the analog ECG region and the high-current LED driver region to reduce coupling from stress or power transients. The LIS3DHTR's interrupts are routed directly to microcontroller GPIO pins without excessive firmware overhead.

2.2.3 Microcontroller Subsystem

The ESP32-C3 microcontroller is the central component of the board. It manages sensor communication, timestamping, and preprocessing, and transmits collected data to the host. The device receives ECG samples over SPI and obtains PPG and accelerometer data over I²C. All sensors provide interrupt lines to enable event-driven data capture, which reduces power consumption and processing overhead.

The EN pin of the ESP32-C3 is pulled up using a 10 kΩ resistor for reliable startup. The module supports native USB operation, allowing firmware to be flashed directly without an external UART interface. Because the ESP32-C3 contains a 2.4 GHz Wi-Fi radio, careful attention was given to placement based on RF layout from the footprint. The antenna keep-out region is free of copper and high-speed traces. Ground stitching vias and isolated return paths prevent RF emissions from coupling into the ECG analog region. In addition, every power pin cluster includes multiple decoupling capacitors for digital transients.

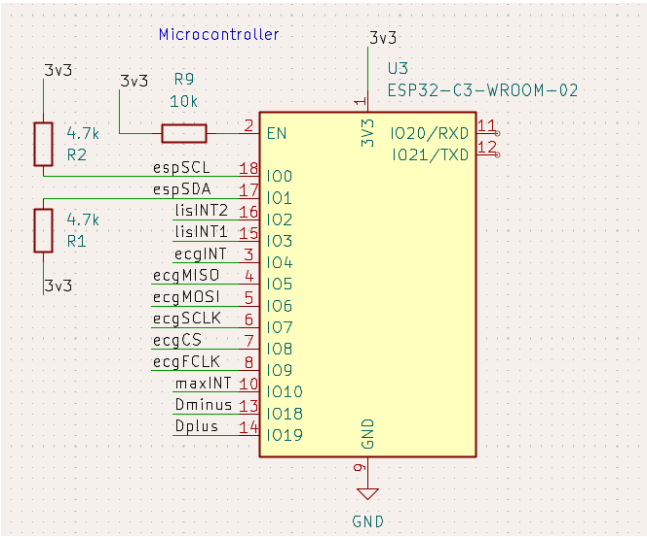

Figure 2.2.3: KiCad MCU(ESP32-C3) Schematic

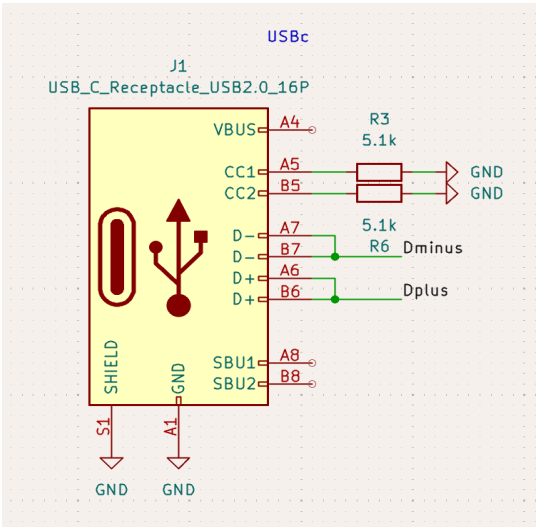

Figure 2.2.4: KiCad USBC Schematic

2.2.4 Communication Subsystem

The communication subsystem is centered around a USBC connector that supports data communication. The CC1 and CC2 pins each include 5.1 kΩ pull-down resistors, which identify the device as a downstream port during USBC negotiation. The USB D+ and D– lines route directly to the ESP32-C3's native USB interface and are designed as a length-matched differential pair with spacing to reach the target 90Ω differential impedance. These traces avoid crossing analog sections of the PCB and are kept short to preserve signal integrity. The USBC port enables serial debugging and firmware updates, making it essential for both development and testing.

2.3. Software: Disease Detection System(PC side)

2.3.1 Data Processing and Display Subsystem

The Data Processing and Display Subsystem runs as a Python program on a laptop and reads a continuous stream of ECG, PPG, and status values over a USB serial connection from the PCB. Each line from the board contains a timestamp, ECG value, infrared PPG value, an estimated heart rate, a motion spike flag, and a finger detection flag. The program ignores lines without a finger detected or with large motion spikes, smooths the incoming heart rate with a simple filter, and only accepts a recording window once the heart rate has stayed within a narrow band for a few seconds. For each accepted 10-second window, the script stores the cleaned ECG, PPG, and heart rate series for feature extraction.

From this window, the program computes three groups of features that map to our three conditions. First, it uses the filtered heart rate to compute the average heart rate and how much it varies. Second, it detects R peaks in the ECG signal and converts the time between consecutive beats into a sequence of R-R intervals, then measures how much those intervals vary. Third, it estimates pulse transit time by measuring the delay between each ECG R peak and the following PPG pulse peak within a physiologic time window. These features drive simple rule checks: we label sinus bradycardia when the average heart rate is below about 58 beats per minute and does not vary much, arrhythmia when the beat-to-beat timing variation is greater than about 150 milliseconds or the heart rate jumps around by more than about 10 beats per minute, and elevated blood pressure risk when the average pulse transit time is shorter than about 180 milliseconds. The program then summarizes these metrics and condition flags in a desktop dashboard so the user can see, in plain language, whether the recording suggested any of the three risk patterns.

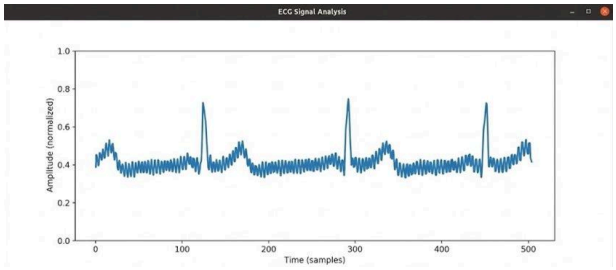

Figure 2.3.1: ECG Signal Analysis

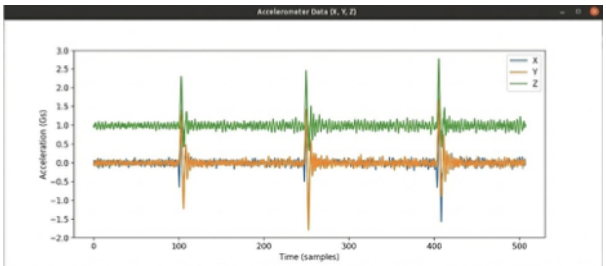

Figure 2.3.2: Accelerometer Data Graph

The ECG signal shows the typical cardiac waveform with a small P-wave, a Q dip, the sharp R-peak, and the S-wave. The R-peak is the most important point because it marks ventricular depolarization and is the strongest part of the cycle, which makes it easy to detect in real time. By measuring the time between consecutive R-peaks, known as the RR interval, we can calculate heart rate and evaluate rhythm regularity. Consistent RR intervals indicate a normal sinus rhythm, while irregular spacing can point to arrhythmias. The accelerometer data shows clear spikes during movement across all three axes. In our system, this motion data is used for motion gating. When acceleration jumps above normal levels, we assume the ECG or PPG readings are being corrupted by motion and we ignore that window.

Once the accelerometer returns to a stable baseline, we resume feature extraction. This prevents motion artifacts from skewing HR or PTT calculations.

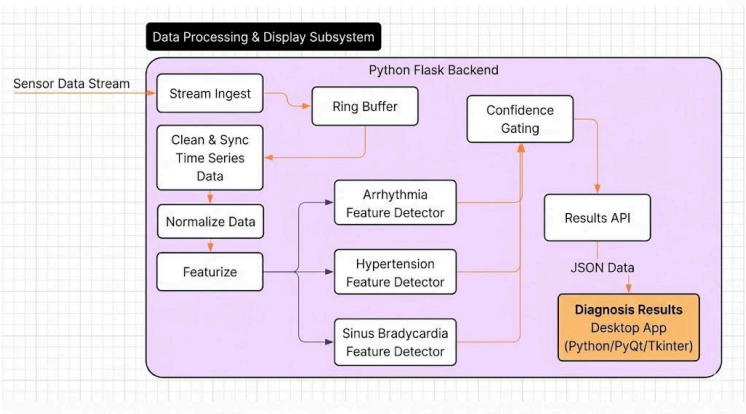

Figure 2.3.3 Data Processing & Display Block Overview

3. Design Verification

This section summarizes the tests used to verify the Data Acquisition System (DAC) and the Disease Detection System. For each subsystem, we describe what was tested, the method, and whether the behavior met the requirements. The formal mapping between requirements and verification procedures is listed in Appendix A.

3.1 Data Acquisition System Verification

3.1.1 Power Subsystem Verification

The 3.3 V and 1.8 V rails were measured under no-load and full-load conditions using a multimeter and oscilloscope. The 3.3 V rail remained within 3.29–3.33 V, and the 1.8 V rail remained at 1.80 V during all tests, satisfying Requirement A1.1. No rail droop occurred during PPG LED activation or SPI activity. A deliberate short applied downstream of the polyfuse confirmed correct current limiting and automatic reset, satisfying Requirement A1.2.

3.1.2 Sensing Subsystem Verification

3.1.2.1 ECG Front End(MAX30003)

SPI reads the INFO register and returns valid values, confirming correct bus operation. A 1 mVpp test signal produced the expected digital waveform within the required error margin, and shorted-input testing showed a low noise floor. These results satisfy the ECG requirements in Appendix A.

3.1.2.2 PPG Sensor(MAX30102)

The sensor appeared at I²C address 0x57 and returned the correct PART_ID. A clear signal was observed when a finger was placed on the device, and the derived heart rate matched a reference device within ±7 BPM, meeting Requirement A2.3.

3.1.2.3 Accelerometer(LIS3DHTR)

The sensor responded at the correct I²C address and returned WHO_AM_I = 0x33. Logged XYZ data tracked expected motion, and the motion interrupt triggered reliably. This satisfies the accelerometer verification requirements.

3.1.3 Microcontroller and Communication Verification

The ESP32-C3 booted reliably and consistently detected all attached sensors (Requirement A3.1). I²C and SPI communication remained error-free during multi-minute tests. USB and Wi-Fi streaming both transmitted continuous sensor packets without frame errors or packet loss, satisfying Requirement A3.2.

3.2 Disease Detection System Verification

3.2.1 Data Pipeline Verification

The host-side software successfully ingested synchronized sensor packets from the DAC. Preprocessing removed DC offsets and aligned ECG, PPG, and accelerometer streams. The ring buffer held continuous data without overflow. These behaviors satisfy Requirement B1.1.

3.2.2 Diagnostic Algorithm Verification

Arrhythmia, hypertension, and bradycardia detectors were tested using repeated runs with identical data inputs. Each detector produced consistent classifications across at least five trials, fulfilling Requirement B1.2. Threshold-based behaviors (e.g., HR < 60 BPM) triggered correctly in controlled tests.

3.2.3 API & Dashboard Verification

Backend API responses contained the correct JSON fields, and the dashboard updated diagnostic results in real time during live data streaming. This satisfies Requirement B1.3.

4. Costs

4.1 Parts & Labor

Table 1 Parts Costs

Part	Manufacturer	Unit Cost ($)	Qty	Actual Cost ($)
1nF, 1uF, 4.7uF, 10uF 0805 SMD Capacitors	Murata Electronics	$8.59	1 pack	$8.59
1k, 4.7k, 5.1k, 10k 0805 SMD Resistors	Chanzon	$8.59	1 pack	$8.59
SMD Polyfuse	Fielect	$0.06	1	$0.06
DC Barrel Jack	Same Sky	$1.25	6	$3.90
Conn Jack Sterio	Same Sky	$0.65	5	$6.25
USBC Ports	Mouser Electronics	$0.273	3	$1.37
3.3V, 1.8V LDO Regulators	Microchip Technology	$0.51	2	$1.02
Level Shifters	NXP USA Inc.	$0.70	5	$3.50
MAX30102 PPG IR/LED Sensor	Analog Devices Inc.	$12.01	1	$12.01
LIS3DHTR Accelerometer	STMicroelectronics	$1.49	3	$4.47
MAX30003CTI_ ECG Sensor	Analog Devices	$13.03	1	$13.03
ESP32-C3-WROOM-02 Microcontroller	Espressif Systems	$3.28	3	$9.84
Grand Total				**$72.63**

Table 2 Labor Cost

Member	Wage/Hr	Hrs/Week	# of Weeks	Total Cost
Jay Nathan	$50	6	13	$3,900
Rishab Iyer	$50	6	13	$3,900
Ethan Pereira	$50	6	13	$3,900
Grand Total				**$11,700**

4.2 Schedule

Table 3 Schedule

Week	Tasks	Members
09/22	Start scouting breakout boards for sensor testing Start conceptualizing on PCB and software side	Rishab Jay, Ethan
09/29	Receive breakout boards, start tests with Arduino Start work on initial drafts of PCB	Rishab, Ethan Jay
10/06	Breadboard Demo 1 Reflect on changes needed for architecture	All Jay, Rishab
10/13	Work on PCB schematic and footprint Work on software/firmware with breakout boards	Jay, Rishab Ethan
10/20	Figure out changes needed in accordance to part availability and compatibility Work on software/firmware with breakout boards	Jay, Rishab Ethan
10/27	Work on PCB schematic and footprint Work on software/firmware with breakout boards	Jay, Rishab Ethan
11/03	Send PCB order by end of the week Work on software/firmware with breakout boards	Jay, Rishab Ethan
11/10	Wait on PCB order, make revisions to footprint for future revisions Work on firmware/software with breakout boards	Jay, Rishab Ethan
11/17	Receive PCB, start soldering components Work on firmware/software with breakout boards Mock Demo	Jay, Rishab Ethan All
11/24	Test PCB connections, integrate software Work on firmware/software integration Not on campus, work on extra credit video and final demo material	Jay Ethan Rishab
12/01	Work on Final Demo, Mock Presentation	All
12/08	Work on Final Report, Final Presentation	All

5. Conclusion

5.1 Accomplishments

We achieved our primary goal of providing a low-cost, at-home cardiovascular screening system capable of detecting indicators of arrhythmias, hypertension, and sinus bradycardia. The device reliably collected data from the ECG, PPG, and accelerometer sensors, processed this information in real time, and displayed clear screening results on a web-based dashboard. The motion-detection feature effectively prevented unreliable readings during excessive movement, ensuring that only valid measurements were reported. We also implemented motion-gating signal validity that halts data reading when either the ECG or PPG sensor does not detect any readings. Overall, the project demonstrated a fully integrated and functional hardware–software system that allows users to perform quick and accessible cardiovascular screenings outside of a clinical setting

5.2 Uncertainties

As we developed this project, there were some uncertainties and challenges we had to overcome. One big challenge was replacing outdated or incompatible components to suit our needed functionality. For example, in our initial implementation, we were planning to utilize an AD8232 ECG sensor as our main ECG sensor. However, due to part availability as well as testing the component synergy alongside the other sensors through breakout boards, we realized that we'll need to try a different ECG sensor to suit our needs. We then decided upon the MAX30003 ECG sensor as it works better with the constraints we have, alongside its compatibility with the ESP32-C3 microcontroller. Another challenge we had come across was grounding faults. In between PCB orders, we found grounding issues regarding some of our sensors not having proper grounding support, and therefore, not functioning properly. Therefore, correcting these issues was paramount in ensuring that our project functions as expected.

5.3 Ethical considerations

This project adheres closely to the IEEE Code of Ethics, particularly in the areas of public safety, honesty, and transparency. The device is clearly presented as a screening tool rather than a diagnostic medical device, and all user-facing outputs explicitly recommend follow-up with licensed medical professionals when abnormal readings are detected. Results are displayed using plain-language indicators and confidence gating, reducing the risk of medical misinterpretation.

From a data privacy standpoint, all signal processing is performed locally, and no physiological data is transmitted to external servers or cloud storage. Motion artifact rejection further upholds ethical responsibility by preventing the reporting of corrupted physiological data, protecting users from misleading outcomes.

5.4 Future work

Several extensions could significantly enhance the system's usability, performance, and long-term impact:

- **Wireless data streaming via Bluetooth or Wi-Fi:** to remove dependence on wired USB connections and enhance portability.
- **Further PCB and enclosure miniaturization:** to improve portability, user comfort, and long-term physiological monitoring applications.
- **Development of a dedicated mobile application (iOS/Android):** to replace the current desktop-based web interface, enabling truly mobile at-home and remote screening.

These future enhancements would move the system closer to a deployable personal health technology platform rather than a laboratory prototype.

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Appendix A: Requirement and Verification Table

Table 4: System Requirements and Verifications

Requirement	Verification	Status
A1. Power Subsystem		
A1.1 The system must provide stable 3.3 V and 1.8 V rails under full sensor load.	Measure rails using an oscilloscope during PPG LED and SPI activity.	Y
A1.2 Over-current protection must activate during a short on the 5 V line.	Apply intentional short downstream of polyfuse; observe trip/reset.	Y
A2. Sensing Subsystem		
A2.1 ECG, PPG, and accelerometer must correctly communicate over SPI/I^2C.	Run enumerations and read device ID registers.	Y
A2.2 All three sensors must produce valid physiological waveforms or motion data.	Collect sample ECG, PPG, and XYZ logs; check for expected patterns.	Y
A2.3 PPG-derived heart rate must match a reference device within ±7 BPM.	Compare PPG HR to the pulse oximeter.	Y
A3. Microcontroller Subsystem		
A3.1 The ESP32-C3 must boot reliably, detect sensors, and stream synchronized packets.	Inspect boot logs; capture continuous sensor packets for 2 minutes.	Y
A3.2 The system must maintain error-free USB or Wi-Fi communication for at least 2 minutes.	Stream data and monitor for dropped frames or packet loss.	Y

B1. Disease Detection System		
B1.1 Sensor data must be cleaned, synchronized, and normalized by the processing pipeline.	Inspect raw vs. processed data; confirm time alignment.	**Y**
B1.2 Diagnostic outputs (arrhythmia, hypertension, bradycardia) must be repeatable across five trials.	Provide identical input streams; verify consistent classifications.	**Y**
B1.3 The dashboard must display updated diagnostic results in real time.	Stream live data and observe interface updates.	**Y**