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Research on the Application of Intelligent Technologies in Safety Management of Engineering Machinery Equipment

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Abstract. Traditional management approaches have increasingly revealed limitations in dynamic response and data coordination. The rapid development of next-generation information technologies, such as the Internet of Things (IoT), Building Information Modeling (BIM), and Artificial Intelligence (AI), provides new solutions to these challenges. This paper adopts a literature review method to systematically examine the research progress and practical applications of IoT, BIM, and AI in the safety management of construction machinery. By analyzing the key shortcomings of traditional management models, this study explores the application of these technologies in condition monitoring, lifecycle visualization management, fault diagnosis and early warning, and intelligent operation assistance. This paper proposes implementation strategies, including the integration of multiple intelligent technologies to build a comprehensive management system and data platform, the enhancement of personnel's digital literacy, and the promotion of preventive maintenance. Finally, the study discusses future development trends such as intelligent decision-making, unmanned operations, and systematic risk prediction.

Keywords: Equipment Management, Intelligent Technologies, Internet of Things, Building Information Modeling, Artificial Intelligence

1. Introduction

With the continuous expansion of China's infrastructure construction scale, construction machinery is increasingly widely used in tunnel construction, rail transit, and large-scale municipal engineering. Its operational safety is directly related to engineering quality and the life safety of construction personnel. Traditional management models cannot meet the demands of high-quality development in modern engineering. In recent years, the rapid development of next-generation information technologies, such as the Internet of Things (IoT), Building Information Modeling (BIM), and Artificial Intelligence (AI), has provided new technical pathways for the safety management of construction machinery.

Existing research has already conducted related studies on these technologies. Hu et al. summarized the progress of BIM research and analyzed its bottlenecks in engineering information technology [1]. Focusing on IoT technology, Wu Jing established an efficient, intelligent, and sustainable safety management system for construction machinery [2]. Zhan Huimin explored the application and achievements of AI technology in the safety management of building construction

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[3]. However, existing studies mostly focus on a single technology. They lack a systematic review and discussion on implementation strategies for the integrated application of IoT, BIM, and AI in the safety management of construction machinery.

Based on an analysis of problems in traditional equipment management models, this paper adopts a literature review method to explore and integrate the specific applications of IoT, BIM, and AI technologies in equipment safety management. Corresponding implementation strategies and development trends are proposed. This study aims to provide references for improving and optimizing the intelligent management of construction machinery.

2. Problems in the traditional management model

2.1. Personnel awareness and safety risks

Technicians and equipment operators rely on traditional experience for long periods, accustomed to judging equipment status and arranging work processes based on accumulated operational experience. There is a general lack of systematic, standardized safety operations thinking. Consequently, problems such as operating equipment in violation of regulations, simplifying equipment inspection procedures, and ignoring abnormal equipment operation signals are common.

Furthermore, on one hand, the implementation of safety responsibility systems at some construction sites is currently inadequate, lacking effective incentives for standardized operations and rigid constraints against rule-breaking behavior. On the other hand, pre-job safety training often becomes perfunctory, with content not tailored to specific equipment models or working conditions and without practical operational assessments. Additionally, phenomena such as one person holding multiple posts and temporary job substitutions often exist on construction sites [4]. Operators' safety awareness is further weakened, making it difficult to effectively avoid potential risks during operational processes. This increases the probability of safety accidents on construction sites.

2.2. Construction efficiency

Equipment fault diagnosis relies on manual inspection. Since this inspection method primarily involves fixed-frequency inspections, it cannot respond promptly to sudden failures. Second, due to this reliance on manual inspection, some key components that are difficult to access are easily overlooked. In addition, the inspection cycle and duration are affected by factors such as weather and the technical personnel's own experience level. This process is not only time-consuming but also prone to judgment errors, which may delay maintenance timing. Such delays lead to extended equipment downtime and delay construction progress.

Meanwhile, due to the lack of information management systems to record equipment operation data, construction sites temporarily find it difficult to conduct precise analysis of individual machine operational efficiency. They also cannot carry out targeted optimization of work processes.

3. Application of intelligent technologies in equipment safety management

3.1. Internet of Things (IoT)

The application of Internet of Things (IoT) technology in the safety management of construction machinery primarily involves equipment identification, sensor-based state perception, data transmission, and remote control.

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IoT uses coding and identification technologies to assign a unique identity to each piece of equipment and its parts. Combined with the structured organization of large databases, this enables rapid equipment querying and data tracking, thereby reducing resource waste and errors caused by manual record management. Installing various types of sensors, such as temperature sensors, vibration sensors, pressure sensors, and current sensors, on key components like bearings, gears, hydraulic systems, and power cores allows for comprehensive capture of equipment operating conditions and real-time data collection. This enables dynamic assessment of equipment status and effective prediction of equipment lifecycle [5].

On this basis, Prognostics and Health Management (PHM) uses advanced sensors to measure information closely related to equipment health status (such as vibration, temperature, current, and voltage). Through the fusion analysis of historical equipment data and current monitoring data, and with the help of signal processing and machine learning methods, it judges the online operating status of equipment, detects early faults, and assesses the degree of failure. Based on these data, it can further reveal the degradation patterns of equipment performance and predict the future health status and remaining useful life of the equipment [6].

Simultaneously, IoT transmits equipment data to a cloud platform in real time via wireless networks. The cloud platform uses big data analysis to assess equipment health in real time and proactively identify potential faults. Through this intelligent monitoring system, equipment can predict faults, reducing downtime and maintenance costs. Moreover, IoT can also support remote control and dispatching of equipment, enhancing the flexibility and automation level of construction operations.

3.2. BIM

Building Information Modeling (BIM) technology achieves visualized management of the entire equipment lifecycle by constructing digital models of projects and equipment. In equipment safety management, BIM technology can integrate equipment structural information, operational parameters, and maintenance records, and visually present equipment status in 3D. This allows managers to rapidly understand equipment operational conditions.

For example, during the construction phase of building projects, BIM technology presents the construction site's terrain, buildings, and surrounding environment comprehensively to the construction team by constructing a comprehensive 3D model. This model can accurately predict storage locations for construction equipment and materials, optimize material flow paths, and reduce operational conflicts caused by narrow sites or unreasonable layouts [7]. Meanwhile, BIM models can be further integrated with sensor networks and monitoring systems. For instance, during the operation phase of water conservancy projects, the addition of sensor networks and monitoring systems enables real-time perception and dynamic management of key equipment operating statuses, performance parameters, and potential faults, thereby improving the reliability and stability of facility operation [8].

Relying on real-time data collection and analysis functions, the BIM platform can integrate, visually display, and intelligently analyze multi-dimensional data. This capability not only enhances the rapid response to emergencies but also provides a scientific basis for operational decision-making, thereby optimizing overall operational efficiency.

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3.3. Artificial intelligence

Artificial intelligence (AI) is changing the safety management model of construction machinery. By integrating sensors, IoT, and big data technologies, AI achieves real-time monitoring of equipment operating status. With the help of machine learning and intelligent algorithms, it performs fault diagnosis and health assessment on key components, thereby enabling timely risk identification. Taking the shield machine of China Railway 14th Bureau Group as an example, its self-developed AI intelligent inspection system can monitor key components such as the main bearing, drive seals, and cutterhead tools in real time. The system accurately assesses equipment health status through vibration analysis and visual recognition technology, and provides early warnings of abnormal conditions such as tool wear [9].

Meanwhile, AI predicts the remaining useful life of key components based on data models, providing a basis for preventive maintenance. Huang Fuduan proposed that augmented reality (AR) technology can intuitively overlay real-time data and operation guides onto the operator's field of view. Through AR glasses, operational guidance and safety warnings are presented in real time based on equipment status. For example, in operations such as crane lifting, AR can calculate and display safe paths, promptly warn and suggest adjustments during abnormal operations, and simulate various working conditions and emergency scenarios. This helps personnel conduct rehearsal training in a virtual environment, significantly improving emergency response capabilities and operational safety [10].

During construction, AI can dynamically optimize tunneling parameters. In combination with digital twin technology, it can simulate multiple tunneling schemes in a virtual environment to select the optimal construction strategy, thereby enhancing construction safety and stability under complex geological conditions. Furthermore, an integrated intelligent control platform built upon AI and cloud computing can achieve collaborative optimization of equipment management, production scheduling, and safety management. It can also promote green and low-carbon operations through energy consumption regulation.

4. Discussion

4.1. Implementation strategies for intelligent equipment safety management

4.1.1. Building an intelligent equipment safety management system and equipment data platform

In promoting the intelligent management of construction machinery, establishing a comprehensive intelligent equipment safety management system is a fundamental task. Enterprises should rely on IoT, big data, and cloud platform technologies to create full-lifecycle digital archives, recording equipment models, operational parameters, maintenance records, and fault records, thereby achieving a centralized equipment information management platform [11]. Simultaneously, by integrating equipment operation data, safety monitoring data, and construction data, information silos should be broken down to achieve data sharing and collaborative management among multiple departments. On this basis, standardized management processes and institutional norms should be introduced to systematically control aspects such as equipment operation monitoring, fault warning, and maintenance, thereby enhancing the standardization and scientific nature of equipment safety management.

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4.1.2. Cultivating personnel informatization awareness

Personnel's informatization literacy is a key factor in implementing intelligent equipment management. Enhancing the professional level and informatization capabilities of construction personnel and establishing an institutional system play a crucial role in mechanical equipment management. Enterprises should regularly implement systematic training plans, providing all staff with training on informatization and safety awareness, and rebuilding a digital knowledge system [12]. For core technical backbones and specialized technical personnel, training on the use of intelligent management systems should be strengthened to enable them to proficiently carry out management tasks such as equipment inspection and fault analysis. Simultaneously, a skills assessment system should be implemented, with regular technical exchanges and assessments to test and consolidate the professional capabilities of construction personnel. In addition, employees should be encouraged to participate in specific matters such as system optimization, data model improvement, and management process innovation. This ensures that the technology application goes beyond the operational level and effectively promotes the upgrading of management models and the advancement of intelligence [2].

4.1.3. Preventive equipment maintenance management

Preventive equipment maintenance management involves monitoring equipment operating conditions and analyzing data to formulate effective maintenance plans, thereby reducing the likelihood of equipment failures and extending equipment service life. Enterprises should establish a real-time data collection system for key equipment to continuously monitor core parameters. Some enterprises have already carried out related research. A provincial-level cement group has currently built a data platform covering all plant equipment, enabling real-time collection and monitoring of parameters such as temperature, vibration, pressure, current, and energy consumption [11]. On this basis, a tiered maintenance strategy and standardized operating procedures should be implemented to transform data analysis results into precise maintenance decisions. Furthermore, through a data-sharing mechanism, departments such as production, equipment, technology, and procurement should be connected to enable collaborative management and optimal resource allocation.

4.2. Development trends of modern intelligent management

The future intelligent development of construction machinery safety management is mainly reflected in the following three directions. First, as current technologies are primarily applied in fault diagnosis and early warning, they will extend towards autonomous analysis and decision making. Equipment will automatically adjust operational parameters based on real-time data to achieve optimal operating conditions, reducing response delays and risks of misjudgment caused by human intervention.

Second, combined with automatic control technology and intelligent equipment, construction machinery in high-risk scenarios will gradually achieve reduced manpower or even fully automated operations, thereby lowering safety risks associated with human operation. For example, in high-risk environments such as tunnel construction, unmanned excavators and remotely controlled loading and hauling vehicles can effectively eliminate the risk of personnel casualties.

Third, based on big data analysis and predictive models, equipment management will shift from single fault prediction to systematic risk prediction, enabling intelligent control of the entire construction process. By identifying joint risks among multiple devices and processes, systemic

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hazards that could trigger cascading failures can be identified in advance. Forming an intelligent management model centered on perception, analysis, decision, and execution will become an important development direction for future safety management of construction machinery.

5. Conclusion

This paper systematically reviewed the current status of IoT, BIM, and AI in the safety management of construction machinery. Traditional safety management models for construction machinery have certain limitations in areas such as personnel awareness, construction efficiency, and informatization levels, making it difficult to meet the safety and efficiency requirements of modern engineering construction. With the continuous development and application of intelligent technologies like IoT, BIM, and AI, equipment safety management has progressively achieved a comprehensive upgrade from information collection and condition monitoring to intelligent analysis and decision optimization.

However, this paper is mainly based on existing literature and secondary data, focusing on theoretical review and application summary, and thus has certain limitations. It lacks practical application, evidence of effect, and quantitative verification. Future research could select representative construction projects for field investigations, improve the evaluation of application effects through empirical analysis, and optimize implementation paths based on actual pain points, thereby making the research results more practically valuable for guidance.

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