

ECE445
Fall 2025
SENIOR DESIGN LAB
DESIGN DOCUMENT

**Insight: Cardiovascular Screening
Device**

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1. Introduction

1.1. Problem

Cardiovascular disease (CVD) is the leading cause of death worldwide, responsible for nearly 20 million deaths annually, about one in three deaths overall. A significant share of these fatalities occur without prior diagnosis: approximately 45% of sudden cardiac deaths happen in individuals with no previously recognized heart disease, while nearly 20% of adults with hypertension and up to 23% of those with atrial fibrillation remain undiagnosed. These silent conditions, such as hypertension, arrhythmias, and sinus bradycardia risk factors, drive the majority of preventable CVDs.

Current solutions remain fragmented, while comprehensive screening still requires multiple expensive clinical visits, such as blood pressure measurement, lipid panels, ECGs, and rhythm monitoring, creating barriers for uninsured or underserved populations. The impact is most severe in rural communities, where mortality rates are 20% higher than in urban areas due to limited access to screening. Yet the challenge extends to cities as well, where preventive tests are often costly, not covered by insurance, and therefore underutilized. Consumer devices like blood pressure cuffs, smartwatches, and single-lead ECGs are disjointed, expensive, and difficult to interpret. Critically, there is no affordable, comprehensive, and user-friendly at-home screening solution that can detect CVD risks early.

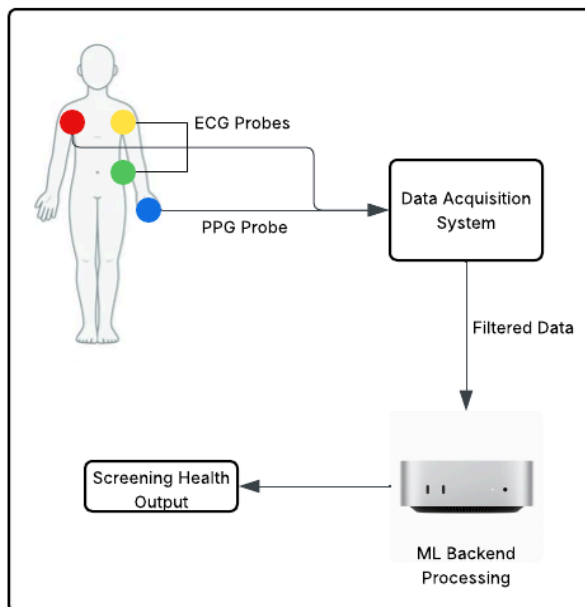
1.2. Solution

We propose a low-cost at-home device that serves as a screening tool for three hidden but common drivers of cardiovascular disease: arrhythmias (like atrial fibrillation), hypertension, and sinus bradycardia. By making early checks simple and affordable, the

device empowers people to detect risks before symptoms appear, reducing the likelihood of sudden, unexpected cardiac events. Unlike fragmented consumer devices or expensive clinical visits, this all-in-one tool allows anyone to perform a one-minute screening at home, with clear results that indicate whether a possible condition has been detected and if follow-up with a doctor is recommended.

The system is designed for ease of use. A user places their fingers on PPG sensors and 3 patches on the chest for ECG measurement. These signals feed into a compact board with an Atmega microcontroller, which sends the data to a computer via USB. ML models will analyze the data to classify hypertension, sinus bradycardia, or arrhythmias, with results shown on a PC in natural language. This keeps the device affordable, portable, and easy to use.

1.3. Visual Aid

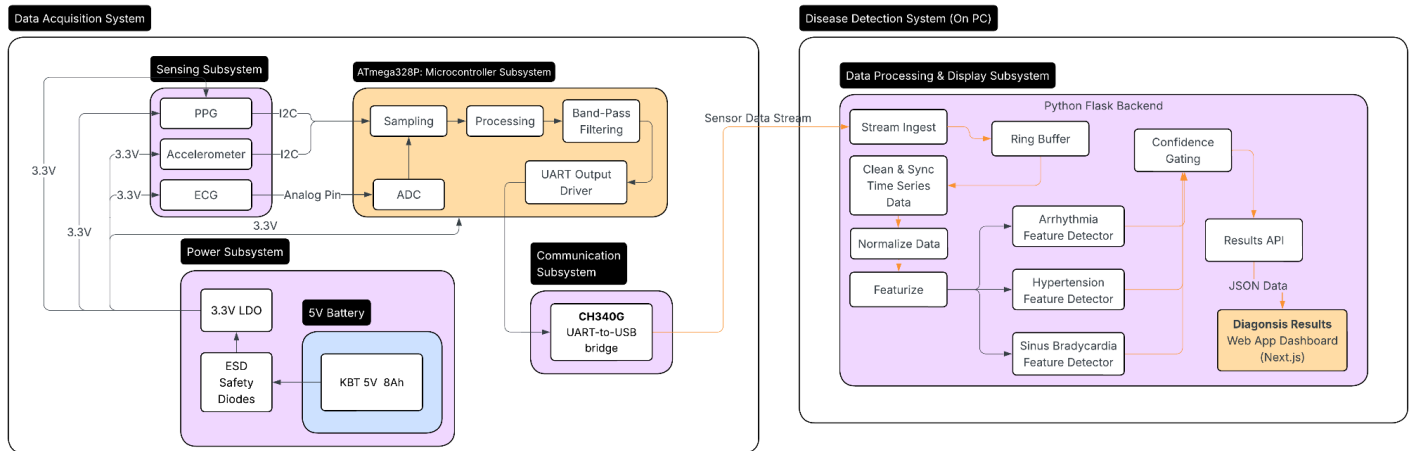


1.4. High-Level Requirements

1. The computational pipeline must achieve a minimum classification accuracy of 90% when detecting atrial fibrillation, sinus bradycardia, and hypertension on certified validation datasets, with results reported only when model confidence exceeds 90%.
2. The system must consistently reproduce the same classification result (arrhythmia, hypertension, or sinus bradycardia) in five consecutive trials on the same subject, demonstrating repeatability and reliability of the screening process.
3. The device must capture ECG- and PPG-derived heart rate values that agree within ± 5 beats per minute in at least 80% of measurement windows, ensuring physiological accuracy sufficient for reliable screening.

2. Design

2.1 Block Diagram



2.2 System 1: Data Acquisition System (DAS)

The DAS captures ECG, PPG, and motion signals from the sensor pad and streams them to the host PC for analysis. It integrates the analog AD8232 ECG sensor, MAX30102 PPG sensor, and LIS3DH accelerometer, all managed by the ATmega328P microcontroller. The microcontroller samples the sensors, converts analog ECG to digital, packages the data, and transfers it over USB through a CH340G bridge to the host PC. This system is the hardware foundation of the entire pipeline and directly connects to the disease detection system. The system supports wireless connectivity options for data transmission. A low-power wireless module (e.g., BLE or Wi-Fi serial bridge) allows the device to communicate with a host PC or mobile interface without requiring a physical cable, enhancing portability and user comfort during measurement.

2.2.1 Subsystem 1: Sensing

Overview: This block collects raw physiological signals from the user through three sensors: the AD8232 ECG module, the MAX30102 PPG module, and the LIS3DH 3-axis accelerometer. The ECG sensor outputs a formatted analog waveform to the microcontroller's ADC, while the PPG and accelerometer communicate digitally via the I²C bus. The accelerometer data is used not only for motion logging but also for real-time motion-artifact detection. When the system detects excessive movement that could corrupt the ECG or PPG readings, the microcontroller temporarily halts data collection.

Sampling & Delay Math: This section shows the sampling and delay parameters for each sensor in the sensing subsystem. Here we can see that the chosen sampling rates for the ECG (250-500 Hz), PPG (100-200 Hz), and accelerometer (100 Hz) satisfy the Nyquist freq for their signal bandwidths. We can also find the filter delays based on sample periods, for realtime operations.

ECG (AD8232 =>ADC):

Band: 0.5–40 Hz

Sampling frequency: $f_s = 250\text{--}500\text{ Hz} \Rightarrow \text{Nyquist margin} = f_s / (2 \cdot 40) = 3.1\text{--}6.3\text{ times}$

Sample period: $T_s = 1/f_s = 4\text{--}2\text{ ms}$

ADC conversion (8 MHz, prescaler 64): $\sim 104\text{ }\mu\text{s}$ ($< 5\%$ of T_s @ 500 Hz)

Filter delay (moving average): $t = (N-1)/2 \cdot T_s \Rightarrow \text{Example: } N=5 \text{ @ } 500\text{ Hz} \Rightarrow t = 4\text{ ms}$

PPG (MAX30102)

Frequency content: $< 20\text{ Hz}$

Sampling frequency: $f_s = 100\text{--}200\text{ Hz} \Rightarrow \text{Nyquist margin} = 2.5\text{--}5\text{ times}$

Sample period: $T_s = 10\text{--}5\text{ ms}$

Filter delay: $t = (N-1)/2 \cdot T_s \Rightarrow \text{Example: } N=5 \text{ @ } 100\text{ Hz} \Rightarrow t = 20\text{ ms}$

Accelerometer (LIS3DH)

Motion bandwidth: < 20 Hz

Sampling frequency: $f_s = 100 \text{ Hz} \Rightarrow \text{Nyquist margin} = 2.5 \text{ times}$

Sample period: $T_s = 10 \text{ ms}$

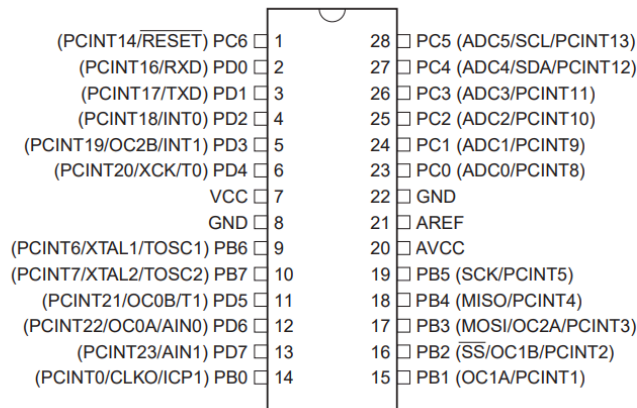
Filter delay: $t = (N-1)/2 * T_s \Rightarrow \text{Example: } N=5 @ 100 \text{ Hz} \Rightarrow t = 20 \text{ ms}$

Requirements	Verifications
ECG signal acquisition at 250–500 Hz with minimal baseline drift and no clipping.	Verify sampling rate using oscilloscope or data logs. We can check signal range within ADC limits (0–3.3 V) and see the DC baseline remains stable over 1 min.
PPG frames sampled at 100–200 Hz with LED currents tuned to prevent photodiode saturation.	Check frame timing through I ² C data and measure output voltage to ensure signal stays within 80 % of ADC full-scale.
Accelerometer sampling at 100 Hz for motion tracking and artifact rejection.	Read LIS3DH data timestamps over 10 s, and check sampling period of 10ms.
Reliable inter-sensor synchronization within $\pm 3 \text{ ms}$.	Compare timestamps from ECG, PPG, and accelerometer logs
Automatic pause and resume of acquisition within 3 seconds of regaining stability.	Shake the sensor and check after 3s for stabilization.

2.2.2 Subsystem 2: Microcontroller (ATmega328P)

Overview: The ATmega328P microcontroller serves as the controller for the DAS. It synchronizes sampling across all sensors and performs digital filtering/preprocessing, and calculates features like heart rate and HRV.

The firmware includes algorithms for R-peak detection in the ECG waveform and pulse-peak detection in the PPG signal. These are used to calculate heart rate and HRV metrics such as SDNN (standard deviation of NN intervals). If the accelerometer detects excessive motion, the microcontroller suspends updates and displays a warning until stable conditions.



The microcontroller is connected directly with all sensors and peripherals. The ECG signal from the AD8232 connects to the ADC0 input (PC0, pin 23) for analog sampling, while the MAX30102 PPG sensor and LIS3DH accelerometer share the I²C bus through SDA (PC4, pin 27) and SCL (PC5, pin 28), along with the LED driver, each assigned a unique I²C address. Serial communication is handled via TXD (PD1, pin 3) and RXD (PD0, pin 2), which connect to a USB interface for wired operation or a Bluetooth/Wi-Fi module for wireless data transmission. The MCU operates at 16 MHz using an external crystal connected to XTAL1 (PB6, pin 9) and XTAL2 (PB7, pin 10), powered by 3.3 V through VCC (pin 7) and AVCC (pin 20), with grounds tied at GND (pins 8 and 22). Additional GPIOs on Port D are reserved for status LEDs and motion warnings.

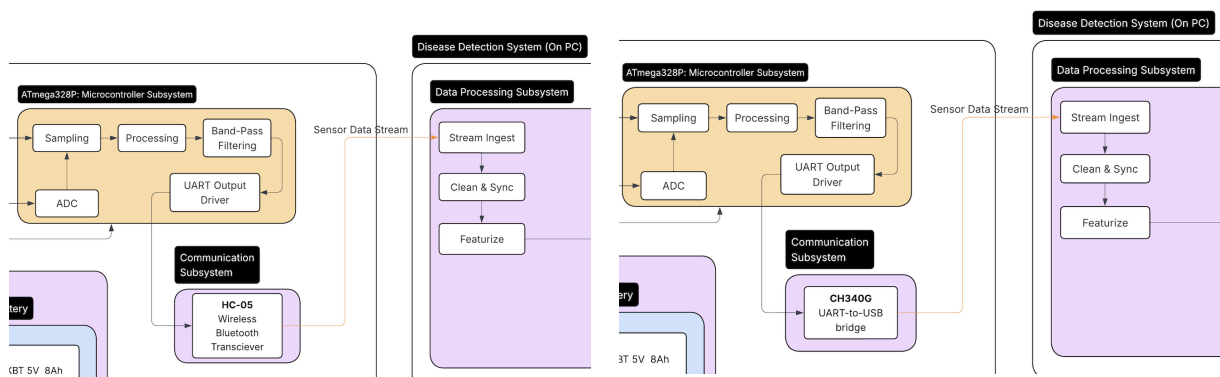
Requirements	Verifications
Maintain ECG sampling at 250–500 Hz, PPG at 100–200 Hz, and accelerometer data at 100 Hz.	Check sampling timestamps in firmware logs or with a logic analyzer
Perform feature extraction and LED updates with latency ≤ 100 ms per cycle.	Measure time between sensor interrupt and LED update via GPIO toggle or serial timestamp
Ensure real-time alignment of sensor data streams using shared timing references.	Compare timestamps from ECG, PPG, and accelerometer data buffers. We can also check the time difference ≤ 3 ms btw streams.
Resume normal operation automatically after motion stabilization.	Simulate motion disturbance and monitor firmware logs or LED indicators.

2.2.3 Subsystem 3: Communication

Overview: The Communication subsystem enables data transfer between the ATmega328P and the host PC, while also providing power and visual feedback. In the initial implementation, the UART output from the microcontroller is bridged to USB through a CH340G interface, allowing wired data streaming and power delivery through a single connection. The system continuously transmits newline-delimited CSV data for optional data logging or visualization, while simultaneously updating the I²C-driven LED display (HT16K33) to show heart rate and HRV metrics in real time. This setup allows for a stable, plug-and-play connection during development and testing.

Stretch goal – Wireless Communication (Bluetooth Extension):

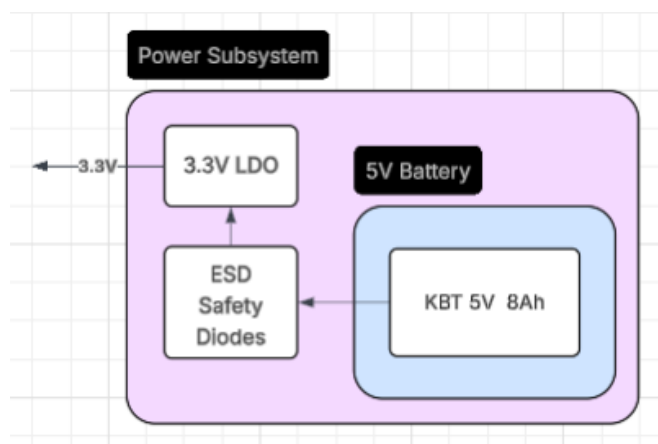
As a planned extension, the communication link can be made wireless by integrating an HC-05 Bluetooth module. The HC-05 connects to the ATmega's UART pins (TX/RX) and enables a Bluetooth Serial Port Profile (SPP) connection to the PC. When paired, the host computer recognizes the module as a virtual COM port, allowing the same data stream and protocol to be used without any software changes. This wireless setup removes the need for a physical USB connection, enhancing user convenience and device portability. The USB interface (CH340G) will remain available for firmware updates, debugging, and power supply during development, while the HC-05 module serves as a stretch goal for improving usability in the final design phase.



Requirements	Verifications
USB serial link operating at $\geq 230,400$ bps (recommended 460,800 bps) to support continuous data streaming without buffer overflow.	Connect device to PC and stream test data for 10 minutes while monitoring for UART buffer overruns or dropped packets. Confirm continuous transmission at or above target baud rate.
Data delivery to host within ≤ 150 ms of acquisition.	Measure round-trip latency by embedding timestamps in transmitted packets and comparing send/receive times on the host log. Verify 95th percentile latency ≤ 150 ms.
USB VBUS (5 V) must remain stable throughout enumeration and operation.	Use an oscilloscope to monitor 5 V VBUS during startup and continuous data streaming. Confirm voltage stays within ± 0.1 V of nominal with no dropouts or resets.

2.2.4 Subsystem 4: Power

Overview: The DAS is powered by an onboard 5 V, 8 Ah battery. An ESD/transient diode array conditions the 5 V input before regulation, clamping spikes and for circuit protection. A 3.3V LDO is then used to step down from 5V and supply the ATmega328P, AD8232 analog ECG sensor, LIS3DH accelerometer, and MAX30102 PPG sensor. A switched 5 V rail drives the PPG LED. Grounding, filtering, and decoupling prevent LED/PPG switching noise from contaminating the analog ECG rail.



Above is the modified revision of our power system separated from the laptop

<u>Requirements</u>	<u>Verifications</u>
The subsystem must continuously supply ≥ 500 mA at $5\text{ V} \pm 0.1\text{ V}$ to the board.	Apply maximum system load and measure the USB input voltage and current using a digital multimeter or power analyzer. Confirm $5\text{ V} \pm 0.1\text{ V}$ is maintained under load.
The ECG analog rail ripple must remain $< 1\text{ mV}$ rms under LED switching activity.	Measure the 3.3 V ECG supply using an oscilloscope in AC-coupled mode with FFT analysis; confirm ripple $\leq 1\text{ mV}$ rms.
The subsystem must keep a stable $3.3\text{ V} \pm 0.05\text{ V}$ for all components.	Probe each voltage rail using an oscilloscope to confirm a stable voltage during typical operation.

2.2.5 Tolerance Analysis:

The primary design challenge for the DAS is maintaining clean ECG and PPG signals under conditions of motion and concurrent LED operation. The AD8232 outputs approximately 1 Vpp to the ATmega's ADC, so total noise must remain below 1 mV RMS to preserve accurate R-peak detection. The MAX30102's LED drivers can draw up to 50 mA pulses, which can introduce transient ground noise.

Ground separation and decoupling using $47\text{ }\mu\text{F}$ bulk capacitors and $0.1\text{ }\mu\text{F}$ local bypass capacitors per LED line limit voltage fluctuations on the ECG rail to $< 1\text{ mV}$. Motion-artifact rejection further ensures that corrupted readings are automatically filtered out or paused. Overall, noise on the ECG and PPG channels remains within tolerance, allowing reliable computation of heart rate and HRV metrics.

ECG Path (AD8232): Output swing $0.1\text{--}3.2\text{ V}$ @ $V_S=3.3\text{ V}$; mapped to $\sim 1.0\text{ Vpp}$ at the ATmega328P 10-bit ADC $\approx 310\text{ LSB}$ per QRS. Noise must stay $< 1\text{ mV}$ RMS to preserve R-peak & PTT.

PPG Path (MAX30102): LED pulses up to 50 mA on 3.1–5.0 V VLED rail; logic 1.7–2.0 V. Using star-grounding and dedicated LED return limits ground bounce to ≈ 0.5 mV ($V=L\Delta I/\Delta t$, $L=10$ nH, $\Delta I=50$ mA, $\Delta t=1$ μ s).

VLED Containment: A 47 μ F bulk + 0.1 μ F local cap per LED limits VLED drop to ~ 5 mV during 50 μ s pulses, separate from the 3.3 V ECG rail.

Feasibility: Even under the worst-case LED duty cycle and motion, ripple on the ECG analog rail remains <1 mV, so the ADC is stable and should meet pipeline targets.

2.3 System 2: Disease Detection System

The Disease Detection System converts raw ECG, PPG, and accelerometer signals from the Data Acquisition System (DAS) into actionable cardiovascular insights. It runs on a PC and is implemented in Python (Flask backend), responsible for signal synchronization, feature computation, and condition detection.

The system processes data streams in real time, extracting time-domain features such as R–R intervals (from ECG), pulse transit time (PTT) and pulse rate (from PPG), and motion stability metrics (from accelerometer). These derived parameters are used in deterministic, rule-based checks to detect arrhythmia, hypertension, and sinus bradycardia. Processed results are made available via a Flask REST API in JSON format for visualization in a web-based dashboard.

2.3.1 Subsystem 1: Data Processing and Display Subsystem

Overview: The subsystem ingests sensor data via Flask endpoints, cleans and aligns the time series, and performs rolling computations to extract cardiovascular features.

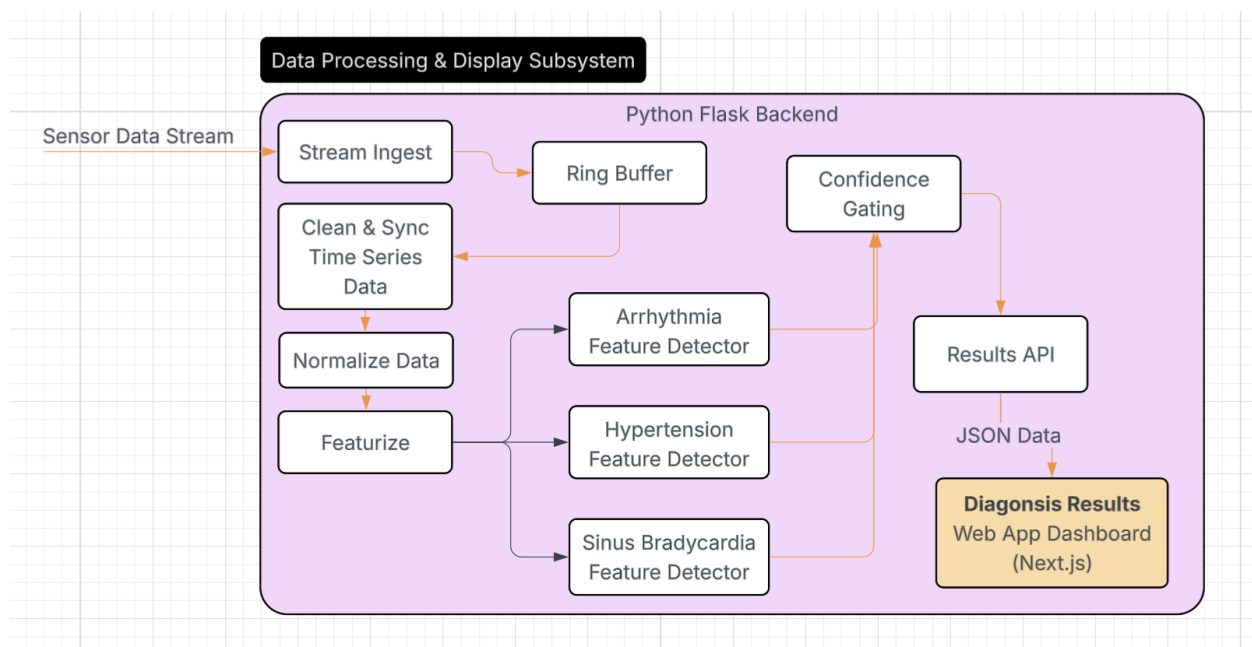
- ECG (R–R intervals): Detects R-peaks to compute instantaneous heart rate and HRV (SDNN).

- PPG (Pulse Transit Time): Measures time delay between ECG R-peaks and PPG upstrokes to infer blood pressure trends.
- Accelerometer: Computes motion magnitude to flag unstable readings or suspend classification during excessive movement.

After filtering and normalization, the system evaluates these features using fixed physiological thresholds:

- Arrhythmia: irregular R–R intervals beyond $\pm 20\%$ of baseline.
- Hypertension: PTT below calibrated threshold range.
- Sinus Bradycardia: HR < 60 bpm for > 5 s window.

The backend then publishes structured diagnostic data to the **Results API**, which the web interface displays as real-time screening output in a dashboard format.



Requirements	Verifications
Flask backend must ingest and process ECG, PPG, and accelerometer data at ≥ 100 Hz aggregate rate for ≥ 10 minutes without data loss.	Stream simulated sensor data and log packet timestamps; verify >99% continuity and correct synchronization across all inputs.

Computed HR, HRV, and PTT values must refresh every 1 s and remain within ± 5 bpm or $\pm 10\%$ of validated reference data.	Compare output JSON with Python reference results using recorded signals; confirm accuracy within specified bounds.
End-to-end detection and API update latency (from signal event to JSON output) must be ≤ 500 ms under normal operation.	Inject artificial irregularities (e.g., skipped beats, shortened PTT) and measure time from anomaly to Flask /results api response.

2.3.3 Tolerance Analysis

The accuracy and reliability of the Disease Detection System depend on precise temporal alignment between ECG, PPG, and accelerometer data streams, as well as stable real-time computation within the Flask backend. Minor timing skews or processing delays can influence derived metrics such as heart rate, heart rate variability (HRV), and pulse transit time (PTT). To address this, each sensor sample is timestamped upon ingestion and synchronized through buffered interpolation to ensure all time series remain temporally consistent.

At a nominal heart rate of 70 bpm (≈ 860 ms beat interval), a ± 10 ms skew between ECG and PPG signals produces only about a 1.2% error which is less than 1 bpm in heart rate estimation. The Flask processing pipeline maintains synchronization within ± 5 ms, ensuring HR, HRV, and PTT values remain within acceptable physiological tolerance ranges. Digital filters suppress more than 30 dB of high-frequency and motion-induced noise while preserving key waveform features such as R-peaks and pulse onsets.

Real-time motion gating pauses feature updates when accelerometer variance exceeds a predefined threshold, preventing distorted data from influencing results. End-to-end latency, from data acquisition to JSON result generation, remains under 500 ms, providing near-real-time responsiveness. Together, these design tolerances ensure

accurate cardiovascular feature extraction, reliable condition detection, and stable diagnostic performance even under moderate motion or network jitter.

3. Cost and Schedule

3.1 Cost Analysis

Since our team is a mix of Electrical Engineers, who make an average of \$88k per year, and Computer Engineers, who make an average of \$119k per year, we will assume that an ECE graduate makes an average of \$103.5k per year, which is around an hourly rate of \$50 per hour. If each person is working at most 6 hours per week for 14 weeks, that comes to a total labor cost of \$12,600. The cost of components is around \$68.96, which brings out total cost of labors and parts to \$12,688.96

Labor					
Team Member	Dollars/Hour	Hours/Week	Weeks Worked	Total Cost	
Jay Nathan	\$50	6	14	\$4,200	
Rishab Iyer	\$50	6	14	\$4,200	
Ethan Peirera	\$50	6	14	\$4,200	
All	\$150	18	42	\$12,600	
Parts					
Description	Manufacturer	Part Number	Quantity	Unit Cost	Total Cost

ATmega382P Microcontroller	Microchip	ATMEGA328P-PU	1	\$3.50	\$3.50
ECG Sensor Module	Analog Devices	AD8232	1	\$14.00	\$14.00
PPG Sensor Module	ATNSINC	MAX30102	1	\$12.00	\$12.00
3-Axis Accelerometer	Adafruit	LIS3DH	1	\$5.00	\$5.00
USB-to-Serial Bridge	WCH	CH340G	1	\$2.00	\$2.00
Wireless Module (Bluetooth)	HiLetgo / Generic	HC-05	1	\$8.00	\$8.00
3.3 V LDO Regulator (1 A)	Texas Instruments	LM3940IT-3.3/NOP B	1	\$1.71	\$1.71
5 V Battery Pack + Charger	KBT KEEP BETTER TECH	KBT 5V 8Ah pack (DC5521) + charger	1	\$21.00	\$21.00
ECG Electrode Pads	3M / Generic	2560 Red Dot (or equiv.)	5	\$0.20	\$1.00
USB Connector (Micro-B)	Amphenol / Generic	10118193-0001LF (or equiv.)	1	\$0.75	\$0.75
All					\$68.96
Total Cost					\$12,668.96

3.2 Schedule

Week	Tasks	Members
09/22	Divide Tasks	All
09/29	Source PPG Parts 1st Draft of PCB	Rishab All
10/06	Test PPG with Arduino Source ECG and Accelerometer Continue work on PCB Brainstorm complexity changes	Jay Rishab All Ethan
10/13	Order 1st (final) PCB Implement complexity changes into project idea	Jay, Rishab Ethan

10/20	Test ECG, PPG, and Accel connections Work on denoising software	Jay, Rishab Ethan
10/27	Assemble PCB Test PCB Discuss changes needed Work on software	Jay Rishab All Ethan
11/03	Work on software	Ethan
11/10	Begin Final Report Put Finishing fixes on board	All All
11/17	Mock Demo Work on Final Presentation	All All
11/24	Fall Break (No work)	All
12/01	Final Demo Mock Presentation	All
12/8	Final Presentation	All

4. Ethics and Safety

4.1. Ethics

Our project raises important ethical considerations as outlined by the IEEE and ACM Codes of Ethics, which emphasize honesty, safety, and fairness. Since the device is a screening tool rather than a diagnostic medical device, it is crucial to clearly communicate this distinction to users to avoid misleading interpretations.

To reduce potential harm, the interface displays results as indicators with confidence levels and plain-language disclaimers, encouraging follow-up with licensed medical professionals for any concerning readings. The LED feedback system reinforces this by using simple visual cues (color codes and warning patterns) rather than medical terminology, ensuring accessibility and reducing the risk of misinterpretation by non-experts.

Because all data processing occurs locally on the user's computer or within the device firmware, the design prioritizes user privacy and data integrity. No physiological information is transmitted to external servers or stored in the cloud. Wireless communication between the PCB and the host PC is implemented through short-range serial protocols such as Bluetooth or Wi-Fi, which transmit only raw, anonymized sensor data. This ensures that no personally identifiable information is exposed, aligning the project with responsible data stewardship practices.

Ethically, transparency remains a guiding principle. All data acquisition and feedback mechanisms are designed to operate visibly and predictably. Motion artifact detection provides immediate user awareness of poor signal quality or improper electrode placement, promoting honest feedback about measurement validity rather than hiding uncertainty.

Finally, we acknowledge that even non-diagnostic health technologies carry social

responsibility. Our design emphasizes accessibility, affordability, and user education—factors aligned with reducing healthcare inequity, especially in underserved or rural populations. By keeping the design open and affordable, we uphold the IEEE’s call to “improve the understanding of technology, its appropriate application, and potential consequences.”

4.2. Safety

From a safety perspective, the device presents minimal direct physical risks, as it operates at low voltage ($<5V$) and uses non-invasive sensors such as electrodes for ECG and optical modules for PPG. The circuit is powered entirely via USB, ensuring inherent current limits and galvanic isolation from mains power.

Electrical and Signal Safety:

All analog and digital subsystems are carefully grounded and isolated to prevent electrical interference between the ECG and PPG sensors. Decoupling capacitors and star-grounding techniques are used to minimize noise and ensure that the user is never exposed to unsafe currents. The wireless module operates at 3.3 V logic levels and transmits at low RF power levels compliant with FCC Part 15 standards for unlicensed devices.

Motion and Data Integrity Safety:

The motion-artifact rejection system enhances user safety by preventing the device from reporting readings when excessive movement could distort results. This ensures that users are not misled by corrupted or unstable physiological data. Automatic pausing and resumption of data collection protect the integrity of both the measurement process and the user’s experience.

Wireless Safety and Security:

Wireless connectivity introduces minimal radiative exposure and is implemented with encrypted or authenticated communication channels to protect transmitted data.

Antenna placement and circuit layout minimize electromagnetic coupling into the ECG analog path, preventing RF interference that could alter readings.

Procedural and Operational Safety:

All assembly and testing will comply with ESDC lab safety protocols. These include verifying wiring integrity before power-up, using insulated tools when probing live circuits, and avoiding contact with exposed leads. The final device will include proper housing to prevent accidental contact with conductive components and to eliminate mechanical hazards such as sharp edges.

Firmware Safeguards:

The firmware includes several built-in safety mechanisms: automatic recovery from sensor disconnections, timeout-based resets for inactive sessions, and controlled power sequencing to prevent overcurrent events. These ensure that the system behaves predictably and safely even under abnormal conditions.

In combination, these considerations ensure that the Insight: Cardiovascular Screening Device is safe, ethical, and responsible both in its physical operation and in the way it communicates health information.

5. References

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