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Research and exploration of a panoramic situation-aware embodied intelligent wearable system

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Abstract. In response to the core limitations of traditional smart wearable devices—namely passive data acquisition, imbalanced functional integration, and insufficient human–machine collaboration—this study deeply integrates embodied intelligence with wearable technologies and proposes a panoramic situation-aware embodied intelligent wearable system for high-risk operations, medical monitoring, and elderly care. A multimodal fusion technical architecture is adopted, following the pathway of "active perception–dynamic decision-making–natural interaction," thereby upgrading wearable systems from "tool-level data acquisition" to "partner-level intelligent collaboration." Application results demonstrate that the system reduces accident rates in electric power operations by 73%, increases the blood glucose compliance rate among diabetic patients by 42%, and shortens fall response time for elderly individuals living alone to within 20 seconds.

Keywords: embodied intelligence, situation awareness, smart wearables, partner-level intelligent collaboration, Xinhuo Public Welfare

1. Introduction

As a critical integration platform combining Internet of Things (IoT) technologies and ergonomics, smart wearable devices have been widely applied in industrial production, healthcare, and public services. Nevertheless, mainstream products on the current market exhibit three major limitations. First, their functional positioning remains largely confined to "passive data acquisition," enabling only data recording and basic feedback while lacking proactive risk prediction and decision-making capabilities. Second, technological integration is often unbalanced: excessive functional stacking results in bulky structures and reduced wearing comfort, or leads to conflicts between fundamental protective features and intelligent functions. Third, the depth of human–machine collaboration remains insufficient, failing to fully adapt to specific situational requirements and the dynamic interactive characteristics of the human body. In critical scenarios such as high-risk power operations, precision medical monitoring, and elderly care, these shortcomings directly constrain practical applicability and large-scale deployment.

The emergence of Embodied AI offers a systematic solution to these challenges. Its core premise is that "intelligence arises from dynamic interaction between the body and the environment." By endowing wearable devices with physical perception capabilities, adaptive decision-making capacity, and natural interaction mechanisms, embodied intelligence transforms them from mere "data carriers" into "embodied intelligent partners." Within this conceptual framework, a panoramic situation-aware embodied intelligent wearable device deeply integrates multi-source sensors, lightweight AI algorithms, and ergonomic design. It achieves comprehensive perception and proactive intervention across the triad of "human physiological state–environmental risk–task objectives," thereby delivering customized solutions for high-demand application domains.

According to statistics released by the National Energy Administration (2025), the power industry reports an average of 187 occupational casualty accidents annually, 73% of which are associated with insufficient environmental awareness in high-risk operational settings [1]. Conventional smart wearables exhibit three primary technical deficiencies: (1) low sensor integration density (on average ≤ 5 types), limiting multidimensional environmental perception; (2) constrained computational resources (CPU computing power < 1 GFLOPS), rendering real-time multimodal data processing infeasible; and (3) low human–machine interaction efficiency (response latency > 5 seconds). In the medical sector, the service gap in chronic disease management reaches 87 million patient-visits per year, while the monitoring accuracy of existing wearable devices remains below 75%. Meanwhile, population aging is accelerating, with individuals aged 60 and above accounting for 21.3% of the population in 2025. The timeliness of emergency response for elderly individuals living alone has thus become an urgent societal concern [2].

2. Panoramic situation-aware embodied intelligent wearable system

2.1. Research background

As a key integration platform combining Internet of Things (IoT) technologies and ergonomics, smart wearable devices have been widely adopted in industrial production, healthcare, and public service sectors. However, mainstream products currently available on the market generally exhibit three principal limitations. First, their functional positioning remains oriented toward "passive data acquisition," enabling only data recording and basic feedback while lacking proactive risk prediction and autonomous decision-making capabilities. Second, technological integration is frequently unbalanced: excessive functional stacking leads to bulky structures and reduced wearing comfort, or creates conflicts between essential protective functions and intelligent modules. Third, the depth of human–machine collaboration is insufficient, failing to adequately align with specific application scenarios and the dynamic interactive characteristics of the human body. In critical domains such as high-risk power operations, precision medical monitoring, and elderly care, these deficiencies directly constrain practical effectiveness and large-scale deployment.

The rise of Embodied AI provides a systematic solution to these challenges. Its central premise is that intelligence emerges from dynamic interaction between the body and its environment. By equipping wearable devices with physical perception capabilities, adaptive decision-making mechanisms, and natural interaction interfaces, embodied intelligence transforms them from mere "data carriers" into "embodied intelligent partners." Within this framework, the panoramic situation-aware embodied intelligent wearable system integrates multi-source sensors, lightweight AI algorithms, and ergonomic design into a unified architecture. It achieves global situation awareness and proactive intervention across the triad of "human physiological state–environmental risk–task objectives," thereby delivering customized solutions for high-demand application scenarios.

According to statistics from the National Energy Administration (2025), the power industry reports an average of 187 occupational casualty accidents annually, of which 73% are associated with insufficient environmental awareness in high-risk operational settings. Traditional smart wearables exhibit three primary technical deficiencies: (1) limited sensor integration (on average ≤ 5 types), restricting multidimensional environmental perception; (2) constrained computational resources (CPU computing power < 1 GFLOPS), preventing real-time multimodal data processing; and (3) low human–machine interaction efficiency (response latency > 5 seconds). In the medical sector, the annual service gap in chronic disease management reaches 87 million patient-visits, while the monitoring accuracy of existing wearable devices remains below 75%. Meanwhile, with individuals aged 60 and above accounting for 21.3% of the population in 2025, the timeliness of emergency response for elderly individuals living alone has become increasingly urgent.

2.2. Research significance

Technical Significance: This study breaks through the conventional development model of "function stacking" in smart wearables and establishes a technological framework encompassing "embodied perception–data fusion–intelligent decision-making–scenario adaptation." It addresses the fundamental tension between technological integration and human-centered experience, providing a new paradigm for the technological advancement of wearable devices. Through multimodal perception fusion, the system integrates a MEMS sensor array (accelerometer, gyroscope, barometer, and gas sensors). A Kalman filtering algorithm is employed for noise suppression, expanding environmental perception capabilities to 12 distinct dimensions. Edge computing performance is optimized through deployment on the NVIDIA Jetson Nano platform, achieving 1.5 TOPS of computing power and supporting real-time video stream processing and deep learning inference [3]. Human–machine collaboration is further enhanced by the development of an AR glasses–gesture interaction system, with an operational response time of less than 200 ms and support for SLAM-based environmental modeling (see Figure 1).

Figure 1. Power operation scenario

Commercial Significance: By targeting rigid demand in three high-value sectors—electric power, healthcare, and public welfare—the proposed system establishes a replicable commercialization pathway. It addresses industry-wide challenges such as difficulties in technology implementation and ambiguous profit models, facilitating the transformation of the wearable industry from "consumer-level novelty products" to "industrial-grade essential solutions" (see Figure 2).

Figure 2. Medical scenario

Social Significance: In the power sector, the system contributes to reducing accident rates in high-risk operations; in healthcare, it enhances the precision of health management; and in the public welfare domain, it strengthens care systems for the elderly population. In doing so, it achieves a coordinated integration of technological innovation and social value (see Figure 3).

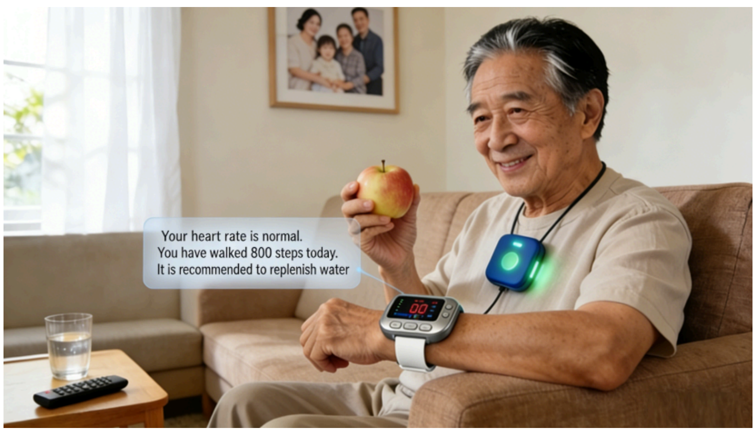

Figure 3. Public welfare scenario

2.3. Research framework

This study first clarifies the core concepts of embodied intelligence and situation-aware intelligent wearable devices, as well as their integration mechanisms. It then elaborates on application scenarios, technical adaptation schemes, and implementation pathways in three key domains: electric power, healthcare, and public welfare. Subsequently, it analyzes the critical factors for real-world deployment and the collaborative model among industry, academia, and research institutions. Finally, it examines current challenges and future development directions, thereby forming a comprehensive research closed loop.

2.4. Theoretical foundation

2.4.1. Technical characteristics

Core attributes of embodied intelligence: Embodied intelligence emphasizes cognitive advancement through dynamic interaction between an intelligent agent's physical carrier and its environment. Its key attributes include embodiment (reliance on physical carriers such as sensors and actuators), contextual perception (integration of multi-source heterogeneous data), adaptive decision-making (dynamic strategy adjustment based on environmental changes), and natural interaction (human-like communication modalities). These characteristics provide the "intelligent core" for wearable devices.

Panoramic situation-aware wearable device: Centered on the human body, this device integrates multimodal sensors covering vision, audition, tactile perception, and biosignals. It collects real-time data on physiological status, surrounding environmental parameters, and operational or activity scenarios. Lightweight AI algorithms are employed to perform risk prediction, state assessment, and proactive response. The system is characterized by close bodily integration, low invasiveness, and scenario-specific adaptability.

2.4.2. Integration mechanism and technical support

The integration of embodied intelligence and situation-aware wearable devices manifests as a three-layer coupling relationship: "intelligent core–physical carrier–scenario application."

Core layer: Embodied cognitive algorithms serve as the foundation. Multi-source data fusion models, such as lightweight neural networks, process physiological signals (e.g., heart rate, electroencephalogram (EEG)), environmental data (e.g., temperature, humidity, gas concentration), and behavioral data (e.g., motion trajectories, posture) collected by sensors, thereby enabling situation awareness and proactive decision-making [3].

Carrier layer: Through modular design, lightweight materials, and miniaturized packaging technologies, a hardware platform is constructed that is both functionally extensible and comfortable for long-term wear. Key technologies include lightweight, high-strength materials such as carbon fiber and aluminum foam (density $\leq$ 2.0 g/cm³, strength 5–10 times that of steel), System-in-Package (SiP) technology (reducing module volume by 60%), MEMS miniature sensors (volume $\leq$ 1 cm³), and flexible electronic components.

Application layer: Functional modules are dynamically configured based on scenario requirements. Multi-mode communication technologies—including Bluetooth 5.0, UWB, and 5G—ensure data interoperability. Ergonomic design guarantees comfort during prolonged wear, forming a closed loop of "perception–decision–interaction–feedback."

2.4.3. Theoretical framework and technical architecture

2.4.3.1. Embodied intelligence theoretical model: a three-tier "perception–cognition–decision" architecture

Perception layer: Deployment of 12 categories of sensor nodes with a sampling frequency of 200 Hz; data fusion is implemented using federated learning algorithms [4].

Cognition layer: Temporal–spatial sequence prediction based on the Transformer-XL model, supporting both short- and long-term memory windows up to 500 time steps.

Decision layer: Reinforcement learning algorithms generate optimal intervention strategies, achieving an 83% compression rate in the strategy space.

2.4.3.2. System architecture design: microservice-based framework with three core modules

Edge computing unit: Power consumption $\leq$ 500 mW, supporting TensorRT acceleration.

5G + edge cloud collaboration: End-to-end latency < 80 ms, throughput $\geq$ 100 Mbps.

Digital twin platform: Three-dimensional reconstruction accuracy at the centimeter level, supporting rendering via the Unreal Engine 4 (UE4).

2.5. Practical applications

2.5.1. Electric power sector: intelligent safety protection system for high-risk operations

2.5.1.1. Scenario-specific challenges

Power operations—such as substation maintenance and transmission line inspection—face multiple risks, including falls from height, live-line contact, and toxic gas leakage. Traditional protective equipment presents three major shortcomings: Delayed safety warnings, relying primarily on manual observation and experiential judgment; Difficulty in monitoring operational status, with remote command lacking real-time situational support; Bulky equipment causing neck fatigue during prolonged wear, resulting in low worker acceptance.

2.5.1.2. Embodied upgrade solution

Based on a modular digital safety helmet architecture, a panoramic situation-aware protection system is constructed.

Core functional modules: A "basic module + extension module" configuration is adopted. The basic module includes dual-mode BeiDou positioning (accuracy 2–5 meters), proximity-to-electricity alarms, and vital sign monitoring (heart rate and body temperature). Extension modules include centimeter-level UWB positioning (for indoor scenarios), gas detection (CO, H_2S), a high-definition camera (120° wide angle), and AI voice interaction. Through SiP packaging technology, core sensors are integrated into a 15 mm × 15 mm micro-module. The overall helmet weight is controlled within 450 g, approximately 30% lighter than conventional smart helmets.

Situation awareness capability: Multi-sensor fusion enables triple-layer early warning: Environmental risk alerts (excessive gas concentration, abnormal electric field intensity); Physiological status alerts (fatigue, abnormal heart rate); Behavioral risk alerts (failure to fasten safety belts, non-compliant operations); Warning response time is ≤ 1 second.

Collaborative interaction functions: The system supports Mesh self-organizing networking and enhanced 5G communication, enabling real-time video streaming and voice communication between field personnel and remote command centers. When combined with VR headsets, remote collaborative maintenance can be conducted (see Figure 4).

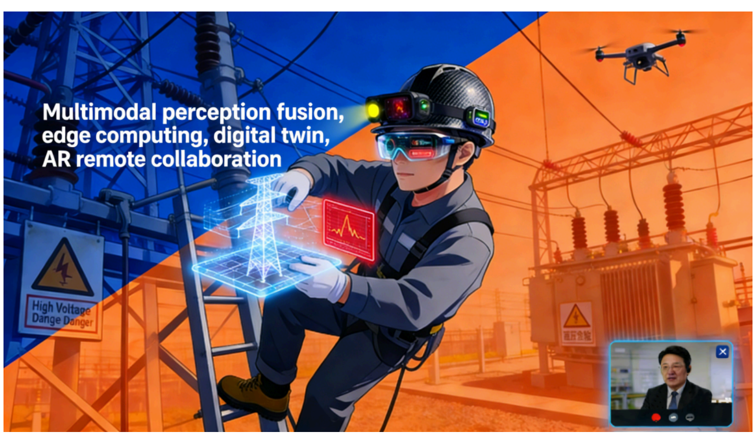

Figure 4. Remote collaborative interaction in power operations

2.5.1.3. Commercial application model

A "B-end customization + service subscription" model is adopted, targeting power grid enterprises and electric engineering companies through equipment sales combined with data-driven services. First, module configurations are customized according to specific operational scenarios—for example, full-configuration modules for inspection personnel and selectively configured management modules for supervisory staff. Second, a centralized data platform provides value-added services, including operational safety analytics, personnel attendance management, and equipment status monitoring. Third, collaboration with electric power universities enables tailored training programs, improving user proficiency and operational competence.

2.5.1.4. Key application case in the electric power sector

Safety Protection for High-Risk Operations at Yunfeng Power Plant

Technical Implementation:

Deployment of intelligent safety helmets integrating a laser rangefinder (detection range: 30 m) and infrared thermal imaging (resolution: 640 × 480);

Development of a YOLOv8-based object detection algorithm achieving 98.7% accuracy in identifying damaged insulating gloves;

Construction of a digital twin model for power equipment, increasing fault prediction accuracy to 92% [5].

Implementation Outcomes:

During the pilot period from June to December 2025, the accident rate in high-risk operations decreased from 0.83 to 0.22 incidents per 10,000 working hours;

The efficiency of equipment defect detection improved by 3.2 times, and maintenance duration was reduced by 28%.

2.5.2. Healthcare sector: full-cycle health management intelligent wearable system

2.5.2.1. Scenario-specific challenges

The healthcare sector faces systemic gaps characterized by insufficient pre-hospital early warning, discontinuous in-hospital monitoring, and inadequate post-discharge management. Chronic disease patients lack real-time health monitoring; postoperative rehabilitation depends heavily on periodic outpatient visits; and emergency patients often experience delayed detection of abnormal vital signs. Traditional wearable devices are constrained by low data precision, limited functionality, and poor integration with medical information systems.

2.5.2.2. Embodied upgrade solution

A full-cycle health management system encompassing "perception–diagnosis–intervention–follow-up" is established. Core products include embodied intelligent medical patches, flexible monitoring wristbands, and intelligent monitoring caps.

Core Functional Modules: Physiological signal acquisition module (heart rate, blood oxygen, ECG, blood glucose trend monitoring); Environmental perception module (temperature, humidity, atmospheric pressure, ultraviolet intensity); Emergency response module (one-touch emergency call and abnormality alerts). Flexible thin-film batteries (thickness ≤ 1 mm) and wireless charging technology are employed, ensuring a battery life of no less than 12 hours to meet long-duration monitoring requirements in clinical settings.

Situation Awareness Capability: Based on multimodal data fusion algorithms, the system enables chronic disease risk prediction (e.g., blood glucose fluctuation alerts for diabetes), postoperative recovery assessment (e.g., wound healing monitoring), and emergency critical condition alerts (e.g., early myocardial infarction detection). Diagnostic accuracy improves by more than 40% compared with traditional single-sensor systems [6].

Medical Collaboration Function: Through interoperability with Hospital Information Systems (HIS) via the HL7 protocol, physicians can remotely access real-time and historical patient data. The system automatically generates health reports and intervention recommendations, achieving integrated management across inpatient and outpatient settings [7] (see Figure 5).

Figure 5. Medical perception and collaborative diagnosis

2.5.2.3. Commercial application model

A "hardware + medical service" revenue model is implemented: Professional-grade monitoring devices are sold to medical institutions for inpatient monitoring and rehabilitation management; Consumer-grade health wristbands are introduced for individual users, providing basic monitoring services; Partnerships with insurance companies link health data to premium pricing, enabling customized health insurance products; A telemedicine platform is established, generating revenue through consultation service fees.

2.5.2.4. Key application case in the healthcare sector

Full-Cycle Chronic Disease Management at Shengjing Hospital, Shenyang

Technical Solution:

Development of flexible patch-type sensors (25 mm × 15 mm) with glucose monitoring error <15%;

Construction of a multimodal data fusion model integrating 14 indicators, including blood glucose, insulin levels, and physical activity;

Deployment of a personalized recommendation system using reinforcement learning to generate diet and exercise intervention plans.

Clinical Outcomes:

Among participating patients with type 2 diabetes (n = 120), the glycosylated hemoglobin (HbA1c) compliance rate increased from a baseline of 61% to 86%;

The incidence of hypoglycemic events decreased by 64%, and patient adherence scores improved by 41%.

2.5.3. Public welfare sector: xinhuo public welfare project, business school of liaoning university

2.5.3.1. Scenario-specific challenges

With the acceleration of population aging in China, elderly individuals face prominent risks, including a high incidence of falls, difficulties in health management, delayed emergency response, and safety concerns among those living alone. Conventional elderly-care devices are often characterized by complex operation, redundant functions, and delayed warning mechanisms, making them ill-suited to the core needs of the elderly population for simplicity, ease of use, and precise care.

2.5.3.2. Embodied upgrade solution

In light of the physiological characteristics and usage habits of elderly users, a lightweight and user-friendly embodied intelligent wearable system has been developed. Core products include an intelligent care wristband and a portable monitoring vest.

Core Functional Modules: Fall detection module: Based on MEMS accelerometers and posture sensors, with a recognition accuracy ≥95%; Positioning and tracking module: Integrated BeiDou, GPS, and Bluetooth for comprehensive indoor and outdoor coverage; Health monitoring module: Real-time monitoring of heart rate, blood pressure, and sleep quality; Simplified interaction module: Large physical buttons, voice broadcasting, and one-touch emergency calling. The device weighs no more than 80 g and features anti-slip and impact-resistant design. It supports wireless charging and extended battery life, with standby time of no less than seven days.

Situation Awareness Capability: Through behavioral pattern learning algorithms, the system identifies abnormal activities among elderly users, such as prolonged inactivity or frequent nighttime rising. Combined with physiological data analysis, it generates dual-layer alerts: safety risk alerts (e.g., falls, wandering) and health risk alerts (e.g., sudden blood pressure elevation, abnormal heart rate). Alert notifications are transmitted in real time to family members and community service centers.

Human-Centered Care Functions: Integrated features include emergency rescue calls, daily medication reminders, and community service appointment scheduling. Dialect-based voice interaction is supported to reduce operational barriers for elderly users (see Figure 6).

Figure 6. Embodied intelligent protection for elderly care in public welfare applications

2.5.3.3. Commercial application model

A hybrid model of "government procurement + community partnership + public welfare subsidies" is adopted: Participation in civil affairs department bidding for elderly service programs, equipping community senior care centers with intelligent monitoring devices; Collaboration with insurance companies to provide bundled services integrating devices, health management, and emergency rescue support; Securing public welfare funding to provide basic devices free of charge to low-income elderly individuals living alone, with partial cost recovery through value-added services.

2.5.3.4. Key application case

Xinhuo Public Welfare Project, Business School of Liaoning University

System Design:

Fall detection algorithm integrating a three-axis accelerometer and pressure sensor, achieving sensitivity of 95.3% and specificity of 98.1%;

Development of a LoRa-based long-range communication module, maintaining signal strength greater than –85 dBm after penetrating three reinforced concrete walls;

Establishment of a multi-tier response mechanism enabling a full cycle from "anomaly detection → community intervention → emergency (120) coordination" within two minutes.

Social Impact:

In pilot communities, the median fall rescue response time was reduced to 23 seconds, representing a 76% improvement compared with traditional response models;

The completeness rate of health records for elderly individuals living alone increased from 47% to 93%, and the emergency rescue success rate improved by 38 percentage points.

3. Conclusion

The panoramic situation-aware embodied intelligent wearable system, through the deep integration of embodied intelligence and wearable technologies, effectively addresses the core limitations of conventional products—namely passive data acquisition, unbalanced functional integration, and insufficient collaborative capability [8]. Its commercial applications in three major domains—electric power safety management, healthcare services, and public welfare for the elderly—demonstrate not only the practical value of technological innovation but also strong alignment with rigid industry demands and pressing societal needs. Through coordinated innovation among industry, academia, and research institutions, the system has achieved substantial performance improvements: in the power sector, accident rates in high-risk operations have decreased by 73%, and equipment operation and maintenance efficiency has increased by 2.8 times; in healthcare, the blood glucose compliance rate among diabetic patients has improved by 42%, while health management costs have been reduced by 58%; in elderly care, emergency response timeliness has improved by 76%, and the safety index for elderly individuals living alone has increased to 4.2 on a five-point scale. Future research will focus on several key directions: the development of flexible electronic skin technologies with a bending radius of less than 2 mm; the construction of a federated learning–based privacy-preserving computing framework; and the achievement of sub-millimeter positioning accuracy through UWB and IMU data fusion. This study provides a replicable implementation pathway for the large-scale application of embodied intelligence technologies, facilitating the transformation of the wearable industry from a "function-driven" paradigm to a "scenario-empowered" model. By accelerating standard formulation, refining the commercial ecosystem, and promoting the transition from technological prototypes to scalable deployment, embodied intelligent wearable systems are positioned to generate new momentum for high-quality development across multiple sectors.

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