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Signal Transmission and Feedback Control in Wearable Devices: Review

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Abstract:

Wearable devices have become a critical driving force in areas such as smart health management, sports tracking, smart homes, and remote healthcare, thanks to advancements in signal transmission and feedback control technologies. This paper systematically reviews the key technologies involved in signal acquisition, transmission, and feedback control in wearable devices, focusing on how closed-loop control enhances user experience and health management through real-time monitoring and dynamic adjustment. By utilizing sensor technology, wearable devices can gather various physiological signals and collaborate with smart systems to provide personalized health and environmental adjustment solutions. The paper also discusses the technical challenges related to latency, energy management, and data security in wearable devices. Additionally, it explores the potential of 5G, artificial intelligence, and next-generation communication technologies to improve device performance. The integration of feedback transmission and closed-loop control offers more intelligent and personalized solutions for future applications in health management, sports tracking, and smart living.

Keywords: Wearable devices; signal acquisition; feedback control.

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1. Introduction

Wearable devices are rapidly becoming an important tool in medical health, physical fitness, and daily life. They can not only monitor human physiological signals in real-time but also provide personalized feedback and adjustment through intelligent algorithms. With the increasing demand for health management and telemedicine, especially in the context of aging and the growth of the number of patients with chronic diseases, the market demand for wearable devices is expanding. The core functions of these devices depend on accurate signal transmission and real-time feedback control to achieve remote monitoring and automatic adjustment. Wearable devices have become a vital tool for real-time health monitoring, especially in managing chronic diseases such as cardiovascular conditions and diabetes [1]. The application of wearable devices in health monitoring has become the focus of global research, especially in the development of advanced health systems within the EU [2]. Signal acquisition and transmission are key aspects in wearable devices. The sensor collects physiological signals through physical contact or non-contact methods, such as electrocardiogram (ECG), electroencephalogram (EEG), blood oxygen saturation, body temperature, etc. After amplification, filtering, and analog-to-digital conversion, these signals are transmitted to the data processing unit for further processing and analysis. To achieve real-time transmission, wearable devices usually use wireless communication technologies, such as Bluetooth low power (BLE), Wi-Fi, near-field communication (NFC), and ZigBee. These technologies provide an efficient and low-power transmission mode for wearable devices, enabling devices to continuously monitor physiological data without affecting users' daily activities.

Feedback transmission and closed-loop control are other core functions. The closed-loop control system can automatically adjust according to the current state by collecting the real-time data of users and feeding it back to the control unit of the equipment. For example, the insulin pump can automatically adjust the drug release according to the blood glucose monitoring results, reducing the need for user intervention. This closed-loop feedback mechanism improves the device's intelligence and provides a personalized health management solution.

In the following sections, this paper will first explore the fundamental principles of signal transmission and feedback control in wearable devices, highlighting their roles in real-time monitoring and personalized adjustment. It will then delve into the key challenges faced by these technologies, including issues related to latency, data security, and energy management. The discussion will also cover advanced technologies, such as multimodal communication and low-power feedback control, that are driving innovation in wearable systems. Finally, the paper will address the future development directions, focusing on the potential impact of 5G, artificial intelligence, and next-generation communication technologies in enhancing the performance and functionality of wearable devices for health management, sports tracking, and smart living applications.

2. Principle of signal transmission and feedback

As a cutting-edge tool for human signal acquisition and monitoring, wearable devices undertake the important task of collecting physiological signals, motion data, and environmental information. Signal transmission and feedback control are the core parts of wearable devices to achieve real-time monitoring, data communication, and automatic adjustment. To achieve effective signal transmission, the device first collects biological signals and environmental data through various sensors, such as the ECG sensor, optical sensor, accelerometer, and temperature sensor. These sensors collect physiological signals through physical contact or non-contact, and convert them into electronic signals for subsequent processing and transmission [3].

In the signal transmission link, the sensor collects signals through physical contact or non-contact [4], the collected signal needs to be transmitted to the data processing unit through the signal conditioning circuit (including amplification, filtering, analog-to-digital conversion, and other processing). The unit is usually composed of a microcontroller (MCU) or embedded processor, which is responsible for preliminary signal analysis, feature extraction, and data compression [5]. In addition to the forward transmission of signals, feedback control is also important in wearable devices. Feedback transmission is to feed back the processed data to the equipment or users to trigger the corresponding adjustment measures and realize closed-loop control. For example, in the heart rate monitoring device, after the heart rate signal is transmitted to the mobile phone or cloud, the exercise intensity can be adjusted or the user can be reminded to relax through the feedback control mechanism. In this process, the control unit of the equipment adjusts the sensitivity, signal acquisition frequency, and data transmission rate of the sensor in real-time according to the feedback information to adapt to the current environment and use requirements. The core of closed-loop control is to make dynamic adjustments according to real-time signals to improve the accuracy of monitoring and user experience.

Remote control and communication technology provide a wider range of application scenarios for wearable devices, such as telemedicine monitoring, smart home control, and personalized health management. With the increasing demand for health management and telemedicine, especially in chronic disease management, wearable devices have become an effective daily monitoring tool [6]. The core technology of the signal transmission link involves the acquisition and processing of sensor signals, wireless transmission, and the implementation of feedback control. The cooperative operation of these links ensures the real-time and reliability of the equipment. With the development of communication technology and adaptive feedback mechanisms, wearable devices are making breakthroughs in the field of signal transmission and control, providing users with more intelligent and efficient solutions.

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3. Key challenges in signal transmission and feedback control

In wearable devices, signal transmission and feedback control are key technologies for achieving intelligent and personalized functions. Although these technologies have made significant progress, they still face a series of challenges, especially in terms of real-time performance, data security, and energy management. These issues directly affect the performance of the device, user experience, and data security. The following will discuss in detail these key challenges and their potential solutions.

3.1 Real-time performance and latency

The real-time and delay problems in signal transmission directly affect the performance of equipment, especially in the field of medical monitoring, rapid response is the key [7]. For example, heart rate monitoring devices must immediately sound an alarm when detecting abnormal heart rate, and medical devices such as insulin pumps need to adjust drug release in real time based on fluctuations in blood sugar levels. If the transmission delay of feedback signals is too large, it may result in users being unable to receive important health reminders promptly, and may even lead to serious consequences.

Reducing the delay of signal transmission and feedback is a multifaceted challenge. Firstly, the choice of communication technology has a direct impact on latency. Bluetooth Low Energy (BLE) and Wi-Fi are currently the most commonly used wireless communication technologies. The former performs well in low power consumption and short-distance transmission, but Wi-Fi provides higher transmission rates when large-scale data transmission is required.

To reduce latency, future wearable devices may adopt 5G or upcoming 6G technologies, which not only provide higher bandwidth and lower latency but also support simultaneous connections of large-scale devices, thereby reducing data congestion and improving real-time feedback. By introducing edge computing technology, devices can process data locally, thus reducing dependence on cloud computing and significantly reducing data transmission delay [8]. Through data pre-processing and analysis on the device, edge computing reduces the dependence of the device on the cloud, reduces the frequency of data transmission, and improves the response speed of the system. For example, in motion monitoring devices, edge computing can process motion data in real-time, generate feedback signals without relying on remote servers, and ensure that devices can respond within milliseconds.

3.2 Data transmission and security

With the increasing sensitivity of health data, how to ensure the security of data in the process of transmission becomes crucial. Especially in the wireless communication environment, preventing data leakage and tampering has become a key challenge [9]. Wearable devices not only involve users' daily exercise data but may also involve personal health information such as heart rate, blood sugar, blood pressure, etc. Once these data are leaked, they may have a serious impact on users' privacy. Therefore, ensuring the security of data during transmission is crucial.

Encryption communication protocol is the primary defense line to ensure the security of data transmission. For example, commonly used wireless communication technologies such as Bluetooth and Wi-Fi already support multiple encryption methods, such as AES encryption (Advanced Encryption Standard), to ensure that data is not intercepted or tampered with during transmission. However, relying solely on encryption technology is not enough to fully protect data, and authentication is also an important means of protecting data. Biometric methods have been proposed to improve the security of wireless body area networks [10]. In wearable devices, two-factor authentication or biometric technology can ensure that only authorized users and devices can access and control data.

In addition, privacy protection regulations such as the General Data Protection Regulation (GDPR) have raised higher requirements for the privacy management of wearable devices. Equipment manufacturers and service providers must ensure transparency and controllability of user data collection, transmission, and storage processes, and users should have the right to choose which data to share and how to use it. In the future, with the advancement of privacy protection technologies such as homomorphic encryption and differential privacy techniques, devices will be able to perform data analysis and processing without exposing user data, further enhancing data security.

3.3 Energy consumption and stability

The energy management of wearable devices directly affects their operating time and user experience. Energy management has a direct impact on the performance of equipment, especially in real-time health monitoring, which requires equipment to provide efficient feedback control while ensuring endurance [11]. Due to the small size and limited battery capacity of wearable devices, how to extend battery life while ensuring device functionality is a crucial technical challenge. The continuous operation of closed-loop control systems, especially frequent signal acquisition, transmission, and feedback processing, consumes a large amount of energy, which puts high demands on the battery life of the equipment.

To solve the energy consumption problem, device manufacturers have taken various measures at both the hardware and software levels. For example, in terms of hardware, the use of low-power sensors and communication modules is key, and Bluetooth Low Energy (BLE) is a typical example. BLE significantly reduces the energy consumption of signal transmission through intelligent sleep and wake-up mechanisms. In addition, optimized signal processing algorithms and data compression techniques can reduce unnecessary transmission, thereby reducing communication energy consumption. In terms of software, the device can dynamically adjust the acquisition frequency and transmission interval according to user needs through adaptive control algorithms to extend battery life.

Stability is another important aspect of energy management. The core function of wearable devices relies on their stable operation around the clock, especially in closed-loop control systems. If the device experiences power outages or malfunctions during operation, it may lead to serious health risks. Therefore, energy harvesting technologies such as solar or thermal energy harvesting have gradually become a research hotspot. By obtaining energy from the environment, devices can operate continuously without relying on traditional batteries.

4. Advanced technologies

In the development process of wearable devices, signal transmission, and feedback control technology continue to make progress. To ensure that devices can achieve efficient, stable, and low-power feedback control in different usage scenarios, many emerging technologies are being applied in device design. Multimodal communication, adaptive feedback mechanisms, and low-power feedback control systems play a crucial role in this process.

4.1 Multimodal communication

Multimodal communication refers to achieving optimal signal transmission and feedback control in different usage scenarios by combining multiple communication methods. By combining a variety of communication technologies, devices can achieve stable data transmission and feedback control in different environments to ensure user experience, shown on Fig.1 [11,12]. Every communication technology has its advantages and limitations, and a single technology may not be able to meet all needs in specific scenarios. Therefore, by combining technologies such as Bluetooth Low Energy (BLE), Wi-Fi, Near Field Communication (NFC), and Zigbee, wearable devices can flexibly switch between different environments, ensuring the stability of data transmission and the timeliness of feedback.

For example, BLE performs well in short-distance and low-power transmission, making it suitable for applications such as daily health monitoring and motion tracking that require real-time and low latency. When big data transmission is needed, such as synchronizing health data to the cloud or video surveillance, Wi-Fi provides higher bandwidth and longer transmission distance. By combining BLE with Wi-Fi, devices can use low-power Bluetooth for transmission when the data volume is small, and automatically switch to Wi-Fi when transmitting big data or remote communication, thereby achieving efficient and stable feedback control in different usage scenarios.

This multimodal communication technology can also be applied to remote medical monitoring. For example, electrocardiogram monitoring devices use BLE to record electrocardiogram signals during daily use. When abnormalities are detected, the device automatically switches to Wi-Fi and quickly uploads the abnormal data to the medical platform, ensuring that doctors can timely obtain the patient’s condition and make corresponding decisions.

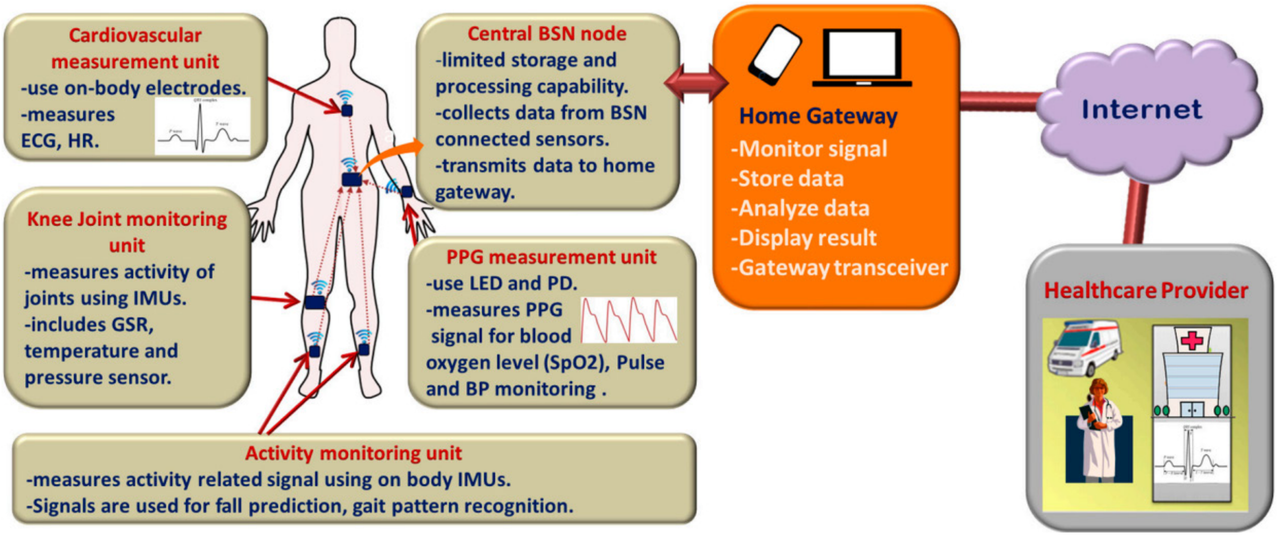

Fig. 1 General overview of the remote health monitoring system [11].

4.2 Adaptive feedback mechanism

Adaptive feedback mechanism refers to wearable devices automatically adjusting their signal processing and feedback strategies based on dynamic changes in environmental conditions and user needs. Wearable devices are often subject to environmental interference, such as noise and electromagnetic interference generated during movement, which can affect the quality of signals and the accuracy of device feedback. Therefore, it is crucial to use adaptive technology to adjust the feedback mechanism to ensure that the device can provide high-precision feedback in various complex environments.

An adaptive filter is a commonly used technique in adaptive feedback mechanisms. Adaptive filter can monitor and process environmental noise in real time, so as to improve the accuracy of physiological signals, especially in dynamic environment [13]. For example, in electrocardiogram (ECG) monitoring, human movement can produce artifacts that interfere with the accurate acquisition of signals. Adaptive filters can automatically adjust filtering parameters based on the characteristics of noise, effectively removing artifacts and interference signals, and ensuring that the device obtains more accurate biological signals. Through adaptive feedback mechanisms, devices can improve signal quality, enhance system reliability, and reduce error rates.

In addition, adaptive feedback mechanisms can also be used to optimize the operating status of devices, for example, motion-tracking devices can adjust the data collection frequency based on the user's exercise intensity. When users engage in vigorous exercise, the device will automatically increase the frequency of data collection such as heart rate and respiratory rate to provide more accurate feedback; In a stationary state, the device can lower the acquisition frequency and reduce power consumption. Through this dynamic adjustment, the device can not only meet the needs of users but also optimize resource utilization and extend battery life.

4.3 Low power feedback control

With the increasing functionality of wearable devices, energy consumption has become a key challenge. How to extend battery life while ensuring device performance is the focus of feedback control system design. Low-power Bluetooth (BLE), Low-power sensor, Thread, and other protocols provide effective solutions for this.

Low Energy Bluetooth (BLE) is a low-power communication technology widely used in wearable devices. BLE can use extremely low power consumption during signal transmission through intermittent communication mode. The device maintains a sleep and wake-up mechanism to reduce power consumption when data transmission is not required; When feedback transmission is required, the device quickly wakes up and performs data transmission, effectively extending the battery's usage time. This mechanism is particularly suitable for long-term monitoring devices, such as heart rate monitoring bracelets or sleep monitoring devices, which can maintain battery life for several days or even weeks while ensuring real-time feedback. The application of low-power sensors in chemical and physiological signal monitoring significantly prolongs the battery life of wearable devices, while ensuring the accuracy of real-time feedback [14].

Thread protocol is a low-power, low-bandwidth network communication protocol mainly used in Internet of Things (IoT) devices. It can establish a reliable and energy-saving communication network between multiple devices, especially suitable for scenarios that require long-term stable operation such as home monitoring and health monitoring. Through the Thread protocol, devices can form a mesh network, ensuring low power consumption and high stability when data is transmitted between different devices.

In low-power feedback control systems, optimizing control algorithms is equally crucial. For example, using adaptive control algorithms to dynamically adjust the monitoring frequency and feedback intensity of the device based on the user's current needs and physiological state. Sports monitoring equipment can reduce data collection frequency and unnecessary energy consumption when users are in a stationary state; Increase the frequency of data collection when users engage in high-intensity exercise to ensure the accuracy of feedback.

5. Remote applications of feedback transmission and closed-loop control

Feedback transmission and closed-loop control technology are playing an increasingly important role in remote applications of wearable devices, widely used in fields such as medical monitoring, sports and health tracking, and smart homes.

In remote medical monitoring, wearable devices provide a reliable solution for chronic disease patients and health management by real-time collection and transmission of physiological signals. For example, electrocardiogram monitoring devices can collect heart rate data in real-time, and transmit the data to smartphones or the cloud through Bluetooth or Wi-Fi, and doctors or health managers can monitor the patient's heart status in real-time. The closed-loop feedback system can automatically adjust equipment parameters by collecting real-time data, so as to realize personalized health management [15]. Once an abnormality is detected, the closed-loop control system of the device can immediately trigger an alarm and even guide the patient to make breathing adjustments or take medication through feedback mechanisms. For patients with diabetes, the closed-loop control technology of the insulin pump can automatically adjust the injection dose of insulin according to the real-time blood glucose monitoring data, reducing the burden of daily management of patients and improving the quality of life [16].

In sports and health tracking, feedback transmission and closed-loop control also provide personalized guidance. The smart sports wristband monitors users' heart rate, steps, calorie consumption, and other data in real-time through sensors, and transmits this information to mobile applications. Mobile applications analyze this data and provide recommendations on exercise intensity, duration, and rest. Closed loop control enables devices to adjust exercise plans in real time based on the user's current state, providing more scientific fitness guidance. For example, when the device detects that the user's heart rate is too high, it can remind the user to slow down movement through vibration or voice to avoid excessive movement [17].

By monitoring the user's body temperature, heart rate and ambient temperature, wearable devices can be connected with smart home devices to achieve automatic adjustment and personalized settings of the environment [18]. By monitoring users' body temperature, heart rate, and ambient temperature, wearable devices can be linked with smart home devices to automatically adjust room temperature, lighting, and air quality, creating a more comfortable living environment. This feedback control not only enhances user experience but also achieves personalized environmental adjustment.

These cases fully demonstrate the advantages of feedback transmission and closed-loop control in remote applications, providing a new solution for health management and intelligent living through real-time signal monitoring, dynamic adjustment, and personalized services.

6. Future Development Direction

In the future, wearable devices will see more breakthroughs and innovations in signal transmission and feedback control.

With the rise of new generation communication technologies such as 6G, wearable devices will be able to achieve faster and more stable signal transmission and feedback, and further improve the real-time performance of remote health management [19]. Firstly, the application of 6G and new-generation communication technologies will significantly improve the speed and reliability of signal transmission. Compared to 5G, 6G networks have higher bandwidth and lower latency, which will support large-scale real-time data transmission and efficient remote feedback control. This will enable wearable devices to provide more accurate closed-loop control and personalized services in scenarios that require real-time response, such as medical monitoring and sports training.

The combination of artificial intelligence and adaptive control will be another important development direction. With the progress of artificial intelligence technology, the device can continuously optimize its feedback mechanism through adaptive control to provide more accurate health monitoring and personalized suggestions [20]. Through machine learning and deep learning algorithms, devices can perform pattern recognition and self-optimization in large amounts of user data, achieving more intelligent

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feedback control. For example, the device can autonomously adjust the frequency of heart rate monitoring or predict fatigue status during exercise based on the user's historical health data, thereby dynamically adjusting the exercise plan. Meanwhile, artificial intelligence algorithms can also improve the efficiency of data transmission and analysis, achieving more accurate remote monitoring and diagnosis.

In terms of energy harvesting technology, utilizing environmental energy (such as body temperature and exercise energy) for energy harvesting will provide support for the continuous operation of wearable devices. In the future, technologies based on energy harvesting and wireless charging will effectively extend device endurance and meet the needs of continuous signal transmission and feedback control. In addition, the research will focus on developing communication protocols with lower power consumption to reduce energy consumption during signal transmission.

These development directions will promote the intelligence, low power consumption, and personalized services of wearable devices, further expanding their applications in healthcare, sports, and daily life, providing users with more comprehensive health management and intelligent experiences.

7. Conclusion

The signal transmission and feedback control technology in wearable devices is the core of achieving real-time monitoring, remote control, and personalized services. This article explores the current mainstream signal transmission methods, such as Bluetooth Low Energy (BLE), Wi-Fi, and Zigbee, as well as the practical applications of feedback transmission and closed-loop control in healthcare, sports, and smart homes. These technologies enable wearable devices to provide efficient, stable, and low-power signal transmission in various scenarios, thereby meeting the needs of real-time monitoring and dynamic feedback. Meanwhile, the adaptive processing of signals and the development of low-power communication protocols have further enhanced the endurance and user experience of devices.

In the future, technologies such as 6G communication, artificial intelligence, and energy harvesting will lead to the further development of wearable devices, providing more intelligent and personalized services. Although facing challenges such as data security, real-time performance, and power management, with the continuous advancement of technology, wearable devices will play a more important role in healthcare, sports, and daily life, bringing users more convenient and comprehensive health management and intelligent living experiences.

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