Research and Application of Intelligent Early Warning System for Tower Crane Safety

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Abstract: Tower cranes are indispensable vertical transportation equipment in construction engineering, and their operational safety is directly related to the safety of personnel and the smooth progress of projects. Traditional tower crane safety management has long relied on manual inspection and empirical judgment, with problems such as insufficient equipment hazard monitoring, prominent blind spots in human operation, and lagging warning mechanisms restricting the improvement of safety management. Based on a systematic analysis of the pain points in traditional tower crane safety management, this study constructs a technical framework for an intelligent early warning system for tower crane safety and evaluates its practical application effects in engineering projects. The research shows that the intelligent early warning system can effectively realize real-time monitoring of tower crane operating status, early identification of potential risks, and graded warnings, reducing the interference of human factors in safety management and promoting the transformation of tower crane safety management from post-event rectification to pre-event prevention. The promotion and application of this system are of great significance for improving the safety management level of tower cranes in construction engineering and reducing the occurrence of safety accidents.
***Keywords*:** tower crane, intelligent early warning system, hook visualization, wire rope monitoring

1. Introduction

Tower cranes, with their advantages of high lifting height, large working radius, and strong load capacity, have become indispensable construction machinery in municipal and civil building construction in China. However, the frequent occurrence of tower crane safety accidents has not been effectively curbed, causing serious casualties and economic losses. Tower cranes are prone to instability, overturning, boom fracture, collision and other accidents due to factors such as tower structure, operation behavior, and meteorological environment. Therefore, research on dynamic monitoring technology for tower crane safety based on multi-sensor integration is particularly important [1]. Data from the National Engineering Quality and Safety Supervision Information Platform show that from 2024 to 2025, a total of 31 crane-related injury accidents occurred in housing construction and municipal engineering nationwide, of which tower crane accidents accounted for 55%, resulting in 25 deaths, indicating a severe safety situation.

In recent years, information and communication technologies have been gradually applied to tower crane safety management. However, current applications in this field are mostly single-point developments with low intelligence levels, failing to adequately meet existing tower crane safety management needs [2]. Zheng Shiliang proposed and implemented a tower crane safety monitoring system integrating the Internet of Things (IoT), sensors, and intelligent algorithms [3]. Zhang Ying conducted optimization research on the intelligent visualization system for tower crane hook safety, providing a technical solution to eliminate blind spots in lifting operations [4]. Liu Yuhan's research focused on the construction of digital twin virtual entities for tower crane lifting operations and early warning methods for unsafe events, achieving an early warning sensitivity of 94.1% under laboratory conditions [5]. Jiang Weiguang addressed typical unsafe lifting behaviors such as inclined lifting, sudden braking, and sudden unloading, establishing a deep learning-based intelligent recognition model, offering new ideas for the intelligent transformation of tower crane safety management [6]. Ma Shun and colleagues provided a systematic review of non-destructive testing technologies for wire ropes of mechanical and electrical special equipment, laying a theoretical foundation for the development of online wire rope monitoring technology [7].

In summary, tower crane safety control is a complex systematic project. Intelligent early warning systems integrating advanced technologies such as the IoT, big data analytics, and artificial intelligence are becoming an important technical pathway to promote the intelligent and refined development of tower crane safety management. Based on a systematic review of the pain points in traditional tower crane safety management, this study constructs a technical system for an intelligent early warning system for tower cranes and evaluates its practical application effects in engineering projects, aiming to provide a reference for improving tower crane safety management.

2. Pain Points of Traditional Tower Crane Safety Management

The traditional tower crane safety management model has long relied on manual inspection and empirical judgment, and its limitations are increasingly prominent in actual operation, mainly manifesting in the following three aspects.

2.1 Insufficient Equipment Hazard Monitoring

In traditional tower crane construction site safety management, some projects suffer from inadequate routine equipment inspections and symptomatic hazard rectification ("treating the head when the head hurts and treating the foot when the foot hurts"), making it impossible to promptly identify and rectify potential risks during tower crane operation. Safety training and education often remain superficial, failing to transfer responsibilities and pressures to the frontline. The shortage of on-site supervisors and their limited professional competence make it difficult to achieve comprehensive real-time supervision of multiple tower crane operating points.

2.2 Prominent Blind Spots in Human Operation

Due to the special operating environment of tower cranes, the driver cannot directly observe the lifting site with naked eyes and must operate based on the commands of the signaler via intercom, making it impossible to independently judge lifting risks. This easily leads to operational errors such as overload lifting, illegal luffing, and swing collisions during operations.

2.3 Lagging Warning Mechanisms

Traditional tower crane safety management generally relies on manual maintenance at least once a month and a comprehensive inspection once a year. The inspection cycle is long, making it impossible to monitor the tower crane's operating status in real time. Between two adjacent maintenance periods, the tower crane may develop faults due to adverse weather conditions, fatigue aging, and other factors, which often cannot be detected promptly.

3. Research on Key Technologies of the Safety Intelligent Early Warning System

Based on the concept of smart construction technology, the tower crane safety risk intelligent early warning system integrates four core technologies to achieve multi-dimensional risk precision control.

3.1 Safety Warning Technology for the Area Below the Hook

This technology uses "visual recognition + directional audible and visual alarm" to prevent personnel from entering the area within the tower crane hook's working range. Through the real-time tracking function of the lifting visualization system, the zoom dome camera or gun camera sensor automatically focuses and continuously tracks the hook's motion trajectory, eliminating lifting blind spots. High-definition images are transmitted in real time to the driver's cab display screen and the remote platform, with infrared fill light available at night. Remote viewing and recording are also supported, enabling accident traceability. Compared with traditional manual warning methods, this technology improves the hazard perception ability of workers and supervisors.

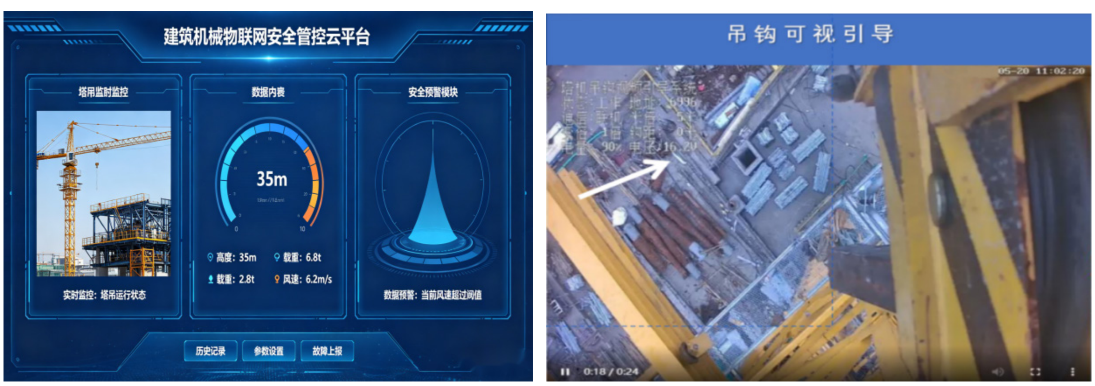

Figure 1. Schematic diagram of the lifting visualization remote platform

3.2 Full-Process Detection Technology for the Tower Crane Hoist Wire Rope

For common defects and hazards such as wire breakage, wear, rust, and deformation of wire ropes, a "non-contact monitoring + data fusion analysis" technology is adopted to achieve full lifecycle monitoring. Geomagnetic induction technology is used to magnetically plan the wire rope, transforming the disordered magnetic field into an ordered one. Sensors and edge computing chips are installed to capture magnetic field changes caused by wire rope damage in real time. Meanwhile, detection data is uploaded to the cloud platform or the driver's cab terminal via IoT protocols. A monitoring module records operating conditions such as wire rope running speed and length. Through algorithmic data fusion analysis, a three-level damage standard (light, medium, severe) is established, with different actions taken according to different levels. This system can accurately identify internal and external damage to wire ropes and achieve 24-hour uninterrupted monitoring.

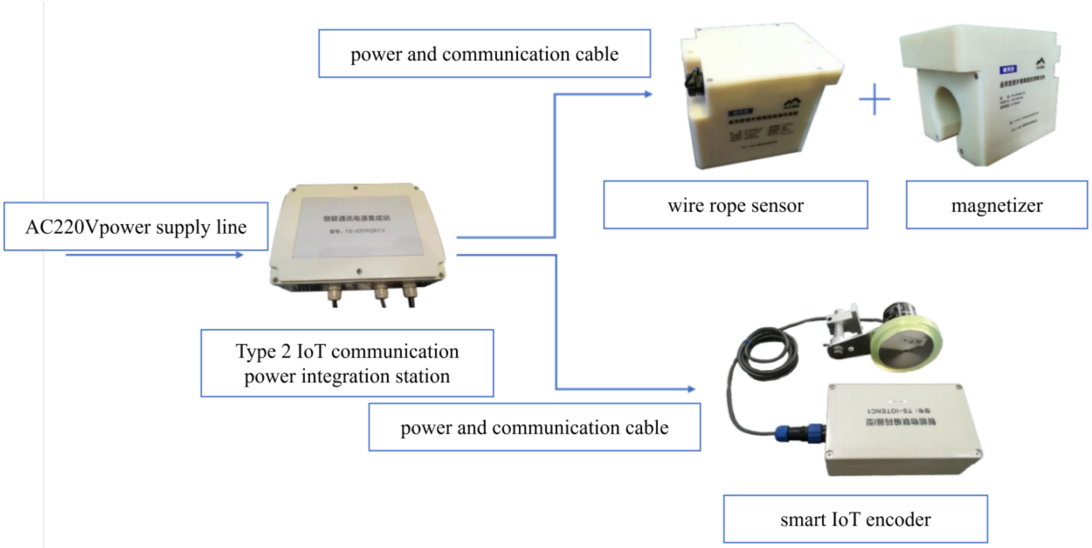

Figure 2. Structural diagram of the tower crane wire rope monitoring device

3.3 Early Warning Technology for Tower Body Bolt Loosening

A "pressure sensing + IoT" technology is adopted to achieve early warning of bolt loosening. Intelligent warning nuts are installed at key joint bolts of the tower body. The sensor has its own battery and a built-in wireless transmission module, and can be reused multiple times. A data acquisition host is provided, with a communication distance of up to 200 meters between the host and the nut terminal, and no obstructive shielding between them is required during installation. The intelligent warning nut is installed on the outer side of the high-strength nut. When the high-strength nut loosens and backs off, it triggers the sensor on the back of the intelligent warning nut. The warning nut activates an LED alarm and transmits an alarm signal to the intelligent terminal. IoT technology collects bolt status data, and the system platform synchronously displays the nut loosening warning information. The system supports remote real-time viewing of bolt status. Compared with traditional manual torque detection methods, the intelligent warning nut can detect bolt loosening hazards at the first moment, leaving ample time for maintenance.

3.4 Real-Time Crack Monitoring Technology for Key Components

For crack hazards in key parts such as the tower crane main beam and welds, a "drone + intelligent analysis" technology is adopted to achieve real-time crack monitoring. The drone is equipped with a scanner or high-resolution camera, flies stably under conditions of visual positioning and obstacle perception, and collects image data that meets requirements. The images are subjected to superpixel segmentation to better distinguish cracks from surrounding areas. This technology utilizes the flexibility of drones to enable non-contact monitoring of tower cranes installed in high-risk areas such as deep foundation pits and slopes. By collecting and analyzing images at different time points, it can comprehensively understand the crack propagation trend, providing support for tower crane maintenance and safety monitoring.

4. Engineering Application

The tower crane safety intelligent early warning system has been deployed and applied in several construction projects, achieving remarkable results. The system covers functional modules such as hook visualization monitoring, online hoist wire rope detection, tower body bolt loosening monitoring, and key component crack inspection, realizing comprehensive real-time monitoring of the tower crane's operating status. During system operation, the time to detect tower crane-related safety hazards was shortened from days or even weeks with traditional inspections to real-time detection, and the closed-loop rate of hazard rectification was significantly improved. Warning information is simultaneously pushed to project management personnel's mobile terminals via the cloud platform, enabling multi-level coordinated response and effectively reducing the probability of safety accidents caused by equipment hazards and human error.

5. Conclusion

This study reviewed the pain points of traditional tower crane safety management, including insufficient equipment hazard monitoring, prominent blind spots in human operation, and lagging warning mechanisms. Focusing on four core technologies — safety warning for the area below the hook, full-process hoist wire rope detection, early warning for tower body bolt loosening, and real-time crack monitoring for key components — a technical framework for an intelligent early warning system for tower cranes was constructed. The research shows that the system, integrating the IoT, big data analytics, and artificial intelligence technologies, can achieve real-time monitoring of tower crane operating status, early identification of potential risks, and graded warnings. It effectively reduces the over-reliance of safety management on manual inspection and empirical judgment, promoting the transformation of safety management from post-event rectification to pre-event prevention.

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