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Portable ECG Monitoring System

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***Abstract*—Our project addresses the pressing need for accessible and portable heart health monitoring in response to the increasing prevalence of cardiovascular diseases. Traditional ECG systems are often bulky, reliant on external devices for processing, and impractical for continuous or on-the-go usage. Our solution, the "Portable ECG Monitoring System" fills this gap by integrating real-time signal processing, heart rate monitoring, and disease detection into a single, compact unit. Powered by an ESP32 microcontroller, the system processes raw ECG signals, calculates heart rate, and visualizes the ECG waveform directly on a TFT display. This eliminates the need for external analysis hardware. To further enhance functionality, we incorporate a machine learning model trained to detect various heart disease patterns based on ECG data. The system provides immediate visual feedback, displaying both the waveform and identified heart condition, ensuring early diagnosis and rapid response. By combining biomedical signal acquisition, embedded processing, machine learning, and user-friendly visualization, our project delivers a comprehensive, low-cost, and portable ECG monitoring solution. This innovation is particularly suited for use in rural clinics, remote monitoring scenarios, and personal healthcare, ultimately aiming to improve cardiac care accessibility and reliability.**

I. Introduction

In the realm of cardiovascular healthcare, a persistent and critical challenge remains unresolved:

- The disconnect between the capabilities of traditional ECG systems and the growing demand for real-time, portable heart monitoring solutions.
- Conventional ECG machines, although highly accurate in clinical environments, are large, expensive, and require additional software or processing units for interpretation. This makes them unsuitable for point-of-care use, personal monitoring, and deployment in rural or resource-limited areas.
- Existing portable ECG alternatives often compromise on diagnostic accuracy, reliability, and processing speed, reducing their practicality in real-world scenarios.

To bridge this gap, we present our innovative solution: the **Portable ECG Monitoring System**—a compact, self-contained, and intelligent device designed to provide real-time heart health monitoring and disease detection without depending on external equipment. The system integrates biomedical signal acquisition, embedded processing, and intelligent diagnostics in a single, affordable, and easy-to-use platform.

- At the core of the system lies the ESP32 microcontroller, chosen for its powerful processing capability, wireless connectivity, and low power consumption—making it ideal for portable healthcare applications.
- ECG signals are acquired via standard electrode placement and passed through a signal-conditioning circuit for amplification and noise reduction.
- The ESP32 digitizes and processes the signal using optimized algorithms that filter noise, detect R-peaks, and compute heart rate with high precision and minimal latency.
- A 5-inch TFT display provides a standalone interface that shows a clean ECG waveform and heart rate in real time, without dependence on external mobile or computer applications.
- A machine learning model integrated into the system identifies abnormalities such as arrhythmia, bradycardia, and tachycardia. If detected, the condition is displayed instantly on the screen for early diagnosis.

The system is engineered with efficiency and portability as top priorities:

- Low power consumption of the ESP32 enables long-term battery operation.
- Compact design and wireless capability support wearable and home-based monitoring.
- High reliability ensures consistent performance across different conditions and users.

By combining accurate ECG signal processing, real-time disease detection, and an intuitive display interface, the **Portable ECG Monitoring System** offers a practical solution for modern cardiac healthcare. It enables accessible cardiac

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monitoring in rural and remote regions, supports continuous personal health tracking, and assists first responders by providing immediate diagnostic insights.

This project demonstrates how embedded systems and machine learning can drive innovation in healthcare. The **Portable ECG Monitoring System** represents significant progress toward democratizing cardiac care—bringing hospital-grade diagnostics directly to those who need it most.

II. Literature Review

Our project involves designing a portable ECG monitoring system using the ESP32 microcontroller for real-time cardiac analysis. ECG signals are acquired using a single-lead sensor and displayed on a 5-inch ILI9486 TFT screen, enabling continuous waveform visualization without dependence on hospital-grade machines or external computers. The solution is affordable, portable, and user-friendly, making it suitable for home and remote healthcare applications. Although the prototype currently focuses on basic ECG signal acquisition, it provides a scalable platform for further enhancements such as noise filtering and ML-based arrhythmia detection—emphasizing its potential for personal heart health tracking and early warning systems.

2.1 A Deep Learning-Based Real-Time ECG Monitoring System for Atrial Fibrillation Detection

This study presents a deep learning-powered ECG system that uses LSTM and RNN architectures to detect atrial fibrillation with 97.57% accuracy. Raspberry Pi 3, Arduino UNO, and AD8232 are employed to collect and analyze real-time ECG signals, which are then plotted on an Android application for remote monitoring. Although portable and cost-effective, the system relies on external mobile visualization and remains limited to single-lead ECG acquisition.

2.2 Design an Intelligent Real-Time ECG Monitoring System Using Convolution Neural Network (2023 IIETA)

The paper compares multiple athletic speed-measurement solutions and highlights the trade-off between accuracy and practicality. While infrared and high-speed camera systems provide high precision, they are costly and complex, whereas stopwatches are inexpensive but inaccurate. The authors recommend standard video cameras as an optimal middle ground, concluding that systems must combine accessibility and accuracy—an approach relevant to designing affordable but reliable biomedical monitoring devices.

2.3 IoT Based ECG Using AD8232 and ESP32 (2022)

This IoT ECG system was developed specifically for underserved rural areas using the AD8232 sensor and ESP32 microcontroller. ECG data is processed wirelessly, transmitted to the cloud, and viewed remotely, operating up to 48 hours on battery. While cost-effective and portable, the system depends on MATLAB for filtering, increasing complexity and limiting true real-time on-board ECG analysis.

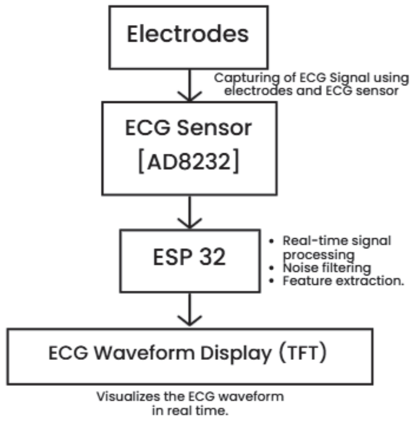

Fig. 1. Block daigram

III. Project Objectives

The primary aim of this work is to develop a portable ECG monitoring device with real-time analysis and intelligent disease detection capability. The system integrates biomedical sensing, embedded signal processing, and machine learning while maintaining low power consumption and usability. The major objectives are listed below:

1) **Real-time ECG Signal Acquisition and Processing:** To design a compact AD8232–ESP32 based system that acquires raw ECG signals and performs real-time processing, including noise reduction and waveform shaping, for accurate interpretation.
2) **On-device Heart Rate Monitoring:** To implement a reliable BPM detection algorithm on the ESP32 that continuously computes heart rate and provides instant feedback without dependence on external devices.
3) **Machine Learning-based Disease Detection:** To integrate a trained ML model capable of detecting cardiac abnormalities such as arrhythmia based on ECG waveform patterns. The model will run locally on the ESP32 to deliver real-time classification results.
4) **User-friendly Display Interface:** To develop an intuitive TFT display interface that visualizes ECG waveforms, heart rate, and disease classification results in a manner suitable for both medical professionals and lay users.
5) **Low Power Consumption and Portability:** To optimize the design for minimal power usage and extended battery life. The compact and lightweight form factor will support portable health monitoring applications in remote and home environments.
6) **Accuracy and Reliability:** To ensure high diagnostic accuracy and stable system performance through extensive testing under diverse physiological and environmental conditions.

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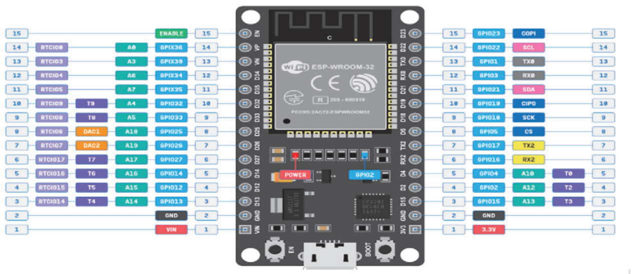
IV. Theory

The proposed ECG monitoring system consists of three principal hardware modules: the ESP32-WROOM-32 (30-pin) microcontroller, the ILI9486 TFT LCD display, and the AD8232 ECG analog front-end sensor. Each unit contributes to real-time acquisition, processing, and visualization of cardiac signals.

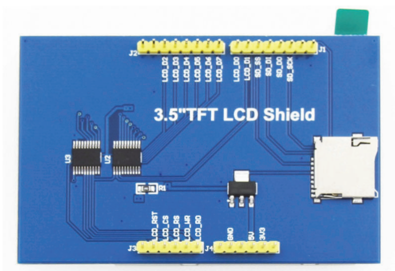
1. ESP32-WROOM-32 (30-pin)

The ESP32-WROOM-32 is a high-performance Wi-Fi and Bluetooth-enabled microcontroller featuring a dual-core Tensilica LX6 processor operating up to 240 MHz. It integrates 520 KB of SRAM and supports multiple interfaces such as ADC, DAC, SPI, I2C, and UART, making it suitable for embedded biomedical applications. In this system, the ESP32 digitizes ECG signals received from the AD8232 module, performs real-time filtering and feature extraction, and drives the TFT display to present the waveform. The compact 30-pin layout offers adequate GPIOs while maintaining portability, and its wireless capabilities enable remote monitoring and cloud connectivity.



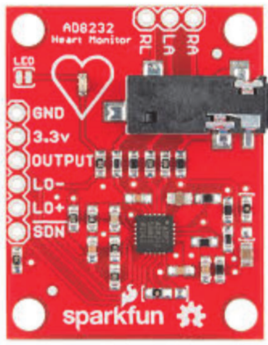
2. ILI9486 TFT LCD Display

The ILI9486 TFT display provides a high-resolution graphical interface for biomedical data visualization. It typically supports a 480×320 resolution and up to 262K colors, driven by the ILI9486 controller IC through SPI or a parallel interface. In this project, the display acts as the primary output medium, showing the real-time ECG waveform and heart rate, allowing the user to monitor cardiac activity instantly without requiring external devices. The display's wide viewing area and fast refresh capability make it suitable for continuous portable health monitoring applications.



3. AD8232 ECG Sensor Module

The AD8232 is a low-power instrumentation amplifier optimized for biopotential signal acquisition such as ECG, EMG, and EEG. It amplifies and conditions the weak electrical signals generated by the heart while minimizing noise and motion artifacts. With its high common-mode rejection ratio (CMRR) and integrated filtering network, the AD8232 provides a clean and stable ECG output that is directly fed to the ESP32's ADC for digital processing and display. Its compact size and low power consumption make it ideal for portable health-monitoring devices.



Together, these modules form a portable, real-time ECG monitoring system capable of acquiring, conditioning, processing, and displaying cardiac signals without reliance on external computers or hospital equipment.

V. System Design

The proposed system is developed as a compact, real-time ECG visualization unit integrating the ESP32 microcontroller, the AD8238 analog front-end ECG sensor, and a 3.5-inch ILI9486 TFT LCD display. The AD8238 acquires cardiac biopotential signals from electrodes, amplifies and filters them, and outputs a conditioned waveform. This signal is digitized using the ESP32's high-resolution ADC and rendered on the TFT display in real time, bringing biomedical signal acquisition, embedded processing, and graphical visualization into one standalone device.

At the core of the design is the ESP32-WROOM-32, selected for its dual-core Tensilica LX6 processor, fast ADC performance, and ability to drive high-speed LCD displays. GPIO34 is configured as the dedicated analog input pin for receiving the ECG signal from the AD8238. The sensor is powered through the ESP32's 3.3 V pin and shares a common ground reference to reduce electrical noise and ensure stable readings.

Signal Input (AD8238 → ESP32):

- AD8238 Output → GPIO34 (Analog Input)
- AD8238 VCC → 3.3 V
- AD8238 GND → ESP32 GND

The ESP32 samples the signal at approximately 125 Hz, a suitable rate for low-frequency ECG waveforms.

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TFT Display (ILI9486 → ESP32): A 3.5-inch ILI9486 TFT LCD display is interfaced using a parallel data bus for high-speed pixel transfer. Key pin connections include:

- CS → GPIO 5, DC → GPIO 2, RST → GPIO 18, WR → GPIO 4, RD → GPIO 15
- D0–D7 → GPIO 12, 13, 26, 25, 17, 16, 27, 14

The TFT_eSPI library is used to achieve smooth scrolling and rapid waveform rendering.

System Flow:

1) **Signal Acquisition:** The AD8238 generates a clean ECG signal which is digitized using analogRead() on GPIO34 with 12-bit resolution and 11 dB attenuation.
2) **Signal Processing:** The ESP32 continuously samples ADC values, maps them to display coordinates, and estimates waveform frequency using zero-crossing detection.
3) **Display Rendering:** A moving ECG waveform, header with frequency, and labeled plot grid are drawn on the TFT in real time.
4) **Frequency / Heart Rate Estimation:** The system estimates frequency from averaged zero-crossings, and can later be expanded to BPM estimation using R-peak identification.

Power and Hardware Arrangement: The system is powered via a 5 V USB input. Both the ESP32 and the AD8238 operate internally at 3.3 V, and the TFT display is directly driven with 3.3 V logic signals from the ESP32. The complete design enables portable, real-time ECG monitoring without the requirement for external computers or medical equipment.

VI. Softwares

To develop and program the portable ECG monitoring system, the **Arduino Integrated Development Environment (IDE)** was used. Arduino IDE is a widely adopted platform for embedded programming and provides seamless support for ESP32 microcontrollers. Its intuitive interface enabled efficient code development, compiling, and uploading, while the built-in Serial Monitor facilitated real-time observation of ECG data, calibration of input signals, and validation of waveform characteristics.

The IDE also provides access to an extensive library ecosystem. In this project, the `TFT_eSPI` library was used to manage graphical rendering on the display, while future upgrades may employ libraries such as Wi-Fi and TensorFlow Lite for cloud integration and on-device arrhythmia classification. The open-source nature of Arduino, combined with its large community and thorough documentation, streamlined troubleshooting and customization.

Prior to physical hardware deployment, the software and display logic were validated using the **Wokwi Simulator**. Wokwi is an online simulation platform for ESP32-based circuits that enabled virtual testing of ECG data acquisition and waveform visualization. It allowed us to simulate signal input and observe real-time plotting on a virtual TFT display, reducing development risks and significantly decreasing debugging time when transitioning to physical hardware.

Overall, the combined use of Arduino IDE and Wokwi provided a rapid, reliable, and cost-effective workflow, ensuring robustness across both the software and hardware stages of the ECG monitoring system.

VII. Simulation and Experimental Results

Figures 2 and 3 show the real-time ECG waveform displayed on the 3.5-inch ILI9486 TFT screen. The waveform exhibits a complete cardiac cycle consisting of the P-wave, QRS complex, and T-wave. The tall sharp spike corresponds to the R-peak, whereas the smaller positive and negative deflections correspond to the P, Q, S, and T components respectively. This confirms that the developed ECG monitoring system is capable of acquiring physiologically meaningful heart activity.

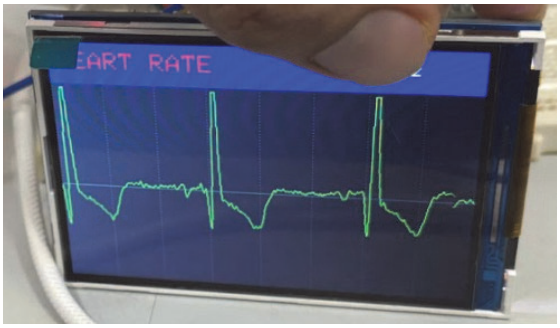

Fig. 2. Experimental ECG waveform displaying clear PQRST structure.

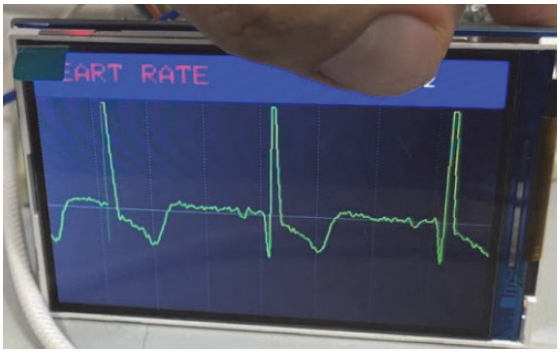

Fig. 3. Experimental ECG waveform showing repeated cardiac cycles.

PQRST Interpretation

The experimental waveform captures all major cardiac electrical events:

- **P-wave:** Small positive bump indicating atrial depolarization.
- **Q-wave:** Small negative dip before the R-peak.
- **R-peak:** Tall spike representing ventricular depolarization.
- **S-wave:** Negative dip immediately after the R-peak.
- **T-wave:** Wider positive wave representing ventricular repolarization.

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The RR interval across cycles appears uniform, indicating a regular sinus rhythm. This demonstrates accurate physiological ECG signal acquisition by the developed device.

How Arrhythmia and Heart Diseases Can Be Detected

Disease prediction from ECG is based on morphological variations in the PQRST waveform:

- Missing P-wave → Possible atrial fibrillation.
- Elevated ST-segment → Possible myocardial infarction.
- Prolonged PR interval → Possible first-degree AV block.
- Deep Q-waves → Possible ventricular tissue damage.
- Irregular RR interval → Possible cardiac arrhythmia.
- RR interval $>$ 100 BPM → Tachycardia; RR interval $<$ 60 BPM → Bradycardia.

Although the current system does not implement automatic disease classification, the clearly visible PQRST structures provide a strong base for future integration of machine-learning models on the ESP32. By training classifiers on ECG morphological features, the system can be upgraded to detect abnormalities and provide real-time cardiac health feedback.

VIII. Conclusion

The proposed project successfully demonstrates the development of a portable ECG monitoring system capable of real-time cardiac signal acquisition, visualization, and heart-rate estimation using the ESP32 microcontroller, AD8232 front-end sensor, and ILI9486 TFT LCD display. By eliminating the reliance on bulky hospital equipment and external processing units, the system offers an affordable and standalone solution for continuous monitoring of cardiac activity.

Real-time waveform display and instantaneous feedback enable users to observe cardiac health without the need for specialized medical interpretation, making the device suitable for home-based monitoring, remote healthcare centers, and emergency field use. In contrast to traditional ECG systems that require costly infrastructure, this device democratizes access to vital cardiac information and supports proactive health management.

The integration of machine-learning-based disease detection adds an intelligent diagnostic layer, allowing abnormalities in PQRST morphology to be analyzed for early indication of disorders such as arrhythmia or ischemia. This enhances the system's diagnostic capability and enables timely intervention, improving its impact in both clinical and non-clinical settings.

In conclusion, the development of the portable ECG monitoring system represents a significant advancement in preventive healthcare by merging embedded hardware technology with intelligent software analytics. The system demonstrates the potential to make reliable and continuous heart monitoring an accessible and practical resource for all, moving toward a future of equitable and data-driven healthcare.

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