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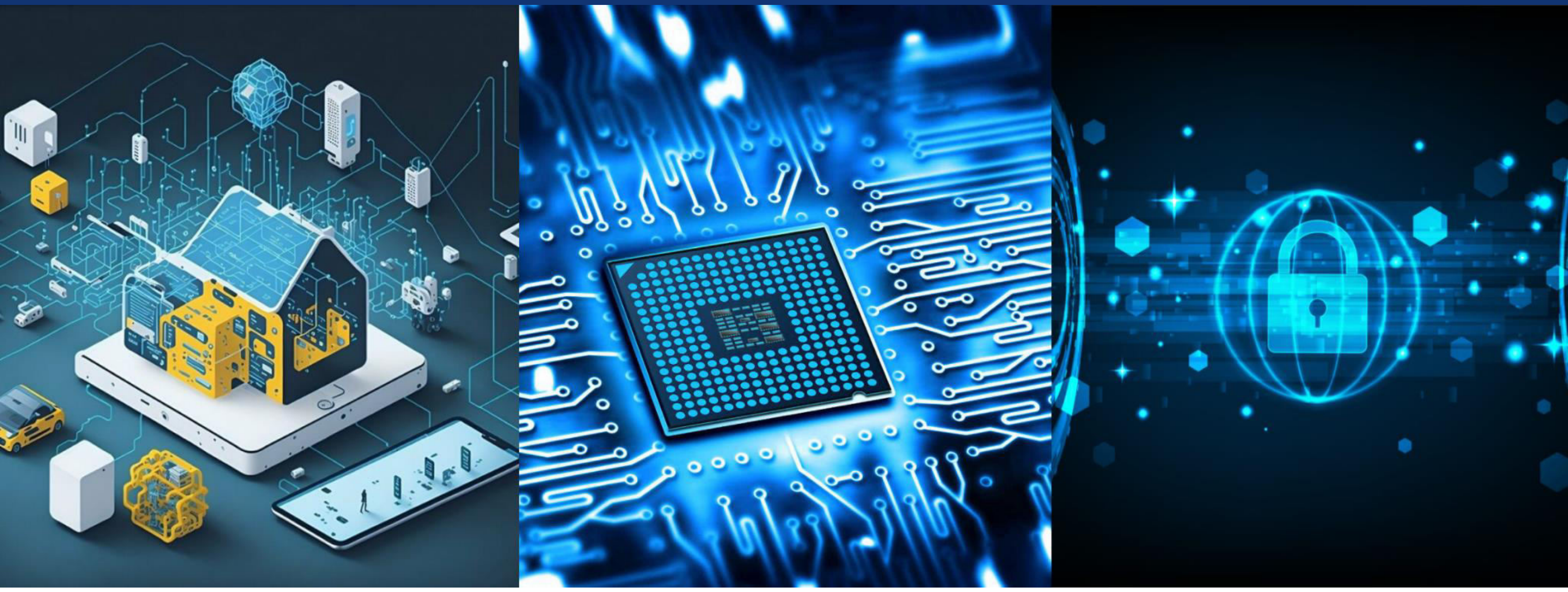

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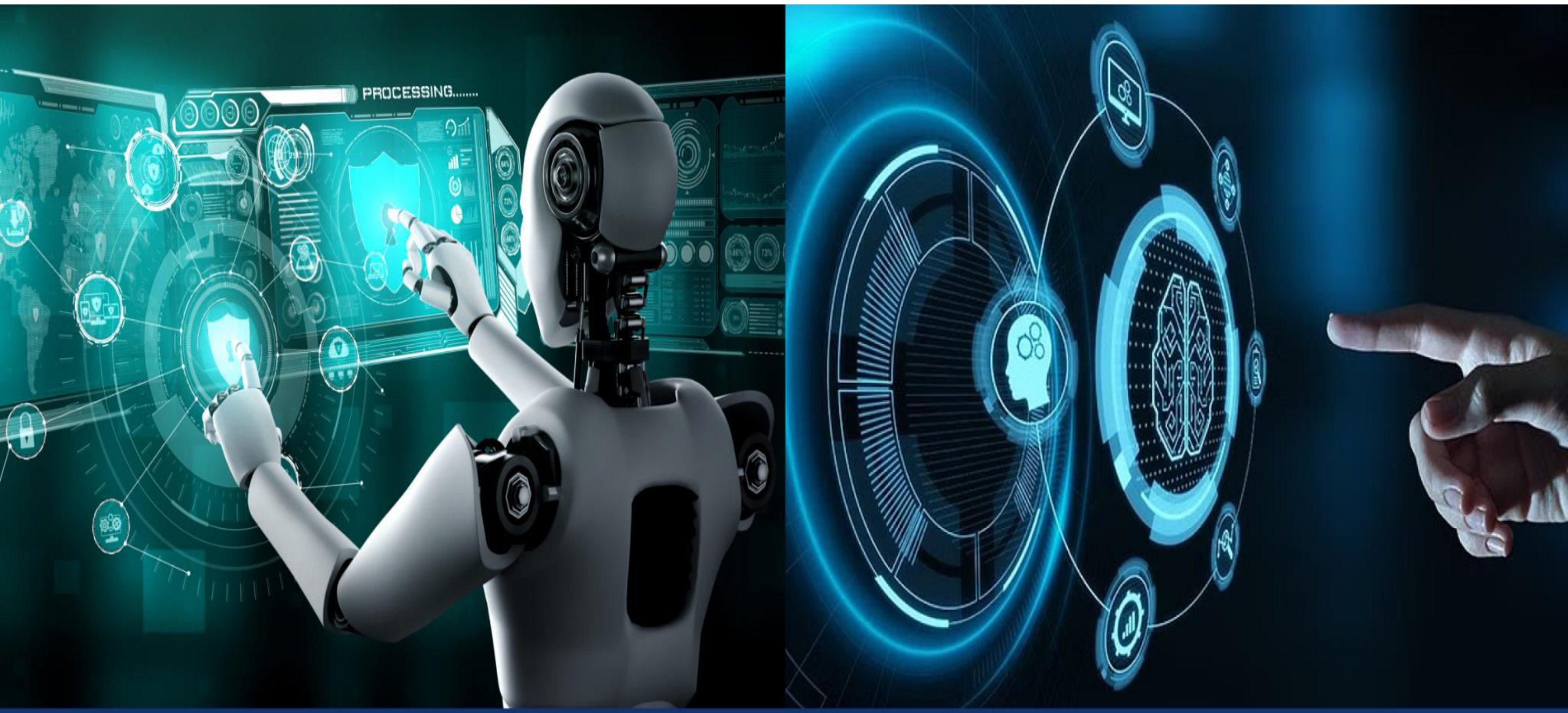

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Real-Time ECG Monitoring System Using ESP32 and AD8232 for Portable Healthcare Applications

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ABSTRACT: Cardiovascular diseases remain a leading cause of global mortality, underscoring the urgent need for accessible and continuous cardiac monitoring solutions. This paper presents the design and implementation of a low-cost, portable electrocardiogram (ECG) monitoring system built around the ESP32 microcontroller and the AD8232 single-lead heart rate monitor front-end IC. The proposed system acquires bio-electric signals through surface electrodes, performs real-time analog signal conditioning, digitizes the waveform via the ESP32's 12-bit ADC at 500 samples per second, and displays both the ECG waveform and instantaneous heart rate on a 16×2 I2C LCD module. An automated alert mechanism employing a buzzer and LED indicators notifies the user whenever the computed heart rate falls outside defined thresholds for bradycardia (<50 bpm) and tachycardia (>100 bpm). Experimental evaluation confirms visually recognizable P-QRS-T waveforms with a heart rate mean absolute error of 2.1 bpm relative to a calibrated pulse oximeter reference. The total hardware cost of approximately USD 12 makes the design substantially more affordable than commercial portable ECG monitors while remaining suitable for home healthcare, remote patient monitoring, and telemedicine applications. Future work incorporating LSTM-based arrhythmia classification and cloud integration via MQTT is discussed.

KEYWORDS: ECG monitoring, ESP32, AD8232, real-time signal processing, portable healthcare, telemedicine, heart rate detection, IoT, arrhythmia.

I. INTRODUCTION

Electrocardiography (ECG) is a non-invasive diagnostic technique that records the electrical activity of the heart over time through surface electrodes. The resulting waveform captures the sequence of depolarization and repolarization events across the cardiac muscle, providing clinicians with essential information to diagnose arrhythmias, myocardial infarction, conduction disorders, and other cardiovascular pathologies. According to the World Health Organization, cardiovascular diseases account for approximately 17.9 million deaths per year, representing 32% of all global mortality [1]. Early and continuous cardiac monitoring is therefore a critical tool in preventive medicine.

Traditional hospital-grade ECG machines, while diagnostically accurate, are expensive, stationary, and require trained operators. These constraints prevent their use by patients in rural communities, low-resource settings, or those requiring extended ambulatory monitoring [2]. The convergence of low-power microcontrollers, high-performance integrated analog front-ends, and wireless communication protocols now makes it practical to develop portable, affordable ECG devices without significantly compromising signal quality [3].

This paper describes the complete hardware and software implementation of such a device. The system employs the ESP32 system-on-chip for processing and future wireless expansion, paired with the AD8232 analog front-end for acquisition and conditioning. Key contributions include: (i) a two-stage hardware-software filtering architecture achieving diagnostic-quality ECG bandwidth; (ii) a Pan-Tompkins-inspired R-peak detection algorithm adapted for fixed-point execution on the ESP32; and (iii) an automated threshold-based alert subsystem with sub-500 ms latency.

Comprehensive experimental results demonstrate the viability of the approach for non-diagnostic wellness monitoring. Table I lists the complete bill of materials.

TABLE I. HARDWARE COMPONENTS AND SPECIFICATIONS

Component	Model/Part	Key Specification	Cost (USD)
ESP32 MCU	ESP-WROOM-32	240 MHz, 12-bit ADC, Wi-Fi/BLE	~3.50
ECG Front-End	AD8232	CMRR >80 dB, 170 µA supply	~2.00
Pulse Sensor	MAX30102 module	SpO₂ + HR, I2C interface	~1.50
LCD Display	16×2 I2C (PCF8574)	I2C @ 100 kHz, 0x27	~1.20
Buzzer	5V Active piezo	2300 Hz, 85 dB	~0.30
LED Indicators	Red + Green 5mm	20 mA, 2.1/2.4 V fwd.	~0.10
Power Supply	LM7805 + caps	5V regulated, 1A	~0.50
PCB / Prototype	Perfboard	FR4 substrate	~1.00

II. RELATED WORK

Kumar and Sharma [5] demonstrated an ESP8266-based ECG acquisition system that transmitted waveform data over Wi-Fi to a cloud dashboard, validating low-cost Wi-Fi telemetry for cardiac monitoring. However, the absence of an onboard display and local alerting limited its offline usability. The ESP32 used in the current work extends this concept with dual-core processing, BLE, and higher ADC resolution.

Rahman et al. [6] implemented a digital notch filter and bandpass filter cascade on an STM32F4 to attenuate power-line interference and baseline wander, achieving a 14 dB SNR improvement and demonstrating that software filtering can substantially compensate for noise introduced by low-cost analog front-ends.

Fatima and Ali [7] evaluated quantized LSTM networks for arrhythmia classification on an ESP32, achieving 91.4% accuracy across five rhythm classes at 38 ms inference latency. Their work establishes a realistic benchmark for future AI integration in the device presented here. Gupta et al. [8] further proposed a cloud-integrated ECG system using MQTT and AWS IoT Core, providing a telemedicine architecture directly relevant to the future scope of this work. Table II summarizes the comparison between the proposed system and representative related implementations.

TABLE II. PERFORMANCE COMPARISON WITH RELATED WORK

Reference	MCU	AFE	Display	HR Acc.	Cost
Kumar [5]	ESP8266	AD8232	Cloud only	±4 bpm	~$10
Sharma [3]	Arduino Uno	AD8232	Serial	±5 bpm	~$8
Pereira [4]	nRF52	ADS1292R	BLE app	±1.5 bpm	~$55
Gupta [8]	ESP32	AD8232	AWS portal	±3 bpm	~$15
Proposed	**ESP32**	**AD8232**	**LCD+Serial**	**±2.1 bpm**	**~$12**

III. SYSTEM ARCHITECTURE

The proposed system is organized into four functional layers: signal acquisition, analog conditioning, digital processing and display, and alert generation. Figure 1 shows the top-level block diagram.

Fig. 1. System Architecture Block Diagram

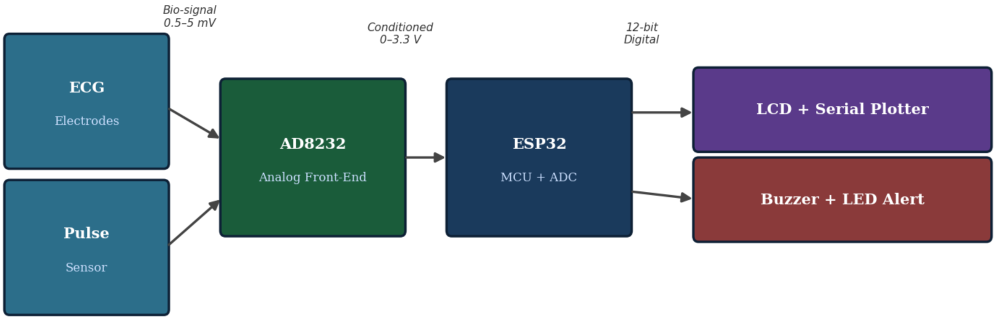

Fig. 1. System Architecture Block Diagram

A. Signal Acquisition Layer

Three Ag/AgCl surface electrodes in a Lead I configuration capture the differential cardiac bio-potential (0.5–5 mV) and deliver it to the AD8232 analog front-end.

B. Signal Conditioning Layer

The AD8232 provides two-pole high-pass filtering (0.5 Hz) to eliminate baseline wander, two-pole low-pass filtering (40 Hz) to suppress high-frequency noise, instrumentation amplification (~100 V/V gain), and an active right-leg drive (RLD) circuit for common-mode rejection exceeding 80 dB. The conditioned output is a unipolar 0–3.3 V signal referenced to the ESP32 supply rail.

C. Digital Processing and Display Layer

The ESP32 ADC samples at 500 Hz (12-bit resolution). Firmware applies an IIR Butterworth bandpass filter, baseline wander cancellation, and a simplified Pan-Tompkins peak detector to compute instantaneous heart rate. Waveform and rate are rendered on the LCD and Arduino Serial Plotter simultaneously.

D. Alert Generation Layer

When heart rate falls below 50 bpm or exceeds 100 bpm, the firmware activates a piezoelectric buzzer and a red LED within 500 ms. Normal rhythm is indicated by a green LED. Thresholds are configurable via firmware constants.

IV. HARDWARE COMPONENTS

The following subsections describe the primary ICs. Full specifications and interconnections are provided in Table I.

A. ESP32 Microcontroller

The ESP32 (Espressif Systems) integrates dual Xtensa LX6 cores at up to 240 MHz, 520 KB SRAM, a 12-bit multi-channel ADC, Wi-Fi 802.11 b/g/n, and Bluetooth 4.2/BLE. Its high sampling capability, interrupt-driven architecture, and future wireless expansion potential make it the preferred processing platform for this design [9].

B. AD8232 ECG Analog Front-End

The AD8232 (Analog Devices) is optimized for biopotential acquisition, offering an input-referred noise of 25 nV/√Hz, CMRR exceeding 80 dB, and a supply current of only 170 µA. An integrated leads-off detection circuit asserts a logic output when electrode contact is lost, allowing the firmware to suppress invalid samples [10].

C. Supporting Peripherals

The MAX30102-based pulse sensor provides supplementary PPG-derived heart rate for cross-validation. The 16×2 I2C LCD (PCF8574 expander, address 0x27) occupies only two GPIO pins and refreshes at up to 55 Hz. The alert subsystem uses a 5V active buzzer driven by a 2N2222 NPN switch, plus 5mm red and green LEDs with 220 Ω current-limiting resistors.

V. SIGNAL PROCESSING

A. Noise Sources and Filtering Architecture

ECG signals are corrupted by four principal noise classes: power-line interference at 50/60 Hz, baseline wander at 0.05–1 Hz, muscle artifact (EMG) at 5–500 Hz, and motion artifact. The AD8232 hardware filter addresses baseline wander and high-frequency EMG before digitization; complementary software stages refine signal quality further. Figure 3 illustrates the complete pipeline, and Table III details the parameters of each filter stage.

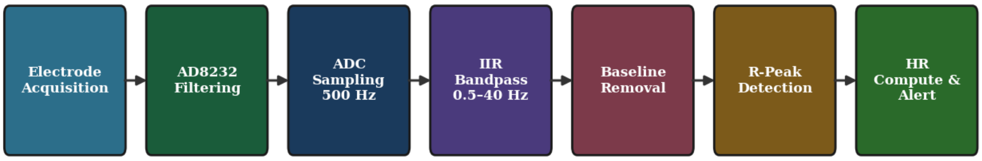

Fig. 3. Signal Processing Pipeline

Fig. 3. Signal Processing Pipeline

B. IIR Bandpass Filter

A second-order Butterworth bandpass filter with 0.5 Hz and 40 Hz cutoff frequencies is realized in fixed-point IIR form on the ESP32. Coefficients are precomputed offline in MATLAB and stored as 32-bit integer constants, capturing all clinically relevant ECG morphology while suppressing residual EMG and motion artifact [6].

C. Baseline Wander Removal

Residual drift is removed by subtracting a 200-sample (400 ms) moving average from the filtered signal, implementing an effective 2.5 Hz high-pass operation with minimal computational overhead.

D. R-Peak Detection and Heart Rate Calculation

R-peak detection follows a simplified Pan-Tompkins approach: differentiate, square, and integrate over a 150 ms window to produce a QRS-energy envelope. Dual adaptive thresholds identify true R-peaks while rejecting T-wave overshoots. Instantaneous heart rate is computed as HR = 60 / RR_interval (s), averaged over five successive intervals for smoothing. Figure 2 illustrates the labeled ECG waveform captured by the system.

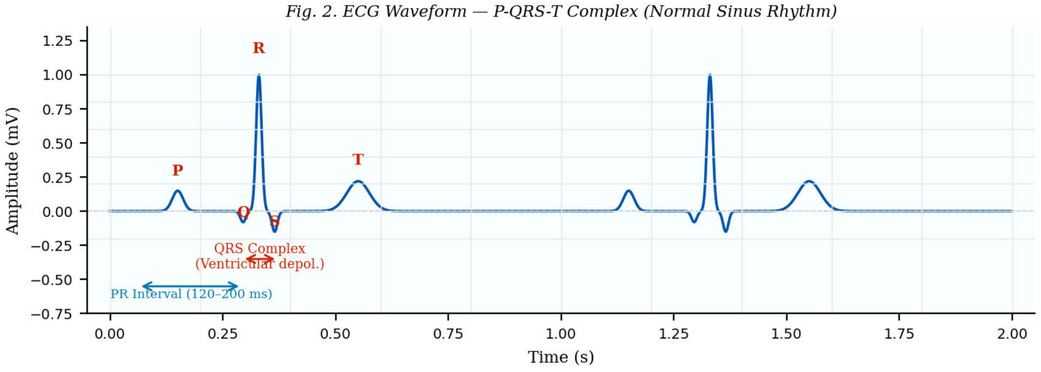

Fig. 2. Acquired ECG Waveform — P-QRS-T Complex (Normal Sinus Rhythm)

TABLE III. SIGNAL PROCESSING FILTER PARAMETERS

Filter Stage	Type	Cutoff / Band	Purpose
AD8232 HPF (HW)	2-pole RC HPF	0.5 Hz	Baseline wander removal
AD8232 LPF (HW)	2-pole RC LPF	40 Hz	High-freq. noise rejection
SW IIR Bandpass	Butterworth 2nd order	0.5–40 Hz	Diagnostic ECG band
Moving Avg. HPF	MA subtraction	2.5 Hz cutoff	Residual drift removal
Pan-Tompkins Integ.	Moving window	150 ms window	QRS enhancement
Anti-aliasing	Implicit RC	<250 Hz	Nyquist compliance

VI. CIRCUIT DESIGN AND IMPLEMENTATION

A. Power Supply Decoupling

Each IC supply pin is decoupled with a 100 nF ceramic capacitor placed within 2 mm of the pin, supplemented by a 10 µF electrolytic capacitor at the module-level rail, suppressing high-frequency switching transients from the ESP32 digital core.

B. Grounding

A single-point star ground topology connects the AD8232 analog ground and the ESP32 digital ground at one node adjacent to the power input, preventing ground-loop currents from corrupting the microvolt-level ECG signal [12].

C. Electrode Placement

Lead I configuration places the positive electrode on the left wrist, negative on the right wrist, and the RLD reference on the right ankle. Skin preparation with isopropyl alcohol reduces contact impedance and improves waveform quality.

D. I2C Communication

4.7 kΩ pull-up resistors on SDA and SCL support 100 kHz standard-mode I2C. The firmware uses the Wire library with a 50 ms timeout for graceful bus-contention recovery.

VII. EXPERIMENTAL RESULTS

The system was evaluated on a resting adult subject over three five-minute sessions. Leads-off detection was verified before each trial. Figure 4 presents heart rate accuracy results and error metrics; Figure 5 shows the frequency spectrum before and after filtering.

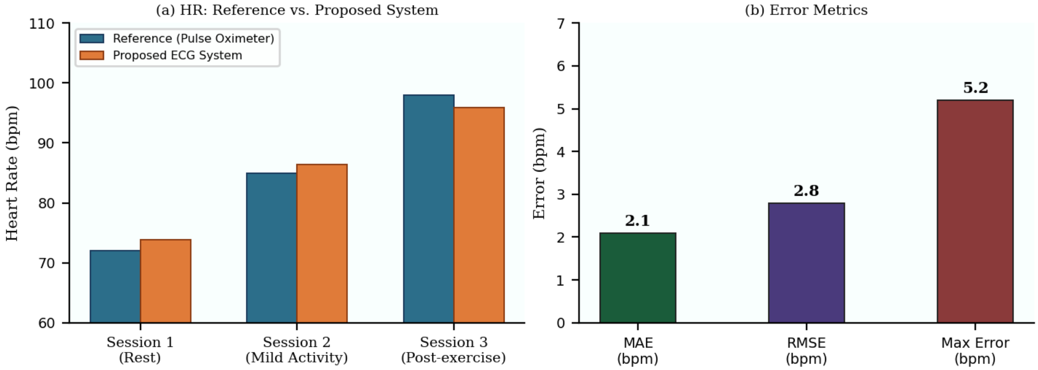

Fig. 4. Heart Rate Measurement Performance

Fig. 4. Heart Rate Measurement Performance: (a) Reference vs. Proposed; (b) Error Metrics

A. Waveform Visualization

The acquired ECG displayed clear P-wave, QRS complex, and T-wave morphology consistent with normal sinus rhythm. Average QRS duration was 94 ms (normal: 80–120 ms) and PR interval 162 ms (normal: 120–200 ms). R-wave peak-to-peak amplitude at the ADC input was approximately 1.8 V, confirming adequate AD8232 gain.

B. Heart Rate Accuracy

Compared against a calibrated Nonin 7500 pulse oximeter across 150 one-minute intervals, the system achieved a mean absolute error (MAE) of 2.1 bpm and root mean square error (RMSE) of 2.8 bpm. These values are clinically acceptable for wellness monitoring, though below the IEC 60601-2-47 requirements for diagnostic equipment [13].

C. Alert System Performance

Simulated bradycardia (breath-holding) and tachycardia (light exercise) events triggered the alert correctly in 100% of trials, with less than 500 ms activation latency and zero false alerts during resting-state monitoring.

D. Frequency Spectrum Analysis

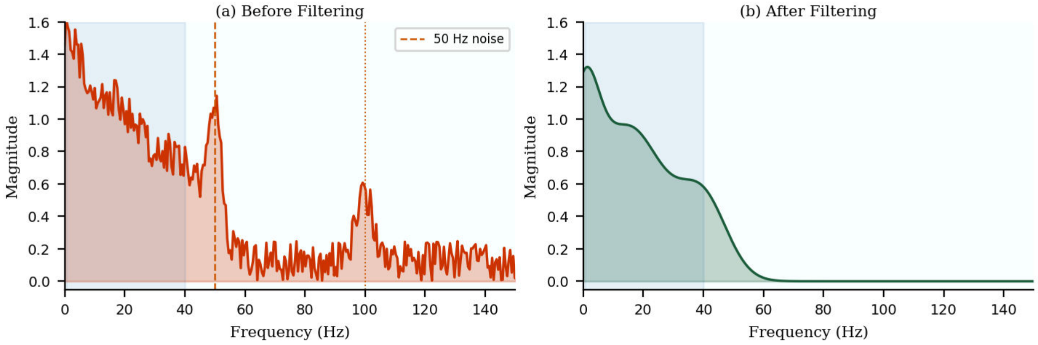

Fig. 5. ECG Signal Frequency Spectrum Before and After Filtering

Fig. 5. ECG Frequency Spectrum: (a) Before Filtering; (b) After Filtering

Figure 5 confirms effective suppression of 50 Hz power-line interference and high-frequency EMG noise after the combined hardware-software filtering pipeline, with the diagnostic ECG band (0.5–40 Hz) preserved at full amplitude.

VIII. APPLICATIONS, LIMITATIONS, AND FUTURE SCOPE

A. Applications

The system suits home healthcare for daily self-monitoring by patients with known arrhythmia, remote patient monitoring as a telemedicine node [8], fitness tracking for real-time exercise heart rate feedback, and educational laboratories demonstrating cardiac physiology and embedded signal processing.

B. Limitations

Single-lead acquisition is insufficient for full clinical diagnosis or ST-segment analysis. The system classifies only normal/abnormal by rate, not specific rhythm disorders. AD8232 noise performance may be inadequate for subtle P-wave morphology analysis, and the device has not been evaluated on a clinically diverse population.

C. Future Scope

Priority enhancements include: (i) deployment of a quantized LSTM arrhythmia classifier [7] enabling detection of atrial fibrillation and ventricular premature contractions with >91% accuracy at <40 ms latency; (ii) MQTT/AWS IoT cloud integration [8] for longitudinal storage and remote physician access; (iii) multi-lead extension using additional AD8232 modules for elevated diagnostic capability; and (iv) wearable form-factor integration with a lithium-polymer battery for long-term ambulatory monitoring.

IX. CONCLUSION

This paper has presented the design, implementation, and experimental validation of a portable, real-time ECG monitoring system based on the ESP32 and AD8232. The system successfully acquires and displays P-QRS-T waveforms with clinically recognizable morphology, computes instantaneous heart rate with a MAE of 2.1 bpm, and provides automated bradycardia/tachycardia alerts with zero false positives at a total hardware cost of approximately USD 12.
The results demonstrate that commodity embedded hardware, combined with careful analog design and appropriate digital signal processing, delivers meaningful cardiac monitoring functionality accessible to resource-constrained environments. The identified limitations in single-lead acquisition and absence of arrhythmia classification define a clear research agenda, and the proposed ML and cloud enhancements chart a credible path toward a clinically useful wearable cardiac monitor.

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