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Design of Real-Time Monitoring and Environmental Monitoring Warning System for Occupational Health Parameters of High-Altitude Construction Workers

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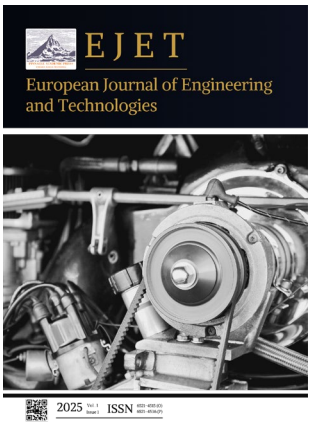

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Abstract: An excellent occupational health and safety management system provides a scientific and effective management tool for enterprises to improve their occupational health and safety performance. Research has shown that in high-altitude areas, many occupational diseases develop without any prior warning signs. Moreover, construction workers are identified as a high-risk group for developing occupational diseases. This urgently requires an intelligent supervision system for monitoring the health of high-altitude construction workers. With the development of intelligent and digital technologies, the design of an intelligent occupational health supervision and early warning system has become possible. In this context, this article has carried out system design and designed real-time monitoring and environmental monitoring modules for occupational health, providing new management methods for occupational health supervision of construction personnel in enterprises. In addition, the system has also designed an emergency module to provide high-quality resource support for ensuring the safety production of enterprises.

Keywords: high altitude construction personnel; occupational health; real time monitoring; environmental monitoring and early warning; systems design

1. Introduction

1.1. The Concept and Importance of Occupational Health

Occupational health is a discipline dedicated to identifying, evaluating, predicting, and controlling harmful occupational factors and their health impacts in the workplace. Its primary aim is to prevent and mitigate health risks posed by workplace hazards, ensure that work is suited to workers' capabilities, and promote both their physical and mental well-being. A sound occupational health and safety management system provides enterprises with a scientific and effective tool to enhance occupational performance. It also facilitates the implementation of occupational health standards and regulatory compliance.

1.2. Occupational Health Challenges in High-Altitude Regions

In high-altitude areas, occupational diseases often manifest without warning, making them difficult to detect early. The unique climatic and environmental characteristics — such as low oxygen levels, extreme temperatures, and intense ultraviolet radiation —

significantly contribute to the increased incidence and prolonged recovery time of occupational diseases in these regions. Existing studies indicate that construction workers are particularly vulnerable, with higher prevalence and longer treatment cycles compared to those in lower-altitude regions [1-3].

1.3. Technological Advances in Occupational Health Supervision

With ongoing economic development and digital transformation, intelligent supervision has emerged as a promising solution for occupational health management. Research from international experts has demonstrated the feasibility and benefits of intelligent regulation in occupational health [4-6]. Meanwhile, Chinese scholars have also proposed and implemented intelligent monitoring systems tailored to occupational health scenarios [7]. These systems leverage technologies such as the Internet of Things (IoT), big data, and artificial intelligence to enhance real-time monitoring and response capabilities.

1.4. Research Gap and System Development Significance

Despite these advancements, there remains a significant gap in the application of intelligent monitoring systems specifically designed for construction workers in high-altitude environments. In particular, systems that integrate occupational health monitoring with environmental early warning are still lacking. Addressing this gap is crucial, as the adoption of intelligent supervisory methods can substantially improve regulatory efficiency, safeguard worker health, and reinforce safety management in high-altitude construction operations. This study, therefore, aims to design a comprehensive monitoring and early warning system that meets the unique demands of high-altitude construction, thereby supporting sustainable development and risk mitigation in this field.

2. Background and Significance of System Development

2.1. The Harsh Construction Environment at High Altitudes

High-altitude regions — such as the Qinghai-Tibet Plateau — present a uniquely challenging environment for construction activities. With an average elevation exceeding 4000 meters, the region experiences low atmospheric pressure and oxygen levels at only about 60% of those in lowland areas. Climatic conditions are highly variable, featuring sharp temperature fluctuations between day and night, intense ultraviolet radiation, and frequent occurrences of extreme weather events such as high winds, blizzards, and low-pressure systems.

These environmental stressors pose serious occupational health risks for construction workers. Acute high-altitude illnesses — including high-altitude pulmonary edema and cerebral edema — can occur suddenly and lead to life-threatening complications. Chronic conditions such as high-altitude heart disease and polycythemia often develop insidiously, going undiagnosed until they reach advanced stages. In addition, cold temperatures increase the risk of frostbite and respiratory infections, while prolonged exposure to ultraviolet radiation may lead to skin cancer and ocular conditions like cataracts. The harsh environment also imposes significant physical and psychological burdens, decreasing worker morale, reducing operational efficiency, and compromising overall safety on-site.

2.2. Limitations of Traditional Management Models

Traditional manual approaches to occupational health and environmental monitoring in high-altitude construction settings have proven increasingly inadequate. Health data collection typically relies on manual recording, which is time-consuming, prone to human error, and fails to provide real-time insights into workers' health conditions. Additionally, the lack of integration between health indicators and environmental parameters makes it difficult to identify causal relationships and proactively manage health risks.

Delayed risk alerts often result in late interventions, reducing the effectiveness of treatment and increasing the likelihood of accidents or medical emergencies. Moreover,

the absence of standardized emergency response protocols hampers the ability to respond quickly and effectively to sudden incidents such as altitude sickness outbreaks or extreme weather events. These limitations not only endanger worker safety but also lead to construction delays, cost overruns, and disruptions to overall project timelines.

2.3. The Significance of System Development

To address these pressing challenges, the Real-Time Monitoring and Environmental Early Warning System for Occupational Health Parameters of High-Altitude Construction Personnel has been conceptualized and developed. This system is specifically tailored to the demands of high-altitude construction, integrating intelligent technologies to establish a comprehensive, responsive, and data-driven management platform.

From a health management perspective, the system enables continuous real-time monitoring of physiological indicators, early detection of abnormalities, and scientifically grounded intervention strategies. This contributes to a robust protective framework for worker health, reducing the incidence of high-altitude illnesses and safeguarding workers' rights and well-being.

From a project management standpoint, the system supports dynamic monitoring of both personnel health and environmental conditions. It facilitates optimized scheduling, resource allocation, and operational planning by minimizing the impact of unforeseen health or environmental disruptions. Ultimately, the system helps construction enterprises enhance their overall management efficiency, reduce operational risks, and achieve high-quality, sustainable development in high-altitude construction projects.

3. System Architecture Design

To effectively safeguard the occupational health of high-altitude construction workers and respond to the challenges posed by extreme environmental conditions, a modular, scalable, and intelligent system architecture has been developed. The system integrates health parameter detection, environmental monitoring, and emergency response management, forming a comprehensive and real-time supervision platform. Each functional module is closely aligned with the practical demands of high-altitude construction, supporting full-process digital management — from data collection and abnormality detection to feedback and optimization. This chapter outlines the core components of the system, beginning with the health parameter detection module.

3.1. Health Parameter Detection Module

3.1.1. Management of Health Indicators for Construction Personnel

This module enables comprehensive lifecycle management of health data for construction personnel. The system supports "add, edit, delete, and query" operations, allowing for the entry of key health indicators such as personnel ID, heart rate, blood pressure, blood oxygen saturation, and body temperature, as well as recording time, to build a standardized health record library. For example, construction workers enter basic health data when they join, and during the operation, their physiological indicators are synchronized in real time through smart wearable devices (such as high-altitude work wristbands), and special scenario data can be manually supplemented. It supports multi-condition combination queries (such as precise search by personnel ID and time-based filtering), enabling quick access to health data. This provides an accurate foundation for further analysis and alerts, helping managers monitor the real-time health status of personnel.

3.1.2. Abnormal Health Record and Tracking

This function focuses on managing abnormal health data, including recording abnormal indicators (such as high heart rate, irregular blood pressure, and low blood oxygen saturation), the corresponding values, timestamps, and associated personnel IDs. The system automatically recognizes abnormal data uploaded by smart devices and also supports

manual input of abnormal situations. For each abnormal record, it is possible to edit and correct information, delete false positive data, and track the progress of abnormal disposal (associated with emergency response processes), forming a "feedback loop for abnormal discovery and resolution" that ensures timely intervention in health risks and minimizes the likelihood of disease progression, such as in cases of altitude sickness.

3.2. Environmental Monitoring and Early Warning Module

3.2.1. Environmental Monitoring Data Collection and Management

The system can deploy multiple types of environmental sensors (temperature, humidity, oxygen concentration, PM2.5 sensors, etc.) to collect real-time construction environment data, including monitoring station IDs, environmental indicators (temperature, humidity, oxygen concentration, PM2.5 concentration), indicator values, and collection time. Sensors are strategically distributed across key locations such as construction camps, work zones, and tunnels to ensure systematic and comprehensive environmental data coverage. The system supports "adding, editing, deleting, and querying" environmental data, automatically synchronizes data with sensors, and also allows manual supplementation of special environmental data (such as manually observed data under extreme weather conditions), providing a basic data source for analyzing the impact of the environment on human health and timely capturing abnormal changes in the environment (such as sudden drops in oxygen concentration and PM2.5 exceeding standards).

3.2.2. Intelligent Management of Environmental Warning Information

Based on environmental monitoring data, set flexible warning rules (such as high temperature warning triggered by temperature >30℃, low oxygen warning triggered by oxygen concentration <16%, pollution warning triggered by PM2.5 concentration >150μg/m ^{3}), and associate warning levels (general, important, urgent). The system monitors environmental data in real-time, triggers rules to generate warning information, records warning ID, monitoring station ID, warning type, warning level, and warning time. The system supports the operation of "editing and deleting" warning information, which facilitates management personnel to deal with false alarms and missed reports. By issuing environmental warnings in advance, the system enables proactive interventions — such as activating ventilation equipment or adjusting work schedules — to mitigate environmental threats to construction workers' health.

3.3. Other Module Design

3.3.1. Retrospective and Analysis of Historical Health Data

The system supports querying historical health data by data ID, employee ID, health indicators, recorded values, and timestamps. It also facilitates the creation of a comprehensive lifecycle archive of personnel health data. Construction personnel can check the trend of personal health indicators (such as heart rate, blood oxygen with the duration of work, seasonal changes) to understand their own health evolution. Management personnel can review workers' health data over the course of the project to identify incidence patterns of high-altitude diseases — such as seasonal and regional variations in risk. This supports the development of optimized health management strategies, including targeted medical examinations and preventive actions. By extracting insights from historical data, the scientific rigor and effectiveness of health management can be improved.

3.3.2. Emergency Response Plan Management

Implement full lifecycle management of emergency response plans, supporting input and query of information such as plan ID, plan name, plan description, creation time, status (valid, invalid, pending review), etc. Management personnel may add emergency plans (such as high-altitude heatstroke, hypoxia, and severe weather emergency plans),

detailing emergency response steps, division of responsibilities, and resource allocation. Edit existing contingency plans and optimize processes based on actual drills and accident handling experience. Delete invalid contingency plans to ensure the efficiency and practicality of the contingency plan library. By standardizing contingency plan management, the system provides clear and effective guidance for emergency situations and enhances the overall consistency of emergency responses.

4. System Advantages and Features

4.1. Tailored Adaptation to High-Altitude Construction Scenarios

The system is meticulously designed to address the unique challenges posed by high-altitude construction environments, characterized by low oxygen levels, sub-zero temperatures, intense ultraviolet radiation, and rapidly changing weather conditions. It incorporates a comprehensive approach — ranging from health parameter monitoring (emphasizing high-altitude-sensitive indicators such as heart rate, blood oxygen saturation, and blood pressure), to environmental monitoring (focusing on critical factors like oxygen concentration, temperature fluctuations, and UV radiation), and emergency response (aligned with protocols for altitude-related illnesses and extreme weather events). Unlike general-purpose occupational health systems, this platform offers a context-specific solution that more precisely identifies and mitigates health and environmental risks associated with high-altitude conditions. By directly addressing these critical "pain points", the system ensures that workers receive targeted health protection and management tailored to their unique operational environment.

4.2. Data-Driven Intelligent Management Loop

At the core of the system is a closed-loop intelligent management mechanism built on cutting-edge technologies, including big data analytics, the Internet of Things (IoT), and artificial intelligence (AI). This loop follows a continuous cycle of "data collection → intelligent analysis → early warning → emergency response → data accumulation → feedback and optimization".

Health and environmental data are captured in real time through wearable devices and sensor networks. When predefined thresholds are breached, the system automatically triggers early warnings and initiates corresponding emergency response workflows. All actions and data from the response phase are logged and stored as historical records, feeding back into the system to optimize future responses — such as refining warning thresholds, adjusting intervention strategies, and enhancing contingency plans. This dynamic learning capability enables the system to adapt to evolving construction conditions and management requirements, progressively enhancing the precision, responsiveness, and scientific rigor of occupational health and safety management in high-altitude settings.

4.3. Multidimensional Collaborative Management Framework

The system fosters an integrated management ecosystem that spans across multiple stakeholder roles — including front-line construction workers, team leaders, medical personnel, project managers, and environmental monitoring specialists.

Construction workers are empowered with real-time access to their own health data and alerts, encouraging self-awareness and proactive participation in personal health management. Team leaders are equipped to swiftly interpret alerts and coordinate on-site interventions. Medical staff utilize system-provided data to conduct informed diagnoses and deliver personalized medical guidance. Project managers oversee the coordination of human and environmental resources, adjusting management strategies based on real-time data insights. Environmental personnel, in turn, provide critical feedback on ambient conditions and coordinate work adjustments to maintain safety thresholds.

This multidimensional framework breaks down traditional information silos, enabling transparent communication and fast, cross-functional decision-making. As a result, it

builds a culture of "full-staff engagement and whole-process control", significantly elevating the overall effectiveness and responsiveness of occupational health and environmental risk management in high-altitude construction projects.

5. Conclusion and Discussion

The continuous advancement of intelligent and digital technologies has created unprecedented opportunities for reshaping occupational health management in challenging environments such as high-altitude construction sites. This paper, grounded in the dual perspectives of occupational health monitoring requirements and the distinct environmental characteristics of high-altitude regions, presents the design of an integrated Real-time Monitoring and Environmental Early Warning System tailored for construction personnel. The proposed system structure and modular functions — including health parameter detection, abnormal data tracking, environmental monitoring, early warning, and emergency response — form a comprehensive technical framework for intelligent health governance.

From a practical perspective, this system addresses long-standing limitations of traditional health management approaches, such as data fragmentation, delayed responses, and weak interdepartmental coordination. By introducing real-time data collection, automated analysis, intelligent alerting mechanisms, and feedback-based optimization, the system enables early detection and intervention in health risks such as altitude sickness, frostbite, and hypoxia-induced disorders. It also enhances the precision and timeliness of environmental risk control, offering construction enterprises an effective tool to ensure safety, reduce work interruptions, and lower long-term operational risks.

From a managerial standpoint, the system provides multidimensional support:

1) It empowers frontline workers with access to personal health records, fostering self-awareness and compliance.
2) It enables medical teams to conduct targeted diagnostics and interventions.
3) It facilitates project-level decision-making through holistic environmental and health data analytics.
4) It enhances the responsiveness of emergency operations via standardized contingency planning.

Despite the system's strengths, certain challenges and limitations remain. The accuracy and reliability of real-time data still rely heavily on the quality and maintenance of hardware devices (e.g., wearables and sensors), and the success of intelligent warnings is subject to the refinement of thresholds and algorithmic models. Moreover, cross-role coordination effectiveness depends on the degree of user training and organizational alignment. Future research and system iterations should focus on improving algorithmic adaptability, integrating machine learning for personalized risk prediction, and expanding applicability to broader altitudes and industrial contexts beyond construction.

In conclusion, this system represents an innovative and scalable solution to the urgent need for intelligent occupational health management in high-altitude environments. By aligning technological capabilities with real-world demands, it contributes to both the health protection of workers and the sustainable development of construction operations in extreme geographical contexts.

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