Innovation and Application of IoT and AI in the Logistics Measurement System of Alumina Production

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Abstract

With the rapid development of modern industrial technologies, the application of logistics measurement and detection systems in alumina production has become a key means to enhance production efficiency and management levels. This paper comprehensively explores the innovation and application of multiple key measurement systems. Traditional systems, such as truck scales, rail scales, and instrument monitoring and management systems, face numerous limitations, including difficulties in detecting extreme conditions for truck scales, low measurement accuracy, poor anti-interference capability and high risks associated with manual data entry for rail scales, and inefficient instrument monitoring. To address these challenges, a series of innovative technologies and upgrade measures have emerged.

Keywords: Flow limit warning system, Logistics measurement system, IoT + AI, Precise measurement and efficient operation, Remote centralized control.

1. Introduction

As a critical measuring device in the railway freight system, rail scales play a central role in monitoring truckload weights, with their measurement accuracy directly linked to transportation safety efficiency, logistics resource allocation optimization, and full lifecycle cost control. Traditional rail scale systems, primarily utilizing mechanical sensors and linear basic algorithms, face significant challenges under complex working conditions: Firstly, mechanical sensing units are susceptible to environmental interference such as temperature and humidity fluctuations and track vibrations, leading to zero drift (empirical data shows error increases of up to 0.8 % in winter low-temperature environments) in long-term operation; secondly, manual operations involve risks of truck number misrecording and data tampering, with a certain railway bureau's 2022 audit report indicating annual settlement disputes exceeding 12 million RMB (1.68 MUSD approx.) due to such issues.

In recent years, breakthroughs in artificial intelligence technologies have provided a new pathway for the paradigm upgrade of weighbridge systems. Through the deep integration of deep learning algorithms and multi-source sensing data, the new generation of intelligent rail scales has achieved three major innovations: At the technical architecture level, a "terminal-edge-cloud" collaborative computing model has been constructed, enabling millisecond-level data preprocessing through edge gateways; at the algorithm optimization level, an improved YOLOv8 model has been adopted to achieve carriage positioning under complex lighting conditions (recall rate > 98 %), combined with LSTM (Long Short-Term Memory) time series networks to predict sensor abnormal states; at the application scenario level, expansion to high-risk areas such as port bulk cargo loading and chemical hazardous materials monitoring has been realized. This paper will systematically discuss dimensions such as heterogeneous data fusion mechanisms, anti-interference weighing algorithm design, and full-process trustworthy measurement systems, and explore the empowerment direction of future weighbridge intelligence development through 5G and digital twin technologies.

2. Research Background and Feasibility Analysis

2.1 Research Background

Alumina, as a core raw material in the metallurgical industry, relies heavily on the accuracy and efficiency of logistics measurement in its production process. Taking a typical production line with an annual output of 1.5 million tonnes of alumina as an example, every 0.5 % increase in raw material warehousing errors will lead to an annual increase in soda consumption costs of approximately 6 million RMB, highlighting the necessity of high-precision measurement. However, traditional measurement systems face the following key bottlenecks:

1. Technical Limitations: Truck scales, due to mechanical limit detection blind spots (empirical error fluctuations of ±1.5 %), struggle to meet the ±0.3 % error threshold required for raw material slurry blending;
2. Dynamic Adaptability Insufficiency: During peak railway transportation periods, dynamic weighing of 200 trains per day is required, but traditional rail scales exhibit a high out-of-tolerance rate of 7.2 % when train speeds exceed 20 km/h (data source: 2023 operation and maintenance report of a large aluminium enterprise);
3. Environmental Tolerance Defects: High temperatures (> 90 °C) of red mud slurry and highly corrosive medium (NaOH concentration > 30 %) shorten sensor lifespans to 40 % of normal operating conditions, with annual replacement costs exceeding 800 kRMB (112 kUSD approx.).

These challenges necessitate the industry to explore the deep integration of IoT and AI technologies to construct a new generation of logistics measurement systems that are both robust and intelligent.

2.2 Current Situation Analysis (Existing Problems)

2.2.1 Technical Bottlenecks of Traditional Rail Scales

Traditional rail scales, based on mechanical levers and analogic sensing technologies, have their inherent defects significantly amplified under complex working conditions:

Efficiency-Precision Imbalance: Static weighing requires interruption of transportation flows, with a single weighing taking ≥ 18 minutes, unable to adapt to high-density freight demands; In dynamic mode, non-linear increases in weighing errors occur with fluctuations in train speeds: errors rise from 0.4 % to 1.8 % as speeds increase from 10 km/h to 25 km/h.

Low Mechanical Reliability: Lever-type sensor arrays have annual maintenance costs accounting for 35 % of total equipment investment, with zero drift frequencies due to rusting reaching 1.2 times per month; track installation accuracy requirements are stringent (horizontal error ≤ 0.15 mm/m), with actual operation and maintenance compliance rate of less than 55 %, requiring frequent manual calibration.

High Environmental Sensitivity: for every 10 °C change in temperature, analogic sensors exhibit a temperature drift coefficient of 0.06 % FS, with cumulative errors exceeding 2.1 % under extreme cold conditions in Northeast China; data anomaly events caused by track dust accumulation or icing occur 4.3 times per day on average, accounting for 68 % of total faults.

2. Electronic weight slips and cloud collaboration reduce financial reconciliation cycles from 5 days to 4 hours, improving capital turnover efficiency by 12 times.

Industry Value
Scalable application across six factories under the China Aluminum Group has yielded annual comprehensive benefits exceeding 50 million yuan, validating the technology's universality and economic viability.

6.2 Outlook

Despite the system's current success, future exploration should focus on the following directions:

Technology Fusion Innovation
1. Deep application of digital twins: Construct a 3D dynamic twin of the track scale for real-time device health state mapping, combined with AR technology for fault prediction and remote expert collaborative maintenance (e.g., intelligent diagnosis of bearing wear).
2. 5G + edge computing optimization: Utilize 5G network slicing to ensure critical data (e.g., overload alarms) transmission delay < 10 ms and deploy lightweight AI models (TensorFlow Lite) to edge devices, reducing inference time from 35to 15 ms.

Algorithm Capability Enhancement
1. Federated learning and incremental learning: Improve AI recognition generalization (e.g., special license plate fonts, new cheating methods) through collaborative model training across multiple sites while protecting data privacy.

Industry Ecosystem Expansion
1. Cross-industry standardization: Jointly develop the "General Specification for Intelligent Weighing Systems in Process Industries" with steel, coal, and chemical sectors to promote multi-industry data interoperability and equipment compatibility.
2. Low-carbon upgrades: Introduce photovoltaic power supply and low-power sensor designs to reduce overall system energy consumption by 40 %, aiding in "dual carbon" goal achievement.

Security System Strengthening
Zero-trust architecture: Implement dynamic identity verification and micro-segmentation to defend against APT (Advanced Persistent Threat) attacks on IoT nodes.

This system, with IoT as its foundation, AI as its core, and trustworthy security as its guarantee, has reshaped the technological paradigm for logistics weighing in process industries. Its successful practice not only provides reliable support for the efficient operation of alumina production but also opens new paths for digital transformation in process industries through modular design and standardized output. In the future, with the deep integration of cutting-edge technologies such as 5G and quantum sensing, intelligent logistics weighing systems will unlock greater industrial internet empowerment value across broader dimensions, driving the leapfrog upgrade from "manufacturing" to "intelligent manufacturing."

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