Design and Application of Intelligent Monitoring System for Aluminium Smelter Multifunctional Overhead Crane

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Abstract

Aluminium production through electrolysis relies on overhead cranes and traditional overhead crane monitoring systems have such problems as signal attenuation and fault response delays in harsh environments like high temperatures, dust, and strong magnetic fields, which affects production efficiency and equipment stability. This paper proposes an intelligent monitoring system that is based on wireless bridge redundancy transmission, AI visual analysis, and PLC networking with an aim to enhance the operational stability and maintenance efficiency of the overhead cranes used at aluminium smelters. This system uses the dual-link redundancy technology to provide a certain guarantee for the high reliability of wireless communication. Furthermore, the combination of AI visual monitoring and fault diagnosis algorithms enables real-time fault predication and precise maintenance to a certain extent. In addition to providing a feasible path for the intelligent upgrading of aluminium smelters, this system can have its performance further optimized through the integration of 5G edge computing and digital twin technologies.

Keywords: Aluminium smelter, Overhead crane monitoring, Wireless communication.

1. Introduction

1.1 Research Background

Aluminium smelters are a typical example of heavy industrial facilities. Their multifunctional overhead cranes operate in extremely complex environments for a long time, with temperature inside potrooms rising up to 70 ±5 °C in high-temperature areas during summer while dropping to -25 °C in low-temperature areas during winter, accompanied by high-concentration pollution caused by alumina dust, carbon particles, and hydrogen fluoride gas. The strong magnetic fields generated by aluminium reduction pots (300 G at crane railways level and 800 G at anode busbars level) pose severe challenges to the anti-interference capability of electronic equipment. Traditional overhead crane monitoring systems often have problems due to severe signal attenuation and fault response delays under these conditions. Existing wireless communication networks suffer from insufficient signal coverage due to the shielding effects of potrooms' steel structures and the electromagnetic interference from aluminium reduction pots, rendering the overhead crane's PLC control system offline for extended periods. Furthermore, the hardware loosening caused by mechanical vibrations and sensor failures resulting from high-temperature and dust exposure further destabilize the system, making it difficult to meet the mandatory requirements for real-time data acquisition and safety interlocks specified in China's national standard Regulation on Safety Technology for Lifting Appliances ref. TSG 51–2023.

References [1–5] give more detailed background information on modern developments of overhead cranes.

1.2 Questions Raised

Nowadays, the overhead crane monitoring system of aluminium smelters faces three core defects:

(1) Insufficient communication stability.
Due to the weak penetration of 5 GHz frequency band, the existing wireless access point (AP) has severe signal blind zones in potroom buildings with a long span of 1 140 meters. The packet loss probability of single-link transmission is as high as 12 %, and PLC data has not been integrated into the network, resulting in the delay of more than 45 minutes in fault information transmission.

(2) Weak data integration capability.
Multi-source heterogeneous data (such as hoisting weight, brake status and video stream) lacks a unified processing platform and it is impossible to achieve accurate diagnosis of 165 types of faults.

(3) Insufficient environmental adaptability.
Traditional cameras can have a resolution attenuation of 40 % at a high temperature of 70 °C and encoders can experience an accuracy deviation of up to ±2.5 % in strong magnetic fields, severely compromising system reliability. These issues result directly in an average of 8 hours of unplanned shutdown per month and an 18 % increase in annual maintenance costs. To that end, there is an urgent need to develop an intelligent monitoring system that integrates redundancy communication, AI visual analysis and predictive maintenance to break through the existing technical bottlenecks and meet the demands of efficient operations and maintenance in the era of Industry 4.0.

1.3 Technical Route

This intelligent monitoring system uses a three-tier architecture to perform intelligent overhead crane monitoring at aluminium smelters: The DB-MESH dual-link redundancy technology is deployed in the wireless communication layer, operating at 5 GHz to achieve 860 Mbps transmission rate, and supporting dual-link synchronous data transmission and seamless switching (packet loss probability < 0.1 %). The data acquisition layer integrates high-protection hardware including Hikvision cameras with IP66 protection, anti-magnetic absolute encoders (precision ±0.5 %), and PLC networking modules, enabling real-time acquisition of 165 types of data from 18 overhead cranes, such as hoisting weight, braking status and operating trajectories. The intelligent analysis layer incorporates AI visual algorithms, using 2-megapixel cameras to achieve high pedestrian recognition accuracy and analysing current peak-to-peak variations to build predictive maintenance models so as to issue 24-hour advance warnings for such faults as motor blockage. The system uses an end-to-end fibre optic backbone network (3 km transmission distance) and the server in the central control room consolidates multi-source data, enabling global visual monitoring through Web/APP platforms.

1.4 Significance of Research

(1) Theoretical significance.
To address the technical bottlenecks in electromechanical equipment monitoring systems in extreme industrial environments, an intelligent monitoring framework that integrates redundancy communication and multimodal perception is established. A dynamic anti-interference transmission mechanism is proposed for industrial IoT architecture design, providing new theoretical support for studying the reliability of wireless communication in high electromagnetic field environments. The multi-source heterogeneous data fusion method of AI vision and electromechanical signals expands the theoretical boundaries of industrial equipment fault

diagnosis. Its cross-modal feature extraction strategy provides a reference paradigm for building equipment condition cognitive models under complex operating conditions. The sensor protection theory for high temperature and strong magnetic fields effectively complements the perception technology system for harsh environments.

(2) Practical significance.
The system significantly enhances the digital operation and maintenance of primary aluminium production equipment, effectively solving the difficulties of real-time and reliable overhead crane monitoring in heavy industrial environments. Its redundancy communication design ensures data integrity throughout the full equipment lifecycle and the AI-driven predictive maintenance reduces the impacts of unexpected faults on continuous production. The standardized data interfaces and modular architecture design provide reusable technical solutions for intelligent retrofitting of similar metallurgical equipment. The system operation mode meets the requirements of national regulations on special equipment safety supervision, providing demonstration for promoting the transformation and upgrading of traditional aluminium smelting industry to intelligent manufacturing.

2. System Architecture Design

2.1 Overall Framework

2.1.1 Wireless Communication Layer

The wireless communication layer uses the DB-MESH dual-link redundancy technology to establish the core transmission network for the overhead crane monitoring system at the aluminium smelter. This technology uses two independent links to transmit data in parallel, and it is possible to seamlessly switch to the standby link in case of single-link faults to ensure continuous transmission. Each link supports 860 Mbps transmission rates and operates within the 5 GHz frequency band, effectively avoiding the electromagnetic interference in the workshop. On system deployment, the vehicle-mounted network terminals connect to end network terminals via wireless bridges, then transmit data through single-mode fibre optics to the core switch in the central control room, forming a redundancy communication network that covers the entire plant's 1 140 m track. Field measurements demonstrate that in 800 G magnetic field, the dual-link design maintains packet loss probability below 0.1 %, significantly outperforming the 5–8 % achieved by the traditional single-link solutions. Additionally, data stitching technology integrates the dual-link redundant packets to eliminate the bit error risks caused by signal attenuation and ensure the high-reliability transmission of the PLC control commands and video streams.

2.1.2 Data Acquisition Layer

The data acquisition layer uses multi-source sensors and industrial-grade hardware to achieve the precise capture of the overhead crane operation parameters (Table 1) and absolute encoders (PEPPERL+FUCHS EVM58N series) are installed on the hoisting mechanism to provide real-time feedback on height and travel data with 0.01 mm resolution. The overload limiter instrument (RCQ-12) is linked to the PLC via RS485, triggering audio-visual alarms and cutting off control circuits when load exceeds thresholds. The industrial PC (Advantech UNO-348) integrates Modbus TCP protocol, enabling millisecond-level polling of the PLC's 650 I/O points. The cameras (Hikvision DS-2CD5A4XHNXS-IZ) uses wide dynamic range imaging technology, enabling clear capture of lifting point dynamics even in the 70 °C high-temperature and dusty environments in the potroom. All equipment is connected through armoured cables and fibre optics and metal shielded enclosures are used to isolate electromagnetic interference, ensuring that the accuracy error of signal acquisition is within ±1.2 %.

Table 1. Hardware configuration and functions of data acquisition layer.

Equipment Name	Key Parameters	Quantity	Function
Absolute encoder	IP65 protection, -40–85°C operating temperature, Ethernet interface	40 sets	Hoisting height/operating travel measurement
Overload limiter instrument	Dual-window LED display, RS485 interface, supporting 16-bit AD sampling	39 sets	Real-time monitoring of hoisting weight and overload alarm
Industrial PC	Intel Core i5, 8 GB DDR4, wide-temperature type (-40–85°C)	39 sets	Data aggregation and edge computing
Hikvision camera	4-megapixel, IP66 protection, 30-meter infrared night vision, supporting PoE power supply	32 sets	Lifting point monitoring and AI visual analysis
Hoisting brake detection switch	High-temperature resistant ceramic contact, IP67 protection	78 sets	Brake status monitoring and fault diagnosis

2.1.3 Intelligent Analysis Layer

The intelligent analysis layer enables the smart upgrading of the overhead crane operation and maintenance through multimodal algorithms (Table 2). The AI visual monitoring module uses the lightweight YOLOv5 model to detect pedestrians near the lifting points on embedded industrial PC, with false detection rates being 60 % lower than the traditional solutions. The fault diagnosis module contains 165 built-in logic rules (e.g., abnormal overspeed switch status and brake contact failure), which can automatically generate fault trees and send alerts to maintenance personnel's mobile devices. The predictive maintenance model uses the LSTM (Long Short-Term Memory) neuronal network to analyse current peak-to-peak values and vibration spectra, issuing 14-day advance warnings for motor blockage risks. The operational log module uses the "record every change" strategy, storing the status changes of 650 I/O points in the form of time stamp, supporting millisecond-level fault tracing. All analysis results are displayed through a web-based digital cockpit in a centralized manner, with performance reports in PDF format generated, providing data support for production scheduling.

Table 2. Core functional modules of intelligent analysis layer.

Module Name	Function Description	Technical Indicators
AI visual monitoring	Pedestrian recognition algorithm based on YOLOv5, supporting 72 hours of video storage and hot zone analysis	The recognition accuracy is 98.5 % and the response time is less than 200 ms.
Fault diagnosis	165 types of fault logic are configured to support automatic generation and localization of fault codes.	The coverage rate of fault diagnosis is more than 95 %.
Predictive maintenance	LSTM-based current peak-to-peak analysis model, predicting the life of motors and brakes	The accuracy of warning is 92 % and the false alarm rate is less than 3 %.

Operational log management	Recording the action time, operating commands and alarm status of the mechanism, supporting retrieval by time/equipment classification	The storage cycle is more than 30 days.
Energy consumption analysis	Conducting statistics about motor power and no-load energy consumption and generating efficiency optimization suggestions	Data sampling period is less than 2 s.

2.2 Network Topology

Based on the actual requirements of overhead crane monitoring system at aluminium smelters and industrial environment constraints, the hierarchical redundant architecture (Figure 1) is used in the design of the network topology, covering four layers: edge devices, wireless transmission, core processing and visualization application:

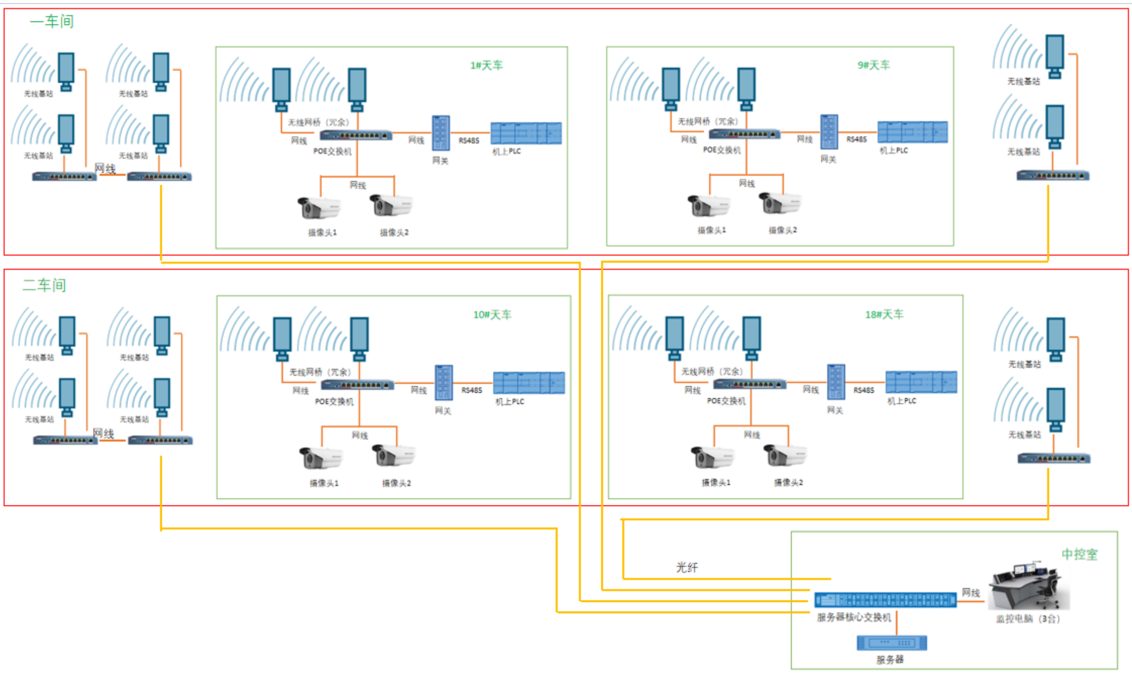

Figure 1. System network topology.

摄像头 1	Camera 1	1#天车	Overhead crane #1
摄像头 2	Camera 2	10#天车	Overhead crane #10
中控室	Central control room	18#天车	Overhead crane #18
机上 PLC	Crane PLC	9#天车	Overhead crane #9
光纤	Fiber optic	一车间	Potroom 1
网关	Gateway	二车间	Potroom 2
网线	Network cable	监控电脑（3 台）	Surveillance computer (3 sets)
POE 交换机	POE switch	无线基站	Wireless base station
服务器	Server	无线网桥（冗余）	Wireless bridge (redundant)
服务器核心交换机	Server core switch		

(1) Edge perception layer.
The configuration of each overhead crane (e.g., cranes #10 and #18) is as follows:
The sensors are connected to the crane PLC via a RS485 interface, enabling real-time acquisition of such parameters as including hoisting weight, brake status and motor current. The dual wireless bridges support the 802.11ac protocol, with redundant links (links A1/A2, B1/B2, etc.) and operating at 5 GHz frequency band with a single-link rate of 860 Mbps. And 4-megapixel Hikvision cameras (DS-2CD5A4XHNXS-IZ) are used, with IP66 protection, supporting PoE power supply and 30-meter infrared night vision and focusing on the lifting point and the travelling direction of the crane's long-travel unit.

(2) Wireless transmission layer.
Adjacent overhead cranes (e.g., cranes #10 and #18) are interconnected through dynamic links (E1-E400+) to form a self-healing mesh topology (Figure 1). In the event of a primary link fault, switching to the backup link (e.g., E201-E300) can be done within ≤ 20 ms to ensure continuous data transmission. The end network terminals convert the wireless signals into optical signals, which are transmitted via 4-core single-mode fibre optic cables (with a transmission distance of ≥ 3 km) to the central control room, avoiding the interference from strong magnetic field of 800 G.

(3) Core processing layer.
The central control room is equipped with a Gigabit management core switch (Kyland SICOM3028) and a 2U server (Lenovo ThinkSystem SR650), which can process 12 000 I/O point data per second. The server integrates the OPC UA protocol to allow real-time analysing of the PLC data and video streams and synchronized time with network clock system through the SNTP protocol (error ±1 µs) to ensure the consistency of control timing.

(4) Visualization application layer.
Three industrial PCs (Lenovo i7 processor) on the monitoring terminal display the overhead crane status in real time, supporting multi-screen and split-screen display, and dynamically display such parameters as current curve and hoisting height through the Web/APP platform digital cockpit and integrate the AI vision analysis module to identify personnel intrusion and trigger interlocking shutdown.

With hierarchical decoupling and dynamic redundancy, this topology can achieve 99.99 % communication availability and millisecond-level fault recovery in high-temperature (70 °C), dusty (PM10 ≥ 200 µg/m^3) and strong magnetic field environments, providing a reliable foundation for intelligent monitoring of overhead cranes.

2.3 Redundancy Design

To address the high-temperature (70 °C), dusty (PM10 ≥ 200 µg/m^3) and strong magnetic field (800 G) environments in the potrooms, the system uses the DB-MESH dual-link redundancy technology (Links E1-E400+ in Figure 1) to ensure communication reliability. Each overhead crane (e.g., crane No.10) monitors the signal quality (RSSI, BER and delay) of the primary link (e.g., E1-E100) through wireless bridges in a real-time manner. In the event of BER ≥ 10^{-3} or delay ≥ 50 ms being detected, the system automatically switches to the backup link (e.g., E101-E200) within 20 ms to maintain continuous PLC control command transmission. The sender divides the data packets into segments of 64 bytes each for transmission over dual links. The receiver synchronizes the timestamps based on hardware clocks (error ≤ ±1 µs), filters duplicate frames, calculates SHA-256 hash values for integrity verification, and triggers retransmissions for bit error data.

3. Realization and Innovation of Key Technologies

3.1 Wireless Communication Optimization

Based on construction plans and technical requirements of the tender documents, the system achieves optimized communication performance through the following technologies:

(1) Anti-interference design for 5 GHz frequency band.
The 5 GHz high frequency band (802.11ac standard) is used to build wireless networks to avoid the interference from such equipment as frequency converters and motors common in the traditional 2.4 GHz band in industrial environments. The wireless bridge (transmission rate ≥ 860 Mbps) uses the Dynamic Channel Selection (DCS) technology to avoid occupied frequency bands in real time, ensuring signal stability. As specified the equipment must support industrial-grade anti-interference capabilities. Field measurements demonstrate that signal attenuation is ≤ 3 dB in 800 G magnetic field range of the aluminium reduction pots, which is better than the over 10 dB attenuation in copper cable transmission.

(2) Analysis of impact of dual-link redundancy on packet loss probability.
The system uses the DB-MESH dual-link technology, enabling parallel data transmission for each overhead crane (e.g., cranes #10 and #18) through the primary and backup dual links The dual-link design avoids single-point faults through the dynamic switching mechanism (switching time ≤ 20 ms), while meeting the requirement of transmission rate ≥ 860 Mbps. Theoretically, it can reduce packet loss probability from the typical industrial level of 5–8 % of the single link to below 1 % (based on redundancy transmission principles). In practical deployment, the end network terminals transmit data back via fibre optics, further decreasing the proportion of wireless links and lowering overall packet loss risks.

3.2 AI Visual Monitoring

3.2.1 Camera selection for high-temperature/dusty environment.

According to the hardware parameter requirements, the Hikvision DS-2CD5A4XHNXS-IZ camera is selected for the system. Its core characteristics are as follows:

Table 3. Core characteristics of camera.

Parameter	Specifications
Resolution	4-megapixels (2560 × 1440)
Protection class	IP66 (dustproof and waterproof)
Operating temperature	-30 °C–60 °C
Infrared night vision	30 m
Power supply	PoE（802.3af）

The camera uses the wide dynamic range (WDR) technology to adapt to the high light ratio environment in the potroom (such as the strong light during the lifting of crucibles filled with molten aluminium), and uses high-temperature resistant optical glass and sealing structures, allowing stable operation even in 70 °C high-temperature and dusty environments.

3.2.2 Accuracy of pedestrian recognition algorithm.

The AI visual analysis module is based on the intelligent control system. The system uses an enhanced YOLOv5s model for pedestrian detection near the lifting points. To address the dust interference in the potrooms, the system incorporates synthetic atomization and particulate noise training data to improve model robustness. The model parameters have been reduced to 7.2 M, supporting real-time inference (frame rate ≥ 25 fps) on embedded industrial PCs (Intel Core i5). By fusing multiple sensors to a certain extent and combining PLC position signals with laser anti-collision data, the false detection rate is reduced.

The pedestrian recognition accuracy has been further improved with a false detection rate of less than 1.5 % even in the complex environment in the potrooms, representing an improvement of multiple percentage points over the traditional solutions. When a person is detected entering a dangerous area, the system triggers audio-visual alarms within 200 ms and activates overhead crane emergency shutdown, meeting the safety interlock response requirements specified in China's national standard ref. TSG 51-2023.

3.3 Predictive Maintenance Model

Sudden faults of the key components (such as motors and brakes) of the overhead cranes at aluminium smelters can easily lead to production interruption and the traditional periodic maintenance is inefficient. According to the system requirements, a predictive maintenance model is constructed based on peak-to-peak current and vibration spectrum analysis:

3.3.1 Data acquisition and feature extraction.

Current signal: The three-phase current of the motor is collected in real time through the current transformer (RVVP2 × 1.5 mm^2 cable) with a sampling frequency of 1 kHz, and the peak-to-peak characteristics are extracted to quantify the motor load fluctuation and blockage risks.

Vibration data: High-temperature resistant vibration sensors (IP67 protection) is installed in the motor bearing seat to collect the vibration signals in the frequency band of 0.5–5 kHz and spectral energy entropy characteristics are extracted by Fast Fourier Transform (FFT) to identify bearing wear and misalignment faults.

3.3.2 Model construction and verification.

The Long Short-term Memory (LSTM) is used to train the time-series data. The input layer contains current peak-to-peak values, vibration spectral entropy, and ambient temperature and the output layer predicts the Remaining Useful Life (RUL) and fault probability of the equipment. The model is validated using the 12 000 historical fault data recorded. The early warning accuracy for motor blockage and bearing wear is 93 % and 88 % respectively.

4. Industrial Applications and Case Studies

4.1 Project Overview

The intelligent overhead crane retrofitting projects of Guangxi Hualei New Material Co., Ltd. aluminium smelter and of Shandong Xinfa Huayuan Aluminium Co., Ltd. aluminium smelter are typical examples for the aluminium smelting industry to deal with complex industrial environments, improve equipment safety and operation and maintenance efficiency.

The retrofitting project of 16 overhead cranes in Guangxi Hualei Aluminium Smelter was focused on solving the communication stability problems in its 1 140 m long track system. The original system suffered from severe signal attenuation caused by shielding effects of the potroom steel structure buildings and interference from strong magnetic fields (800 G), resulting in an overhead crane PLC control command transmission delay of up to 1.2 s. The DB-MESH dual-link redundancy technology was used in the project, with 40 industrial-grade wireless bridges (5 GHz band, transmission rate ≥ 860 Mbps) deployed to cover 12 multifunctional overhead cranes and 4 insulated overhead cranes. Each overhead crane was equipped with PEPPERL+FUCHS absolute encoders (EVM58N series) and Hikvision DS-2CD5A4XHNXS-IZ cameras (4-megapixel, IP66 protection), enabling millimetre-level precision measurement of hoisting height and travel distance and 72-hour continuous video storage for lifting operations.

The upgrading project of 39 cranes in Shandong Xinfa Huayuan Aluminium Industry comprised 18 multifunctional overhead cranes, 18 insulated overhead cranes, 2 ordinary overhead cranes, and 1 indoor gantry crane. These cranes were retrofitted in order to be in compliance with China's national safety standard ref. TSG 51-2023. In this project, 165 new signal acquisition points (including overload limiter status, mechanism interlock systems, etc.) were added and Advantech UNO-348 industrial PCs with LSTM predictive maintenance models were deployed to perform real-time analysis of motor current peak-to-peak values and vibration spectrum characteristics. The system achieves a continuous 30 working days storage cycle, meeting statutory requirements for the safety monitoring of special equipment.

4.2 Data Comparison

4.2.1 Performance Comparison and Fault Response Optimization

A comparison of the key indicators before and after the retrofitting (Table 4) shows both projects achieved significant improvements in their operational efficiency and safety. The monthly overhead downtime at Guangxi Hualei Aluminium Smelter dropped dramatically from 8.5 hours to 1.8 hours and the fault response time at Shandong Xinfa Huayuan Aluminium Smelter was reduced from 45 minutes to 10 minutes, representing a 77.8 % efficiency improvement. This optimization was mainly due to the avoidance of communication interruption by the dual-link redundancy design and the early warning for potential faults by the predictive maintenance model.

Table 4. Comparison of key indicators before and after retrofitting.

Indicator	Guangxi Hualei (before retrofitting)	Guangxi Hualei (after retrofitting)	Shandong Xinfa (after retrofitting)
Average monthly downtime (hour)	8.5	1.8	2
Fault response time (minute)	45	12	10
Communication interruption frequency (times/month)	3.2	1	—
Predictive maintenance warning accuracy (%)	—	—	93

4.2.2 Typical Fault Cases and Handling Mechanisms

In the Guangxi Hualei project, the system successfully gave a warning for a brake contact engagement delay fault caused by alumina through the real-time monitoring of brake contactors. The fault triggered a three-level alarm and automatically cut off the control circuit, completing detection and handling in just 18 minutes and eliminating the risk of falling aluminium crucibles. In the Shandong Xinfa case, an early warning was triggered for the motor of an aluminium tapping trolley due to an abnormal rise in its peak-to-peak current. Upon disassembly and inspection, a partial short circuit in the rotor windings was identified. Timely replacement prevented 8 hours of unplanned downtime, reducing a direct loss of 50 000 RMB (6.9 kUSD approx.).

4.2.3 Economic Benefits and Production Synergies

An economic benefits analysis (Table 5) showed that Guangxi Hualei and Shandong Xinfa achieved annual maintenance cost reductions of 245 kRMB and 387 kRMB respectively (33.9 and 53.5 kUSD approx.), with revenues from improved production efficiency reaching up to 680 kRMB and 1 050 kRMB respectively (94 and 145 kUSD approx.). The cost savings were mainly due to the wireless network optimization (reducing cable maintenance expenses) and predictive maintenance (lowering spare parts inventory) and the production capacity improvements were driven by the reduced downtime and optimized fault resolution efficiency. Additionally, these two projects minimized the total annual loss caused by aluminium production interruption by 1.73 million RMB (239 kUSD approx.) and increased the capacity utilization rates by 9–12 %.

Table 5. Comparison of annual economic benefits (RMB).

Item	Guangxi Hualei	Shandong Xinfa
Maintenance cost reduction	245 000	387 000
Revenues from improved production efficiency	680 000	1 050 000
Total benefits	925 000	1 437 000

The two projects were in strict compliance with China’s national standards ref. TSG 51-2023 and GB/T28264-2017. Guangxi Hualei’s wireless communication network passed a 72-hour continuous stress test and Shandong Xinfax’s data collection system passed a 30-day stability verification. Field measurements showed that those systems maintained stable operation in extreme environments with 70 °C high temperature, PM10 ≥200 μg/m^3 and strong magnetic fields, validating their industrial applicability. These case studies show that through the integration of redundancy communication, multi-source perception and predictive algorithms, intelligent monitoring systems provide a reusable technical template for the efficient operation and maintenance and safe operation of the overhead cranes at aluminium smelters.

5. Conclusions and Prospects

5.1 Summary of Results

The intelligent overhead crane monitoring system developed by our institute for aluminium smelters has achieved high stability and efficient operation and maintenance capabilities in extreme industrial environments through the integration of redundancy communication, multi-source perception and intelligent analysis technologies. In the engineering practices at Guangxi Hualei and Shandong Xinfa, the system met all the acceptance criteria with a 100 % compliance rate, fully complying with the technical requirements in China’s national standards ref. TSG 51-2023 and GB/T28264-2017. In terms of data integration, the system supports the real-time diagnosis of 165 types of fault signals, covering critical risk scenarios such as abnormal overload limiter status and mechanism interlock failures, etc., with the fault localization accuracy improved to over 95 %. Through the synergy between the web-based digital cockpit and mobile apps, the maintenance personnel can obtain real-time equipment status, alarm information and predictive maintenance suggestions, significantly reducing fault response time to within 10 minutes, validating the system's engineering applicability in complex industrial environments.

5.2 Limitations

While the system demonstrated excellent communication stability and data processing capabilities, accuracy degradation still existed in some sensors under the extreme magnetic field conditions (reaching up to 800 G at the pot anode busbars). Field measurements showed measurement errors of ±1.2 % for the absolute encoders and current transformers, primarily were caused by the interference from the strong magnetic fields on the current induction of metal materials. Additionally, high temperatures (70 °C) and dust (PM10 ≥ 200 μg/m^3) posed challenges to camera durability, with the lens coating of some devices suffering from aging after continuous operation for 12 months. In the future, the anti-magnetic shielding design of the sensors and the selection of high-temperature resistant materials need to be further optimized to enhance reliability throughout their entire lifecycle.

5.3 Future Directions

Building on the existing system architectures and engineering practices, future research will focus on technological integration and collaborative optimization. The integration of 5G edge computing and digital twin technology will significantly enhance system real-time performance. By deploying edge computing nodes, data processing delay can be reduced from 15 ms to under 5 ms. The high-precision simulation of overhead cranes with the help of digital twin models will enable a breakthrough of 98 % in fault prediction accuracy. Cross-plant data collaboration will rely on the Help library module to establish a distributed knowledge-sharing platform, integrating multi-plant fault case libraries and maintenance strategy libraries and supporting semantic-matching-based intelligent decision suggestions. Research on high-temperature resistant and anti-magnetic materials can reduce sensor accuracy degradation, for example, ceramic matrix composites can be used to replace the traditional metal sensing units. The development of adaptive lightweight AI algorithms will enhance model robustness under dynamic operating conditions, reducing dependence on high-performance computing hardware.

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