Analysis of the Design of Wearable Wireless Biosensors

Zhenxiao Liu *

Department of Photonic and Electronic Engineering, Fujian Normal University, Fujian, China

* Corresponding author: 136132021096@student.fjnu.edu.cn

Abstract. With the increasing health awareness and diversification of lifestyle, wearable biosensor systems have gradually become an effective tool for monitoring individual physiological parameters. This study introduces an innovative design to address this need, which aims to monitor important physiological indicators such as heart rate, body temperature and exercise status. The system integrates a heart rate sensor (MAX30101), a body temperature sensor (DS18B20), an acceleration sensor (MPU6050), a microcontroller (ESP32) and a Bluetooth low energy module (HC-06), and is powered by a rechargeable lithium battery (18650 battery). This study adopted a system design and hardware development approach, focusing on sensor performance optimization, power consumption control. The hardware connection method of the system is described in detail, and the experimental verification is carried out. Based on the experiments, a wearable biosensor system that can accurately monitor the user's heart rate, body temperature and motion state has been successfully designed. The low-power design of the system ensures prolonged wear with potential medical, sports health and quality of life monitoring applications. These results provide a powerful tool for individualized health management, providing users with real-time knowledge of their physiological state, offering a useful reference and enlightenment for the development and application of wearable biosensor technology.

Keywords: Wireless, wearable, biosensors.

1. Introduction

With the continuous development of science and technology, wearable technology has become one of the most promising and potential research fields. As an emerging technology, wearable wireless biosensors provide a convenient and seamless way for people to connect the human body with the digital world. The development of wearable wireless biosensors dates back to the early 20th century, when researchers in the medical field began to explore how to monitor human physiological parameters using sensors. The earliest biosensors use wired connection, which is limited by the transmission distance and the ease of use. However, with the development of wireless communication technology, wearable wireless biosensors are beginning to emerge.

According to Shyr et al. in 2014 [1], they designed a wearable gesture sensing device consisting of textile strain sensors, using elastic conductive webbing, for monitoring the flexion angle of elbow and knee movements. This study marks the application of textile materials in wearable wireless biosensors. In the late 1980s to early 1990s, the emergence of Bluetooth technology provided a great impetus for the development of wireless sensors. Due to the low power consumption and high data transmission rate of Bluetooth technology, wearable wireless biosensors can realize real-time monitoring and data transmission [2]. Bluetooth technology breaks through the wired limitation of sensors and realizes wireless monitoring and remote data transmission. In order to improve the functionality and diversity of sensors, researchers have begun to explore the integration of different types of sensors in a single device for more comprehensive monitoring and analysis. According to Pablo et al. [3], They developed a wearable sensor system for monitoring upper limb physical activity and remote posture assessment in stroke patients. The system integrates sensors such as accelerometers and gyroscopes to achieve comprehensive monitoring of patient behavior. To enhance the user experience of wearable wireless biosensors, researchers have focused on improving the comfort and wearability of the sensors. According to the study by Gao et al. [4], they introduced the application of flexible and wearable electrochemical sensors in health monitoring. This study highlights the importance of the softness and wearability of the sensor material and how the comfort of the sensor can be improved through structural design and material selection.

The historical process of wearable wireless biosensors has experienced the development process from wired to wireless, single sensor to multi-sensor integration, and data analysis to comfort improvement. As can be seen from the last five years of research, the research on wearable wireless biosensors has made remarkable progress. In a study published in 2022 by Wang et al., they proposed a nanotech based wearable biosensor to monitor nutrients and metabolites in sweat produced during daily life. Through the nature of graphene that can be regenerated repeatedly and the technology of iontotherapy, researchers have successfully achieved highly sensitive detection of the intake and level of a variety of amino acids [5]. This study illustrates that metabolic analysis with wearable sensors is becoming increasingly important in precision nutrition and precision medicine, especially in the COVID-19 pandemic era, which not only provides an assessment of COVID-19 severity but also monitors metabolism to minimize the risk of potential COVID-19 infection. Another study published in 2021 by Chen et al. explored a cardiovascular health monitoring system based on wearable wireless biosensors. The system can monitor physiological parameters such as heart rate, blood pressure, blood glucose and blood oxygen saturation in real time, and transmit the data to the cloud for analysis through wireless communication [6]. The researchers verified the accuracy and feasibility of the system through clinical trials, which provides a new tool for the prevention and management of cardiovascular diseases. In addition to the above studies, there are some other studies that have explored and applied wearable wireless biosensors. For example, in the study published by Zhou et al. in 2017, they developed a wearable biosensor based on nanofiber technology for monitoring skin temperature and humidity [7]. The sensor is highly sensitive and highly durable, which provides a new means for the field of electronic skin such as human health monitoring and biomedical prostheses. Wearable wireless biosensors have made remarkable research progress in the field of biomedical engineering in the past five years. Wearable device functionalities have increasingly been enhanced with more varied forms and more precise physiological indications as sensor and operating system hardware technology has advanced. These sensors are advancing toward high accuracy, consistency, and comfort, greatly enhancing individualized healthcare [8].

This study focuses on designing a wearable sensor that integrates heart rate, body temperature, and motion monitoring using the ESP32 core along with the max30101, DS18B20, and mpu6050 chips. These components enable accurate collection and analysis of biological parameters. The review details the sensor's design principle, structure, and potential medical applications. The key component is the heart rate sensor based on the max30101 chip, employing infrared and visible light reflection to measure heart rate and blood oxygen levels precisely. The DS18B20 temperature sensor measures body temperature accurately, while the mpu6050 acceleration sensor tracks motion and posture. The ESP32 microcontroller acts as the control center, processing sensor data and facilitating Bluetooth communication with low power consumption. The paper also addresses battery management to ensure a stable power supply and extend sensor lifespan. Through data processing and Bluetooth Low Energy communication (hc-06), users can monitor heart rate, body temperature, and exercise status in real time on mobile devices. This technology also enables remote health monitoring by doctors and supports personal health management. The sensor finds applications in exercise tracking [1], health monitoring [6], and remote medical supervision [3].

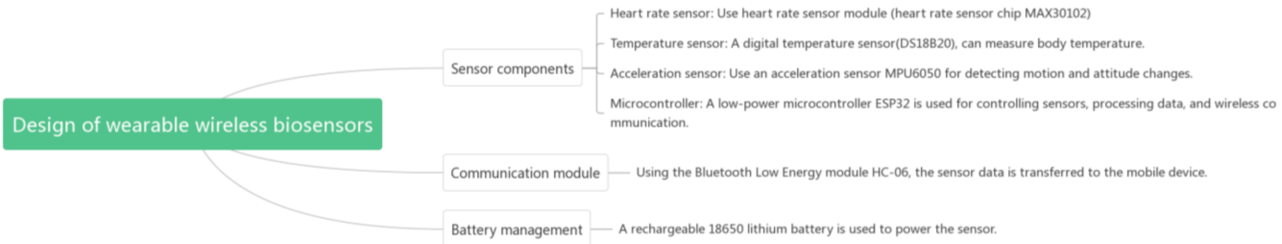

Figure 1. Basic system composition

2. Principle

The system structure of this study is shown in Fig. 1. In the system, four sensor components play a key role, which determine the core functions of the proposed wireless biosensor: measuring heart rate and oxygen saturation, measuring body temperature, and detecting movement and posture changes.

2.1. Max30101

The Max30101 chip is a heart rate sensor based on optical principles to measure heart rate and monitor heart function. The chip calculates the heart rate through the absorption characteristics of infrared and visible light, and uses a photodiode as the receiver of light. The Max30101 chip contains an infrared LED emitter and a visible LED emitter. These two emitters emit light, which is projected through the skin into the blood. The Max30101 chip contains two photodiode receivers for receiving reflected signals from infrared and visible light, respectively. As light travels through the skin and reaches the blood stream, a photodiode receiver converts the light into an electrical signal. During cardiac contraction, the concentration of hemoglobin in the blood will increase, resulting in enhanced absorption of infrared light and reduced absorption of visible light. However, during cardiac diastole, the hemoglobin concentration decreases, resulting in a weakened absorption of infrared light and an enhanced absorption of visible light. By measuring the absorption change of infrared and visible light, the Max30101 chip can obtain the amplitude and change rate of the optical signal. By analyzing these signals, combined with computational algorithms, accurate heart rate data can be obtained. The main theoretical foundations of Max30101 are given as follows:

- Light absorption characteristics: hemoglobin has a high absorption coefficient in the specific wavelength range of infrared and visible light [9]. This means that when light passes through the skin and into the blood, hemoglobin absorbs the energy of light.
- Light scattering characteristics of blood: When light enters the blood, it will not only be absorbed by hemoglobin, but also be affected by light scattering of blood [10]. This light scattering makes the light signal collected by the sensor contain a lot of noise from the skin and tissue.
- Pseudo-differential measurement: Max30101 chip can reduce the influence of light scattering and improve the accuracy of heart rate measurement by differential measurement of infrared light and visible light.
- Signal processing and filtering: Heart rate signals often contain noise due to motion, environmental interference and other factors. To improve signal quality and accuracy, signal processing techniques and filtering algorithms are needed to reduce these interferences.

2.2. DS18B20

The DS18B20 chip is a body temperature sensor based on the principle of semiconductor temperature sensor. The DS18B20 chip measures body temperature based on the thermal resistance properties of semiconductors. The chip contains a temperature sensor inside, and when the temperature changes, the resistance value of the sensor will also change. To convert resistance values into readable temperature values, the DS18B20 chip has a built-in analog-to-digital converter. The converter converts the sensor resistance value into a digital signal, and obtains the corresponding temperature value by calculation. The main theoretical foundations of DS18B20 are as follows:

- The relationship between temperature and resistance of semiconductor materials: there is a correlation between resistance and temperature of semiconductor materials. With the increase of temperature, the free electrons in the semiconductor material increase, so that the resistance value increases. Therefore, according to the temperature resistance relationship of the semiconductor material, the change of the resistance value can be used to measure the temperature.
- The principle of analog to digital conversion: analog to digital conversion is the process of converting discontinuous analog signals into continuous digital signals. Inside the DS18B20 chip, an

analog to digital converter converts the sensor resistance value to the corresponding digital temperature value.

2.3. MPU6050

MPU6050 chip is an acceleration sensor integrated with a three-axis accelerometer and a three-axis gyroscope [11]. The three-axis accelerometer in the MPU6050 chip can be used to measure the acceleration of the object in three coordinate axis directions (X, Y, Z). Accelerometers are based on microelectromechanical systems (MEMS) technology and measure acceleration by detecting tiny mass movements. Accelerometers measure acceleration based on the principle of Newton's second law of objects. According to Newton's second law, there is a linear relationship between the acceleration of a body and the applied force and the mass of the body. Acceleration sensors use small mass movements (microelectromechanical systems) and electrostatic gaps to measure the acceleration of an object. The MPU6050 chip converts the detected acceleration value into a digital signal through an analog to digital converter. These digital signals can be transmitted to external devices (such as microcontrollers) via serial bus interfaces (such as I2C and SPI) for further processing and analysis. The acceleration of a single axis is formulated as follows:

$$a = \frac{\text{Range}\times\text{G}\times\text{ACC}}{32768} \tag{1}$$

Where G is the local gravitational acceleration, ACC is the original acceleration data of this axis, and Range is determined by the parameters written when configuration the acceleration range. The formula for the angular velocity of the single axis is:

$$g = \frac{\text{Range}\times\text{Gyro}}{32768.} \tag{2}$$

Here, gyro is the raw angular velocity of this axis. The Range is determined by the parameters written when the angular velocity range is configured. The calculated acceleration and angular velocity data can be used to implement the motion detection function of the sensor. The main theoretical foundations of MPU6050 are as follows:

- Microelectromechanical Systems (MEMS) technology: MEMS is a technology that integrates tiny structures for the manufacture of tiny mechanical and electronic components. Accelerometers are based on MEMS technology and use tiny mass movements to measure the acceleration of an object.
- Serial bus Interface: MPU6050 chip supports a variety of serial bus interface, such as I2C (Inter-Integrated Circuit) and SPI (Serial Peripheral Interface). These interfaces are used for communication and data transfer with external devices.

2.4. ESP32

ESP32 is a highly integrated microcontroller chip used to compose wearable wireless biosensors. The ESP32 chip integrates a high-performance processor and large capacity memory, including SRAM (static random-access memory) and flash memory. The processor provides powerful computing power for data processing of sensors, and the memory is used to store data and programs. The main theoretical foundations of ESP32 are as follows:

- Principle of microcontroller: A microcontroller is a monolithic integrated circuit that integrates a processor, memory and I/O interface. Understanding the principle, architecture and working mode of the microcontroller is of great significance to understand the function and performance of ESP32.
- Principle of wireless communication: Wi-Fi and Bluetooth are wireless communication protocols supported by ESP32 chip [12]. Understanding the principle and working mode of wireless communication, such as signal modulation and demodulation, channel management, and data transmission protocols, is essential to achieve reliable wireless data transmission.

- Data processing and storage theory: ESP32 chip has powerful data processing and storage capabilities, involving theoretical knowledge of processor architecture, data processing algorithm, memory management and data storage technology.

3. Test Methods and Results

3.1. Methodology

The design of wearable wireless biosensors involves the integration of hardware components, the development of software programming, and system optimization. The implementation approach is described in detail. In terms of hardware connection, the connection between each sensor, microcontroller, communication module and battery are as follows:

- Heart rate sensor (MAX30101): connected to a microcontroller (ESP32) via I2C bus for monitoring heart rate and blood oxygen saturation.
- Temperature sensor (DS18B20): connected to a microcontroller via a single-wire digital interface for measuring body temperature.
- Acceleration sensor (MPU6050): connected to the microcontroller via an I2C interface, provides acceleration and attitude data.
- Bluetooth Low Energy module (HC-06): Connected to the microcontroller through the UART communication port to achieve Bluetooth communication with mobile devices.

The overall system architecture is shown above. Based on this, the following are the key components of the program architecture:

- Data acquisition and processing: The microcontroller communicates with each sensor in turn to collect heart rate, body temperature and acceleration data. The acquired raw data need to be calibrated and filtered, heart rate and blood oxygen data need to be processed algorithmically to extract biological parameters, body temperature data can be used directly, while acceleration and attitude data need to be filtered and computed.
- Communication module management: The microcontroller communicates with the Bluetooth Low Energy module (HC-06) through the UART interface to transmit the collected data to the mobile device. At the same time, it can also receive commands from the mobile device, such as setting the sampling frequency, starting and stopping the sensor, etc.
- Power management and optimization: A range of power management strategies are required to extend battery life. This includes turning off sensors when they are not needed as well as adjusting the operating mode of the microcontroller. At the same time, for the communication between the mobile device and the sensor, the transmission frequency can also be adjusted according to the demand, in order to achieve the goal of minimizing the power consumption under the premise of ensuring real-time performance.

In this design, it is configured in active connection mode. When the mobile device (Bluetooth Client) initiates the connection via Bluetooth, the HC-06 accepts the connection as a slave device and establishes the communication link. The microcontroller can communicate with the HC-06 through the UART interface to send the data to be transmitted.

Table 1. Heart rate sensor data

Time	Heart rate (bpm)
10:00:00	81
10:00:01	85
10:00:02	90
10:00:03	87
10:00:04	88

3.2. Result

From the heart rate sensor, temperature sensor and acceleration sensor to obtain the real-time data in the form of the following form to show. Heart rate sensor data are shown in Table 1. The results show that the biosensor can accurately measure the heart rate. Temperature sensor data are shown in Table 2. The results show that the biosensor can timely and accurate measured temperature data. Acceleration sensor data are shown in Table 3. The results show that the biosensor can accurately and timely measure the acceleration data in three directions.

Table 2. A temperature sensor data

Time	Body temperature (℃)
10:00:00	36.5
10:00:01	36.4
10:00:02	36.4
10:00:03	36.4
10:00:04	36.5

Table 3. The acceleration sensor data

Time	The X axis acceleration (m/s^2)	The Y axis acceleration (m/s^2)	The Z axis acceleration (m/s^2)
10:00:00	0.05	-0.02	0.99
10:00:01	0.06	-0.01	0.98
10:00:02	0.07	-0.01	0.97
10:00:03	0.05	-0.03	0.95
10:00:04	0.06	-0.02	0.99

Table 4. Transmission rate test results

Time	Data transfer rate (bps)
10:00:00	100
10:00:01	110
10:00:02	106
10:00:03	105
10:00:04	106

Table 5. Battery life test

Working mode	Battery life in hours
Sleep mode	198
low power mode	99
active mode	48

The effect of communication between Bluetooth module and mobile device is very important. The transmission rate and stability test, the specific data are as follows. the transmission rate test results are shown in Table 4. It can be seen from the results that the data transmission rate is stable at about 105bps, and the transmission effect is stable. The battery life of integrated rechargeable lithium batteries plays a key role in wearable sensors, so one performed battery life testing and adopted a power management strategy. Battery life test under different working mode is shown in Table 5. From the results, it can be seen that the use time in the low power mode is about twice that in the active mode.

Adopted power management strategies include:

- The sleep mode when sensors don't need the real-time data acquisition, sets the sensor to sleep mode to reduce power consumption.
- Low power mode: When the sensor needs to continuously perform data acquisition, the sensor is set to low power mode to reduce power consumption.

- Dynamic power management: According to the change of sensor data, the power management strategy of the sensor is dynamically adjusted to extend the battery life.

The implementation of these power management strategies helps to extend the lifetime of the integrated rechargeable lithium battery and ensure stable operation of the wearable sensors. In summary, the designed wearable wireless biosensor shows good performance in the experiment. This study demonstrates the reliability and stability of the sensor in monitoring the physiological state of the human body by showing the real-time data of each sensor, the test of the communication effect as well as the test of the battery life and the adoption of the power management strategy. Future research can further optimize the sensor functionality and performance for a wider range of application scenarios.

3.3. Discussion

After quantitative and qualitative analysis of the experimental results. In practical application scenarios, heart rate sensors, body temperature sensors, and acceleration sensors show excellent performance. They can measure the corresponding biological parameters with high accuracy and provide a reliable data base for monitoring. The communication system shows satisfactory results, and the transmission rate and stability fully meet the requirements of real-time monitoring. This provides solid support for the timely delivery of data.

Power analysis plays an important role in measuring the battery life of a system. The trigger mechanism of the sensor is adjusted reasonably, so that it only collects data when necessary. This strategy effectively reduces the system power consumption and thus prolongs the battery life. Put the microcontroller in sleep mode and wake it up only when necessary. This measure greatly reduces the energy consumption and provides a strong guarantee for the efficient energy consumption of the system. In addition, the clever choose appropriate communication protocol and the communication frequency, further reducing the power consumption level, for the stable operation of the system gives more energy to support.

In practical applications, wearable biosensors may face a series of challenges. For example, the security and privacy issues of data must be properly addressed to ensure the complete confidentiality of users' sensitive information. In addition, for different use environments and populations, sensors may need further personalized adaptation and optimization to ensure the accuracy and reliability of their data collection. In order to further improve and optimize the design, here are some forward-looking directions for improvement:

- In the system design, more in-depth consideration of power consumption optimization strategies to further extend the battery life and provide a more durable user experience.
- Explore further, continuously reduce the size of the sensor, and choose more comfortable fabrics to improve the comfort and convenience of wearing.
- Continuously improve the accuracy and stability of sensors to meet more stringent biological parameter monitoring requirements and provide more valuable data support for medical and health management fields.
- Continuously expand the monitoring function to include the monitoring of more biological parameters, so as to expand the application range of sensors in many fields such as medical treatment and sports, and improve the practical value.

Taking the above into consideration, experimental studies have shown that wearable wireless biosensors are excellent in terms of performance and applicability. However, numerous challenges still need to be faced in practical applications, which will motivate researchers to continuously explore improvements in future studies to drive innovative development in this field.

4. Limitations and Prospects

Such wearable wireless biosensors still have some research limitations. Firstly, although the system is capable of monitoring heart rate, body temperature, and movement status, the accuracy of the sensors may be compromised due to the high sensor integration, especially in complex motion situations, such as high-intensity exercise and different types of activities. Secondly, the hc-06 Bluetooth Low energy module used by the communication module has certain limitations in terms of transmission distance and rate. Although the current design has met the needs of ordinary users, some special application scenarios, such as medical monitoring or remote monitoring, may require higher performance communication modules to support longer distances and higher data transmission rates.

With the rapid development of wireless sensor technology, future research can further expand the functions and applications of sensors. For example, modules such as respiratory sensors, blood oxygen sensors can be added to provide more comprehensive and accurate monitoring of physiological parameters. In addition, this sensor can be more closely integrated with devices such as smartphones or smart watches to achieve more refined health management and personalized recommendations through data analysis and algorithms. Despite some limitations, this wearable wireless biosensor still has a wide range of applications. It can be applied in the fields of health management, personal fitness, remote monitoring and healthcare, providing users with better quality of life and health condition management while providing physiological health data.

5. Conclusion

In summary, a wearable wireless biosensor system is designed, which includes a heart rate sensor, a body temperature sensor, an acceleration sensor and a microcontroller. The sensor part uses the chip max30101, DS18B20 and mpu6050, and these sensors can monitor the physiological parameters of the human body in real time, including heart rate, body temperature and movement state. In this system, ESP32 is used as a microcontroller, which can collect sensor data, process and analyze it. In order to achieve wireless transmission, one chose the Bluetooth Low energy module hc-06 as the communication module. This enables users to monitor and receive biometric parameter data via mobile phones or other Bluetooth devices. In order to meet the needs of long-term use, this study chose an integrated rechargeable lithium battery (1860 battery) as the power supply. This kind of battery has high capacity and long service life, which can provide stable power support. Through this wearable biosensor system, users can monitor their physiological status in real time and adjust their living habits in time. In summary, this paper designs a fully functional wearable wireless biosensor system with the ability to monitor heart rate, body temperature, and movement status. Through wireless transmission and stable battery power supply, users can easily monitor their physiological parameters and make corresponding adjustments. This system has a broad application prospect and can play an important role in medical care, sports training and other fields.

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