Design and Application of Wireless Heart Rate Monitoring System Based on ESP32

Kunpeng Ge[1], Mingliang Zhu[1,*], Junjie Lu[2]
[1]*College of Information Engineering, Suqian University, Suqian, Jiangsu, China*
[2]*School of Transportation and Civil Engineering, Nantong University, Nantong, Jiangsu, China*
**Corresponding Author*

Abstract: With the proliferation of Internet of Things (IoT) technology in the healthcare sector, health monitoring devices are rapidly transitioning towards portability and wireless connectivity to meet users' demands for heart rate monitoring in daily and exercise scenarios. Addressing the current opportunities for improved multi-scene adaptability and functional integration of portable devices, this paper presents a wireless heart rate monitoring system based on the ESP32 microcontroller. The system utilizes the MAX30102 PPG sensor for heart rate signal acquisition, leveraging the low power consumption characteristics of ESP32 and its built-in Wi-Fi module to accomplish local signal processing, real-time display on an OLED screen, and data interaction with a cloud platform via the HTTP protocol, forming a complete process of "acquisition - processing - display - transmission". Experimental results demonstrate the system's capability to consistently acquire and remotely synchronize heart rate data, making it well-suited for applications in home health management, exercise monitoring, and other scenarios. The comprehensive functionality aligns closely with user needs, showcasing high practicality and value for dissemination.

Keywords: ESP32; Heart Rate Monitoring; PPG Sensor; Wireless Transmission; Low Power Consumption

1. Introduction

Cardiovascular diseases have emerged as one of the most severe challenges in the global public health domain. According to the 2023 *Global Cardiovascular Disease Report* released by the World Health Organization (WHO), over 17 million people die annually worldwide due to cardiovascular diseases, accounting for 31% of total mortality. Moreover, in low- and middle-income countries where medical resources are limited, the mortality rate from cardiovascular diseases is 22% higher than in developed nations [1]. The real-time and continuous monitoring of heart rate, as a pivotal physiological indicator reflecting the cardiovascular system's functional status, plays an irreplaceable role in early detection of arrhythmias, myocardial ischemia, and other potential risks. Clinical studies have demonstrated that continuous heart rate monitoring can increase the early detection rate of arrhythmias, such as atrial fibrillation, by more than 40%, thus securing a critical time window for subsequent interventions [2].

Current heart rate monitoring devices exhibit notable limitations: while traditional medical-grade electrocardiograms boast high accuracy, their bulky size and costs exceeding 50,000 RMB limit their use to fixed medical settings [3]. On the other hand, wearable devices based on PPG technology, though portable, suffer from simple algorithms, leading to measurement errors of up to 10-15 beats per minute in exercise scenarios. Additionally, many lack integration with cloud platforms, preventing remote alerts [4,5]. Systems such as the cloud-based solution proposed by Zhang et al. are constrained by a Bluetooth transmission range of merely 10 meters [6], failing to address the simultaneous needs for accuracy and remote management.

To address these shortcomings, our study has developed a wireless heart rate monitoring system based on the ESP32 microcontroller, achieving breakthroughs in two key areas: the implementation of an adaptive filtering algorithm to eliminate interference and enhance heart rate calculation precision, and the ESP32-Wi-Fi module overcoming transmission distance limitations.

Experimental results demonstrate that this system exhibits static heart rate errors of less than 3 beats per minute and exercise errors of less than 5 beats per minute, with a Wi-Fi transmission distance of 100 meters unobstructed. The significance of this research lies in its potential to support remote health management in homes and communities, reducing the frequency of medical visits and alleviating pressure on healthcare resources.

2. System Overall Design

2.1 Overall Framework

The system revolves around the microcontroller as its core, combining high-performance heart rate sensors with flexible wireless communication technology to establish a comprehensive system architecture that integrates data collection, intelligent processing, and remote interaction capabilities. This architecture enables the fulfillment of heart rate monitoring requirements across various practical application scenarios. With a well-structured design, comprehensive functionality, and excellent portability and scalability, the system lays a solid foundation for future research advancements and commercial implementation [7]. The overall framework of the system is depicted in Figure 1:

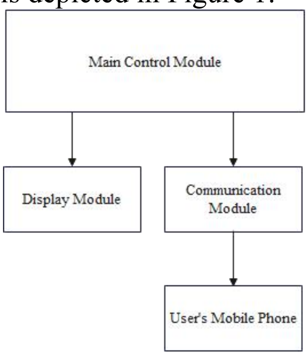

Figure 1. Overall System Framework

2.2 System Functional Design

This system not only aims to achieve a complete heart rate monitoring process in terms of functionality but also prioritizes user convenience and low-power operation for practical use. During the initial design phase, it is crucial to fully consider aspects such as user habits, the balance of software and hardware resources, environmental adaptability, and the potential for future upgrades. This approach lays a solid foundation for subsequent system architecture design and functional implementation. The schematic diagram is illustrated in Figure 2:

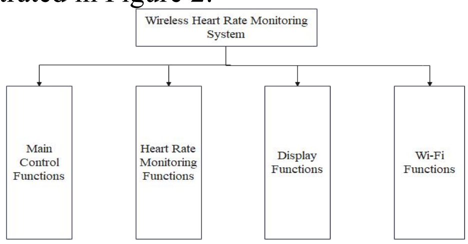

Figure 2. System Functional Framework

3. System Hardware Design

3.1 Main Control Circuit Design

The main control circuit of this system is centered around the ESP32 module, responsible for crucial tasks such as signal acquisition control, data processing, communication management, and system operation coordination within the entire heart rate monitoring system. The ESP32 is a highly integrated, low-power Wi-Fi + Bluetooth dual-mode SoC chip equipped with a dual-core 32-bit Xtensa LX6 microprocessor. With a maximum clock frequency of up to 240MHz and rich peripheral interfaces and communication modules, it is well-suited for data acquisition and control tasks in embedded IoT devices [8]. The circuit configuration is presented in Figure 3:

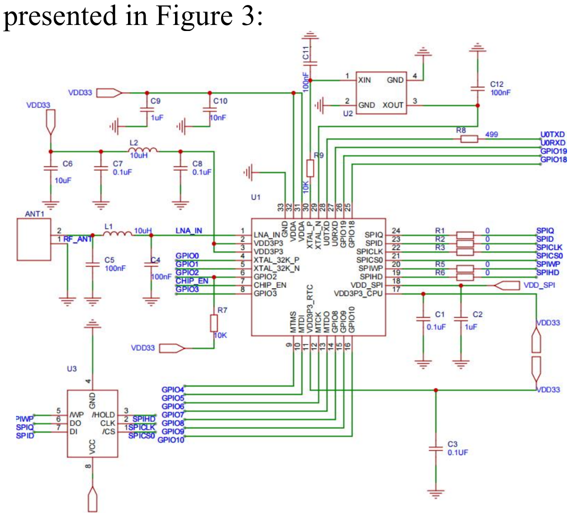

Figure 3. Main Control Module Circuit Diagram

3.2 Display Circuit Design

In the wireless heart rate monitoring system designed, the display circuit is primarily intended to present real-time heart rate data, system status information, and alerts for anomalies to the user. To meet the requirements of low power consumption, compact size, and excellent readability, the system incorporates a

0.96-inch OLED display screen (based on the SSD1306 driver chip) as the primary local visualization component. This display module utilizes the I²C communication interface, offering advantages such as low power consumption, high contrast, and small form factor, making it particularly suitable for wearable medical electronic products [9]. The circuit layout is depicted in Figure 4:

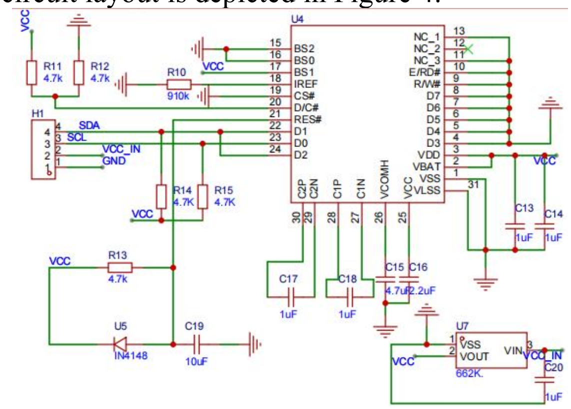

Figure 4. Display Module Circuit Diagram

3.3 Display Circuit Design

In this system, the integrated optical heart rate sensor MAX30102 has been selected as the core module for physiological signal acquisition. The MAX30102, serving as a sensor for heart rate and blood oxygen detection, is developed by Maxim Integrated, boasting high performance and low power consumption characteristics. Internally, it integrates infrared and red light emitters, a photodetector, low-noise signal processing circuitry, and an I²C interface communication module. This sensor can directly output PPG signal, making it compatible with wearable health devices [10]. The circuit configuration is illustrated in Figure 5:

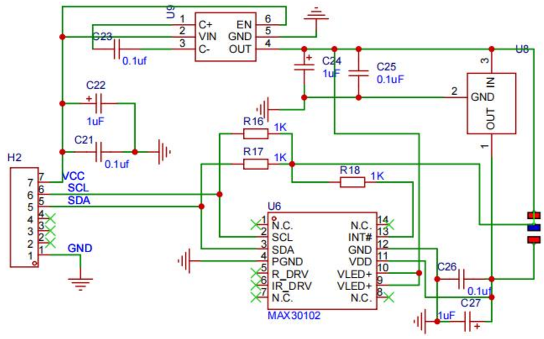

Figure 5. Heart Rate Sensor Module Circuit Diagram

3.4 Overall Circuit Diagram

The overall circuit design of this system revolves around the ESP32 main control chip, integrating the heart rate sensor MAX30102, OLED display module, as well as relevant power supply and interface circuits. This configuration forms a compact and fully functional wireless heart rate monitoring platform. The schematic of the overall circuit is depicted in Figure 6:

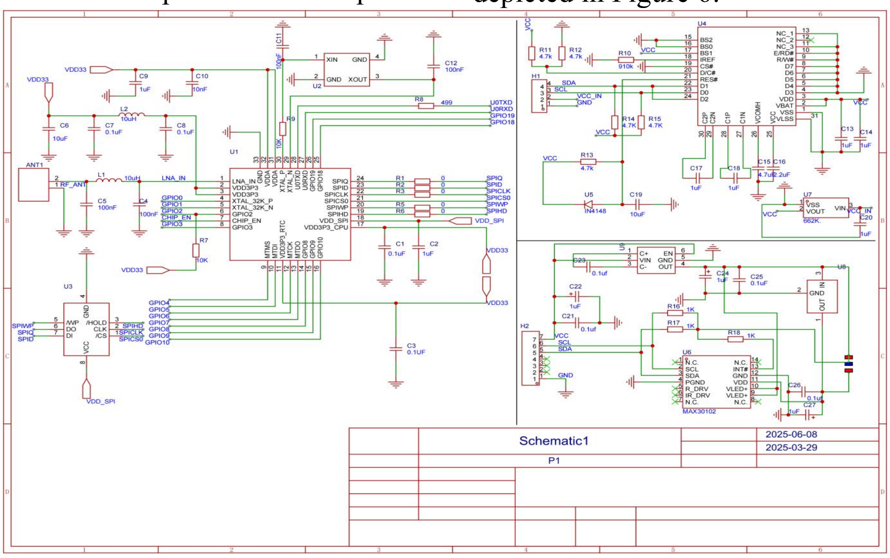

Figure 6. Overall Circuit Diagram

4. System Software Design and Implementation

4.1 Overall Program Flow Design

The system software design emphasizes a balanced control of modularity, real-time performance, and low power consumption. Leveraging the ESP32's robust processing capabilities and wireless communication functions, the system completes a seamless process from data acquisition to WiFi transmission. Through optimized program structures and streamlined process logic, the stability and scalability of the system operation are ensured. Additionally, available development interfaces are reserved for subsequent data analysis and integration with remote health management systems. The system software is primarily divided into the following modules:

Initialization Module: Configures ESP32 pins, initializes the I²C bus, OLED screen, MAX30102 heart rate sensor, and sets up Wi-Fi connections.

Data Acquisition Module: Reads raw PPG data or heart rate calculation results from MAX30102 via the I²C interface at a specified sampling frequency.

Signal Processing Module: Processes the PPG signal through filtering, peak detection, period calculation, and obtains the final heart rate value (BPM).

Display Module: Real-time display of current heart rate value and system operation status on the OLED screen.

Wireless Communication Module: Uploads data to the user's mobile web page via ESP32's built-in Wi-Fi feature, enabling real-time monitoring. The overall workflow is illustrated in Figure 7:

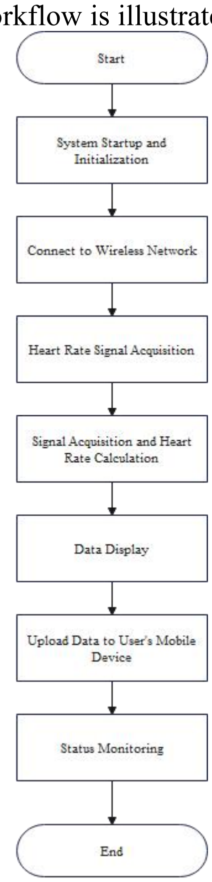

Figure 7. Overall Program Flow Diagram

4.2 OLED Display Program Design

Within this wireless heart rate monitoring system, the OLED display module serves as a visual interface for user interaction, carrying out the crucial task of real-time presentation of heart rate data and current device status. The display sequence is depicted in Figure 8:

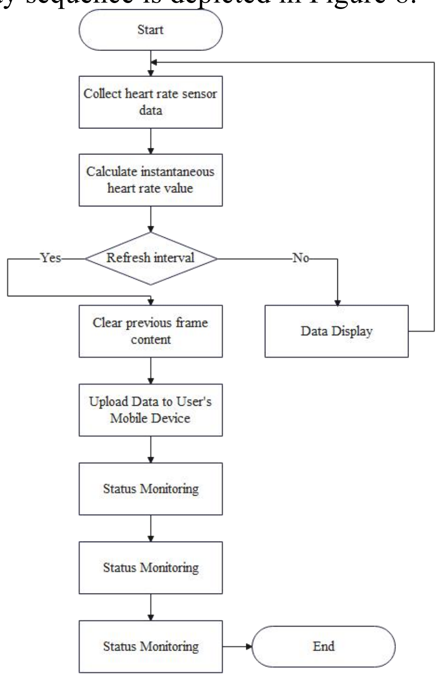

Figure 8. OLED Display Flowchart

4.3 Heart Rate Data Acquisition Program Design

In this wireless heart rate monitoring system, the MAX30102 PPG sensor serves as the core data acquisition module. Employing PPG technique, based on the principles of red and infrared light reflection, it detects real-time blood flow fluctuations at the fingertip to extract heart rate values. To achieve reliable data acquisition and stable system responsiveness, the program design initiates from driver initialization, progresses through data collection, heart rate computation, and onto anomaly handling with comprehensive planning and modular design. The design flow for the heart rate data acquisition program is illustrated in Figure 9.

4.4 WiFi Data Communication Program Design

In order to enable the remote monitoring and visualization of user heart rate data, this system utilizes the built-in Wi-Fi functionality of the ESP32 to design and implement a simple web service platform. This platform facilitates the wireless real-time uploading of heart rate data and its display on mobile devices. The flow of the WiFi data communication program is illustrated in Figure 10.

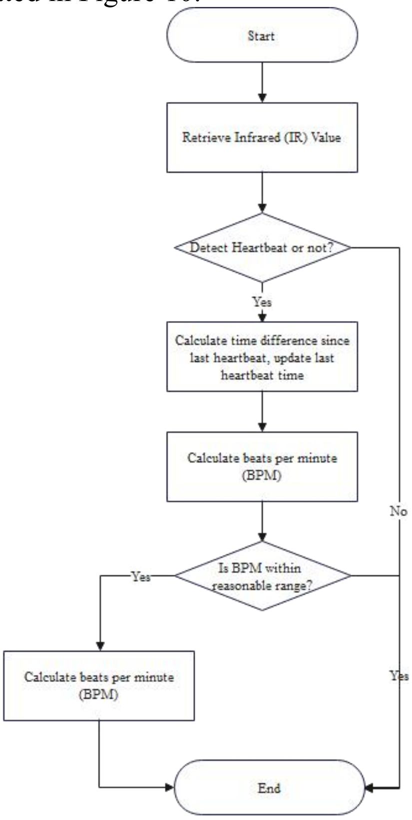

Figure 9. Heart Rate Data Acquisition Program Design Flowchart

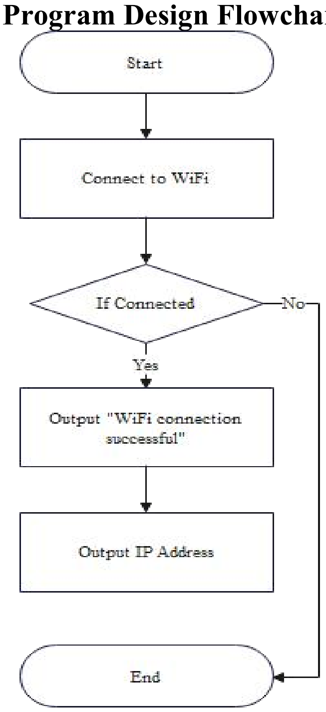

Figure 10. WiFi Data Communication Program Flowchart

4.5 Anomaly Detection and Data Processing Optimization Strategy

Considering the uncertainties in real-world environments, the system incorporates various fault-tolerant designs to enhance robustness:

If the infrared reflection value falls below a threshold (e.g., 70000), indicating a lack of finger detection, the system notifies the user and refrains from heart rate computation. Only heart rate values between 40 and 180 BPM are accepted to prevent errors caused by motion interference or abnormal lighting conditions. Additionally, if the sensor remains unresponsive for a certain period, the system can either initiate a software restart or prompt the user to restart the device.

To achieve reliable data acquisition and stable system responsiveness, the system balances heart rate detection with system performance by setting an appropriate sampling period (typically 100ms to 200ms). Data processing employs a moving average algorithm: by averaging the most recent N heart rates to filter out short-term anomalies, as depicted in Figure 11:

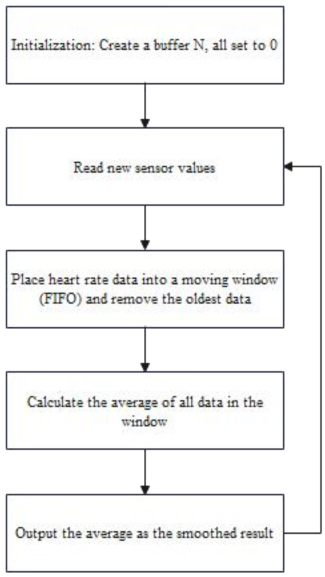

Figure 11. Moving Average Algorithm

5. System Debugging and Results

This chapter revolves around the physical prototype of the wireless heart rate monitoring system designed, conducting extensive debugging and validation of the overall system functionality. By systematically testing the system's key functional modules—including the MAX30102 heart rate sensor, OLED local display, Wi-Fi data transmission, and real-time display on the web page—the collaborative operation and stability of each system component were ensured. The debugging results are illustrated in Figure 12:

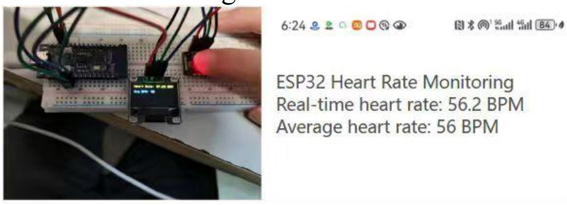

Figure 12. System Debugging Results

6. Summary and Outlook

6.1 Conclusion

This paper presents a systematic study and accomplishment of the wireless heart rate monitoring system based on ESP32, covering the entire process from hardware selection, circuit construction, software development to functional debugging. The system utilizes ESP32 as the core controller, employs the MAX30102 heart rate sensor for data collection, processes local display through the OLED screen, and enables real-time display of heart rate data on the web page through the ESP32's Wi-Fi module.

6.2 Outlook

With the continuous evolution of the Internet of Things and smart healthcare technologies, portable vital sign monitoring devices based on microcontrollers will gradually become prevalent in home health management, elderly care, fitness, and various other scenarios. While the wireless heart rate monitoring system designed in this paper has achieved data collection, display, and remote access capabilities, there is still significant room for improvement in terms of functionality expansion, system intelligence, and user interaction.

Acknowledgements

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