Wearable Wireless Sensors for Healthcare Monitoring: A Review

Jiaqi Lin[1*]

[1] School of Robotics Engineering, Fuzhou University, Fuzhou, China

*Email: 022204036@fzu.edu.cn

Abstract. As the population grows, limited capabilities constrain medical institutions in some countries. This makes it hard to monitor patients' conditions promptly and comprehensively, potentially causing missed optimal treatment opportunities. Thus, researching wearable wireless sensor-based health monitoring systems becomes particularly important. These systems can give medical institutions more intuitive, accurate, real-time data on human health, aiding disease diagnosis. This study systematically analyzes and summarizes relevant literature to examine traditional healthcare sensors' drawbacks, such as poor comfort, high costs, and reliance on fixed environments. It also explains the basic principles of three commonly used wireless sensors in health monitoring. Furthermore, to address resource optimization in these systems, the study develops three innovative algorithms: an improved BFGS quasi-Newton method-based energy-optimal allocation algorithm, a window-based rate control algorithm (w-RCA), and a priority-based task scheduling and resource allocation mechanism (PTS-RA). Empirical validation demonstrates that these algorithms significantly enhance the overall performance of healthcare monitoring networks, providing robust technical support for 5G-enabled telemedicine applications. The study also offers practical cases and technical references for using sensors in scientific fields.

Keywords: Healthcare monitoring system; Wearable wireless sensor; Medical diagnosis.

1. Introduction

In June 2014, the Chinese Academy of Engineering initiated a strategic research project entitled "National Strategies for Public Health and Medical Service Development in China." As a critical component of this initiative, particular emphasis was placed on the "Development Strategy for Medical Instruments and Emerging Wearable Healthcare Devices." Subsequently, in May 2015, the State Council of China promulgated the "Made in China 2025" policy [1], explicitly identifying medical wearable devices as a national strategic priority. This policy aims to enhance the comprehensive competitiveness of enterprises across the entire industrial chain, including research and development, manufacturing, and market operations.

Accelerated global population aging and the rising burden of chronic diseases are creating unprecedented challenges for healthcare monitoring. According to WHO data, the worldwide population aged 60+ will reach 2.1 billion by 2050, with cardiovascular diseases and diabetes now ranking as leading causes of mortality [2]. This crisis reveals three critical limitations in conventional healthcare systems: First, the prolonged latent phase of many diseases often masks early symptoms, delaying diagnosis; Second, traditional medical devices suffer from poor portability, high invasiveness, and excessive costs; and the complex variability of clinical manifestations demands personalized treatment strategies, complicating medical decisions.

Wireless sensor network (WSN)-based health monitoring systems address these issues through multidisciplinary integration, combining biomedical engineering with WSN technology to achieve high precision, adjustable detection ranges, and low power consumption [3]. Miniaturized sensor arrays enable continuous, real-time physiological data collection, while self-organizing multi-hop networks transmit information to end-users. These robust datasets support clinical decision-making and population health analysis. The system's unique data consistency features generate quantitative biomarkers, enabling early detection of chronic diseases and facilitating the shift from reactive treatment to proactive health monitoring.

This study employs a systematic literature review and analytical approach to examine the principal limitations of conventional medical sensors, including suboptimal wearability, high operational costs, and dependence on fixed monitoring environments. Furthermore, the operational principles of three widely utilized wireless sensor technologies in health monitoring are elucidated. To address the critical challenge of resource optimization in health monitoring systems, this research proposes three innovative algorithmic solutions: an improved BFGS quasi-Newton method-based energy optimization algorithm, a window-based rate control algorithm (w-RCA), and a priority-aware task scheduling and resource allocation mechanism (PTS-RA). These algorithms have demonstrated significant improvements in medical data processing efficiency.

2. Literature Survey

Figure 1 presents the annual publication count retrieved from IEEE using "health monitoring system" and "wearable wireless sensors" as search keywords. From 2014 to 2024, the overall trend of related publications shows a consistent upward trajectory. The number of papers increased from 1,838 in 2010 to 6,926 in 2022. It should be noted that although the publication count in 2020 was slightly lower than that in 2019, the difference between these two years is almost negligible. This trend demonstrates that wearable wireless sensors for health monitoring applications are attracting growing research attention.

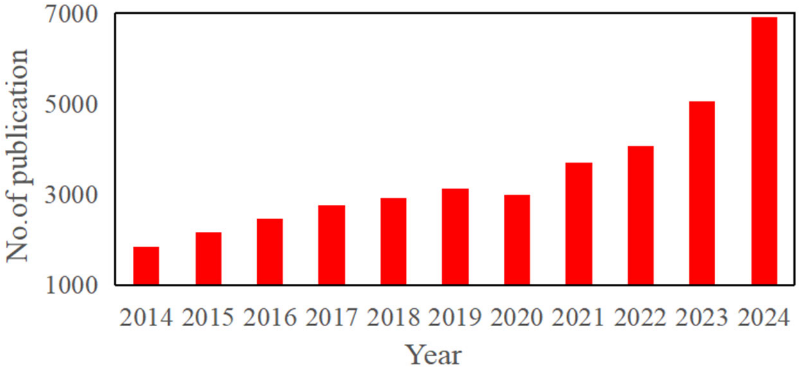

Fig. 1 The number of papers searched using “health monitoring system” and “wearable wireless sensors” per year.

3. Limitations of Traditional Sensors in Health Monitoring

Statistical data indicates that traditional optical sensors (e.g., PPG) exhibit measurement error rates exceeding 20% in populations with darker skin tones, primarily due to light absorption variations causing data distortion [4]. During physical activity, wrist-worn oximeters demonstrate even higher error rates up to 40%, significantly compromising the reliability of dynamic monitoring. More critically, wearable devices show poor agreement with conventional clinical measurements [5]: only 59.7% of heart rate (HR) readings meet the ±5 bpm standard, while 32.9% of SpO_2 measurements achieve the ±2% error margin. These findings demonstrate substantial limitations in traditional health monitoring sensors for clinical applications.

3.1 Invasiveness and Poor Comfort

Take blood glucose monitoring as an example. Diabetic patients frequently face the burden of multiple daily blood collections, with the frequency dictated by the severity of their condition—often ranging from two to six times a day. This repeated skin puncturing, typically on the fingertips, not only causes immediate pain but also leads to cumulative discomfort, including soreness, calluses, and occasional infections, significantly impacting their quality of life. Even minimally invasive alternatives, such as subcutaneous glucose sensors, while enabling continuous 24-hour monitoring, come with their limitations. The body's natural immune response triggers the formation of a fibrous protein layer around the implanted needle, compromising measurement accuracy over time and necessitating sensor replacement every 7 to 14 days. This process often requires professional assistance, adding to patients' logistical hassle and healthcare costs [6].

3.2 Procedural Risks and Economic Burden

From a diagnostic standpoint, traditional approaches to identifying critical illnesses like heart disease are plagued by inefficiencies and risks. Procedures such as invasive angiography, often used to visualize coronary arteries, involve inserting catheters into blood vessels—a process that carries risks of bleeding, infection, or even arterial damage. Beyond the physical hazards, these methods are financially burdensome, with costs encompassing pre-procedure tests, anesthesia, and post-operative care that significantly strain patients and healthcare systems [7].

3.3 Mobility and Continuity Limitations

Moreover, the stationary nature of most traditional medical sensors—such as electrocardiographs and multi-parameter monitors—confines their use to clinical settings like hospitals or clinics. Tethered to power sources and fixed workstations, they fail to capture physiological changes occurring in real-world contexts. This limitation means that transient anomalies, such as nocturnal arrhythmias that strike during sleep or blood pressure spikes triggered by daily stressors, often go undetected during brief office visits. For patients with chronic conditions like hypertension or early-stage heart failure, which require long-term tracking, this lack of continuous data hinders timely interventions. Compounding these issues requires professional operation: applying ECG electrodes correctly, calibrating blood pressure cuffs, or interpreting device outputs demands specialized training, making self-monitoring nearly impossible for most individuals. In emergencies, delays caused by the inability to deploy these devices quickly can result in missed critical data, undermining the speed and effectiveness of life-saving treatments [8].

In essence, the drawbacks of traditional medical sensors—from discomfort and invasiveness to limited accessibility and reliance on professional oversight—highlight an urgent need for innovative technologies. Advancing toward more flexible, user-friendly, and continuous monitoring solutions is essential to enhancing patient experience and healthcare delivery quality.

4. Fundamental Principles of Medical Sensor Technologies

Modern medical sensors demonstrate significant advantages over traditional devices in size control, intelligent functionality, non-invasive features, and power consumption management. This section elaborates on the working principles of three critical types of medical sensors:

4.1 Sweat Analysis Sensors

The sweat monitoring technology was first proposed as an innovative solution by De Rossi's research team [9]. The core design integrates dual humidity sensing units on textile substrates. Measuring the response difference between the two sensors establishes a vapor pressure gradient model to accurately calculate sweat secretion rates based on Fick's law of diffusion. The complex three-dimensional structure of human sweat glands (comprising multiple components, including secretory coils and dermal ducts) leads to significant concentration variations in sweat composition. Therefore, quantitative analysis of key ions such as $Na+$ and $Cl-$ requires technical approaches like ion-selective electrodes or conductivity measurements.

4.2 Blood Oxygen Monitoring Sensors

As a crucial monitoring parameter in intensive care, pulse oximeters employ advanced spectroscopic analysis technology. Their working principle involves precisely calculating arterial oxygen saturation ($SpO2$) by measuring the differences in light absorption characteristics between oxygenated hemoglobin (HbO2) and reduced hemoglobin (Hb) [10]. Modern devices typically incorporate dual-wavelength LED light sources (660nm red light and 940nm infrared light) and photoelectric detection modules. Utilizing the differential absorption properties of hemoglobin molecules at these two characteristic wavelengths, they perform non-invasive detection through light-transmitting human tissues (such as fingertips or earlobes), simultaneously outputting key physiological parameters including oxygen saturation and pulse rate.

4.3 Glucose Monitoring Sensors

Blood glucose detection technology has evolved significantly as a core indicator of metabolic function. Current mainstream detection systems include colorimetric, fluorescence, and electrochemical biosensing technologies [11]. Electrochemical glucose sensors are most widely used in wearable devices due to their high selectivity and rapid response characteristics. This technology can be further categorized into enzyme-catalyzed and non-enzymatic types, with its core detection principle based on enzyme-mediated glucose recognition reactions and electrochemical oxidation processes of H2O2.

Modern sensors have significantly improved detection performance and reliability through continuous technological innovation while maintaining the original theoretical framework.

5. Innovative Approaches for Wearable Wireless Sensor Systems

Modern healthcare monitoring systems impose stringent requirements on data real-time performance, necessitating sensor nodes with superior fault tolerance and sustainable power supply capabilities. Energy depletion in nodes directly leads to network failures, compromising data transmission quality and shortening system lifespan. This study proposes three innovative algorithms to optimize energy utilization efficiency to address this critical challenge. Empirical validation demonstrates that these algorithms significantly enhance the overall performance of healthcare monitoring networks, providing robust technical support for 5G-enabled telemedicine applications.

5.1 An improved BFGS quasi-Newton energy allocation algorithm

The first breakthrough is an improved BFGS quasi-Newton energy allocation algorithm [3]. This algorithm achieves notable improvements in numerical stability by streamlining iterative computation processes while preserving superlinear convergence properties. Experimental results confirm its effectiveness in reducing computational latency and minimizing node energy consumption, thereby substantially enhancing the system's capacity for processing large-scale medical data with improved timeliness.

5.2 A window-based rate control algorithm (w-RCA)

This study introduces a novel window-based rate control algorithm (w-RCA) at the mobile edge computing level [12]. By holistically analyzing critical network parameters—including peak-to-average ratio (PAR), delay jitter, and other QoS metrics—the algorithm optimizes the transmission quality of medical video streams (e.g., 8-minute uterine horn navigation surgeries) over 5G networks. Testing verifies measurable enhancements in mobile edge computing-based medical quality of service (m-QoS) indicators.

5.3 An intelligent priority-based task scheduling system

The third contribution is an intelligent priority-based task scheduling system (PTS-RA) [13]. This system dynamically adjusts task priorities by evaluating the urgency of data collected from wearable devices. Employing a hybrid computing architecture, it intelligently allocates tasks between hospital workstations and cloud platforms to optimize processing efficiency while minimizing bandwidth costs. Clinical validation confirms its capability to ensure the timely delivery of critical diagnostic data to physicians.

6. Future Directions

With the rapid advancement of micro-nano fabrication and 3D printing technologies, coupled with materials science and machine learning algorithms breakthroughs, flexible wearable intelligent sensing technology is ushering in unprecedented development opportunities. Applying ultrathin graphene electrodes and liquid metal materials at the hardware level has significantly improved sensor comfort and signal quality, while miniaturized MEMS gas sensors have achieved multi-parameter environmental monitoring with substantially reduced power consumption. On the algorithmic front, future research should focus on enhancing the contextual understanding capabilities of intelligent sensing systems by improving the adaptive learning functionality of algorithms, enabling dynamic adjustments according to different usage environments and user habits. Integrating multi-source data fusion technology, incorporating environmental parameters such as pressure, temperature, and inertia, will improve sensing systems' information acquisition capability and measurement accuracy.

Notably, new challenges in data interconnectivity have emerged with the maturation of non-contact monitoring technologies like millimeter-wave radar and the widespread adoption of multi-sensor collaborative operation. Regarding privacy protection and data security, it is crucial to make breakthroughs in key technologies such as edge computing to ensure sensitive data is processed locally rather than uploaded to the cloud. This approach effectively prevents privacy breaches while reducing data processing latency. Such technological pathways not only address users' urgent demands for data security but also provide critical safeguards for the healthy development of the industry.

Based on current technological advancements, we recommend future research focus on four key directions: (1) development of novel intelligent materials with self-healing properties and biodegradability; (2) research on multifunctional composite material sensors for integrated multi-parameter monitoring; (3) establishment of dynamic calibration models based on deep learning; and (4) design of ultra-low-power edge intelligent computing architectures. These innovative approaches will address current data interconnectivity and privacy protection challenges and bring revolutionary changes to healthcare monitoring. The organic integration of these cutting-edge technologies is redefining the boundaries of health monitoring and creating unprecedented development opportunities for medical and healthcare fields.

7. Conclusion

In recent years, wearable intelligent sensing technology has demonstrated remarkable advantages in healthcare, providing crucial technical support for the innovation of health monitoring models. The ongoing miniaturization and intelligent development of flexible wearable sensing devices are expected to fundamentally overcome the limitations of traditional medical sensors in terms of comfort, accessibility, and long-term monitoring capabilities.

The improved BFGS quasi-Newton energy allocation algorithm, window-based rate control algorithm (w-RCA), and priority-aware task scheduling and resource allocation system (PTS-RA) proposed in this study effectively optimize the resource allocation efficiency of wireless health monitoring systems. These algorithms significantly enhance real-time data processing and system energy efficiency, laying an algorithmic foundation for 5G-enabled telemedicine.

However, the data security and privacy issues arising from multi-sensor collaboration cannot be overlooked. Future research should strengthen the application of edge computing technology to ensure sensitive medical data is processed locally, avoiding privacy leakage risks associated with cloud transmission. Furthermore, integrating AI technology with sensor data will transform medical diagnosis and treatment models toward personalization and preventive care.

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