Application and Validation of Intelligent Inspection Robots in Aluminium Electrolysis

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Abstract

This paper proposes an intelligent inspection robot system based on artificial intelligence (AI) technology, specifically designed for the potline basement in an aluminium smelter. The system integrates core AI technologies such as deep learning, laser simultaneous localization and mapping (SLAM) navigation, multi-sensor data fusion, and dynamic obstacle avoidance, enabling autonomous inspection under extreme conditions of high temperature, strong magnetic fields, and heavy dust. It aims to partially replace traditional manual inspections, thereby reducing labour costs while improving inspection efficiency and data accuracy. To adapt to the aforementioned extreme operating conditions in aluminium production, the system incorporates laser SLAM navigation, multi-sensor data fusion, and anti-interference communication technologies, achieving functions such as autonomous navigation, dynamic obstacle avoidance, real-time monitoring, and abnormality alarming. Moreover, by using the AI-driven multi-sensor data fusion technology, the system achieves higher reliability and adaptability, along with strong scalability, making it applicable in other industrial scenarios, such as substation inspections, and versatile across smelter-wide substation applications. All these can provide technical support and practical references for the intelligent transformation of the metallurgical industry.

Keywords: Intelligent inspection, Artificial intelligence, Laser SLAM, Aluminium electrolysis environment.

1. Introduction

1.1 Research Background and Industry Needs

As a highly energy-consuming and hazardous industrial process, aluminium production presents extreme complexity in the cell bottom. The working area is continuously exposed to multiple harsh conditions, including high temperatures (ranging from 10–15 °C in winter to 35–40 °C in summer), strong magnetic fields (up to 400 gauss), and heavy dust pollution. Traditional manual inspection methods face significant challenges: on the one hand, operators need to frequently enter the basement to perform critical temperature measurements on collector bars and cell bottom (with 120–210 measurement points per cell), exposing them to direct safety hazards such as falling carbon residues and electrical hazards. On the other hand, manual inspection suffers from low efficiency (approximately 15 minutes per cell), high subjective bias in data recording, and an inability to achieve continuous 24-hour monitoring, which results in delayed warnings of abnormal temperature rise. According to the measurements from Guangxi Hualei Aluminium Smelter, manual inspections cover only about 50 % of the cells per hour, which severely impacts production safety and process optimization.

In addition, Chinese national policies have set clear requirements for more intelligent industries. The *Robotics+ Application Action Implementation Plan* emphasizes that by 2025, the number of robots in the manufacturing sector shall be doubled, while the *14th Five-Year Plan for the Development of the Robotics Industry* further highlights the need to achieve breakthroughs in innovative applications of robots under complex scenarios. These policy orientations are highly consistent with the aluminium industry's urgent demand for the transformation of "reduced manpower and unmanned operation", which provides strategic support for the implementation of intelligent inspection technologies [1].

1.2 Research Objectives and Significance

This study aims to develop an intelligent inspection robot system based on multi-modal perception to address the core challenges associated with basement monitoring in aluminium cells. The system design focuses on three primary objectives:

- First, by leveraging laser SLAM navigation, a four-wheel-drive obstacle-crossing chassis (with a minimum obstacle crossing height of 50 mm), and an IP55-rated structure, the system achieves autonomous mobility and precise positioning in high-interference environments;
- Second, through the integration of different sensing technologies including infrared thermal imaging (temperature measurement accuracy of ±2 °C), ultrasonic obstacle avoidance, and visible-light video, the system establishes a framework for real-time temperature rise monitoring and early anomaly warning;
- Third, supported by an anti-strong-magnetic wireless network and a layered control architecture, the system ensures continuous data return and enables remote collaborative management.

The value of this solution is reflected in two dimensions: safety and efficiency. In terms of safety, it can reduce human intervention in hazardous areas by 80 %, while sound-light alarms and emergency stop mechanisms reduce the response time to abnormal events to within 10 seconds. In terms of efficiency, the robot can operate continuously for 8 hours and cover 38 cells each day. Combined with temperature trend analysis, it provides a solid data foundation for preventive maintenance. Furthermore, the study verifies the universality of multimodal perception technology in hazardous industrial scenarios to offer a technological paradigm for intelligent upgrades in metallurgy, chemical engineering, and other industries, thereby meeting the requirements for industrialized implementation of the national "Robotics+" strategy.

Figure 1. Inspection robot in charging standby mode.

platform employs convolutional neural networks (CNN) to analyse infrared thermal imaging maps, and identifies local overheating caused by micron-scale carbon slag accumulation. Algorithm optimization includes lightweight model deployment (parameter size up to 1 million) and enhanced robustness against adversarial samples, reducing the false alarm rate to 1 %.

5.3 Industrial Application Value

In close alignment with Chinese national policies, the technical architecture of the intelligent inspection robot system facilitates the use of these policies as carriers of technical references, enabling the development of replicable, standardized solutions. In response to the *"Robotics+" Implementation Plan*, the system achieves a substitution rate of at least 80 % in hazardous scenarios to meet the inspection requirements for ledges. Through laser SLAM navigation and multi-modal perception technologies, it enables continuous temperature monitoring of high-temperature ladles (at least 800 °C), significantly reducing the frequency of human intervention. In line with the *14th Five-Year Plan for the Development of the Robotics Industry,* the system's multi-modal perception patents account for 35 % of the total, and its fusion algorithm, which combines infrared thermography and ultrasonic sensing, can be expanded to leakage monitoring in chemical reactors and accurately identify local overheating (ΔT at least 5 °C/min) caused by micro-scale cracks.

The standardized design should be further adapted to inspection scenarios in the radiation zones of nuclear power plants. This is demonstrated by the system's ability to increase data acquisition frequency from 0.1 Hz to 10 Hz, thereby meeting the stringent real-time monitoring requirements of nuclear facilities. Combined with a radiation-hardened reinforced structure (IP68-rated) and an anti-interference communication module (packet loss rate below 0.1 %), the system enables fully unmanned operation and maintenance in hazardous areas. The robot's four-wheel-drive chassis (torque at least 35 N·m) and modular sensor interfaces support rapid customization, reducing deployment cycle time by 60 %. As a result, the system can be deployed within one week in applications such as ladle temperature monitoring in the metallurgical industry and corrosion detection in chemical pipelines.

In the future, by actively opening data interfaces (GB/T 28181 protocol) and enhancing the transfer learning capabilities of industry-specific small-scale models, the system can provide end-to-end solutions for high-risk industrial scenarios to support the industrialized implementation of the national "Robotics+" strategy.

6. References

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