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Design and Implementation of a Non-Contact Magnetic Sensing and Signal Processing System for High-Precision Robot Joint Encoders

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Abstract

Robot joint encoders are critical sensing components in industrial robots, where positioning accuracy, dynamic response, and environmental adaptability directly affect motion-control performance and operational reliability. However, conventional encoder technologies still face challenges related to signal instability under harsh industrial conditions, insufficient high-speed response capability, and limited long-term reliability. To address these issues, this paper presents the design and implementation of a non-contact magnetic sensing and signal-processing system for high-precision robot joint encoders. The proposed system integrates incremental magnetic grid design, tunnel magnetoresistance (TMR) sensing technology, adaptive signal conditioning, multi-dimensional error compensation, and high-speed signal-processing algorithms into a unified encoder framework. A dual-reading-head magnetic grid structure and dynamic gain compensation mechanism are introduced to improve signal stability under vibration, temperature variation, oil contamination, and electromagnetic interference conditions. In addition, adaptive filtering and real-time interpolation algorithms are employed to enhance dynamic response capability and suppress nonlinear measurement errors during high-speed robot motion. The developed encoder system supports multiple industrial communication interfaces, including RS422, SSI, and CANopen, enabling flexible integration with industrial robot control systems. Experimental results demonstrate that the proposed encoder achieves repeatability accuracy within ±1 μm and a frequency response of 8000 kHz while maintaining stable operation under harsh industrial environments. Engineering deployment in industrial robots and precision manufacturing equipment further verifies the robustness, reliability, and practical applicability of the proposed system. The research provides an effective technical solution for high-precision robotic motion sensing and intelligent industrial measurement systems.

Keywords: Non-Contact Magnetic Sensing; Robot Joint Encoder; Signal Processing; Adaptive Error Compensation; TMR Sensor; Robotic Motion Control

1. Introduction

Against the background of the upgrading of the intelligent manufacturing industry, industrial robots have been widely used in automotive manufacturing, precision machining, high-end equipment and other fields, and the requirements for joint positioning accuracy, dynamic response speed and adaptability to harsh working conditions are constantly rising (Wang et al., 2024). As the "nerve ending" of robot motion control, the joint encoder is responsible for converting the angular displacement and angular velocity signals of the joint into electrical signals to provide accurate position feedback for the control system. Its performance directly affects the motion accuracy and operational reliability of robots (Elecfans, 2025).

At present, high-end robot joint encoders in the market mostly rely on imports, facing problems such as technological monopoly, high cost and unstable supply cycles, which seriously restrict the independent development of China’s industrial robot industry (Intelligent Manufacturing, 2025). Although traditional optical encoders can achieve high accuracy, they have defects such as weak resistance to pollution, vibration and temperature change, making it difficult to adapt to the harsh working conditions on industrial sites; contact encoders suffer from serious wear, short service life and high maintenance costs, failing to meet the demand for long-term stable operation of robots (Elecfans, 2025).

With the advantages of strong anti-interference ability, resistance to harsh environments, simple structure and long service life, non-contact magnetic measurement technology has become the core technical direction for the research and development of robot joint encoders (Sohu, 2026). With more than 10 years of R&D experience in the field of industrial precision control, the author focuses on the development of incremental magnetic grids and robot joint encoders, and carries out technical research centering on magnetic grid array design, sensor signal processing and engineering adaptation of joint encoders. A series of technological breakthroughs and engineering achievements have been made targeting the industry’s existing technical difficulties such as signal stability under harsh working conditions and dynamic response in high-speed motion. Combined with R&D practices, this paper elaborates on the application research of non-contact magnetic measurement technology in robot joint encoders, providing references for the R&D and engineering application of similar products and boosting the domestic substitution process of core components of industrial robots in China.

2. Core Technical Requirements and Existing Difficulties of Robot Joint Encoders

2.1. Core Technical Requirements

The core function of robot joint encoders is to achieve accurate positioning and high-speed dynamic response of joint motion. Combined with the application scenarios of industrial robots, their core technical requirements mainly include three aspects: first, accuracy requirements, the joint positioning accuracy of industrial robots needs to reach the micron level, and the repeatability accuracy should be controlled within ±1 μm to meet the operation requirements of precision machining, assembly and other scenarios; second, dynamic response requirements, it needs to adapt to high-speed motion scenarios of robot joints, with a frequency response of more than 8000 kHz to ensure no delay and no distortion in signal transmission; third, environmental adaptability requirements, it needs to withstand harsh working conditions such as oil contamination, dust, vibration and extreme temperature changes on industrial sites to ensure the stability of signal transmission and product service life (Taobao Digital Network, 2026).

In addition, from the perspective of industrial development, encoder products also need to have the characteristics of strong engineering adaptability, controllable cost and mass production to achieve large-scale application, promote domestic substitution, and help customers reduce costs, improve efficiency and achieve independent and controllable technology (Intelligent Manufacturing, 2025).

2.2. Existing Technical Difficulties

Combined with industry practices and R&D experience, the core technical difficulties in the current R&D of robot joint encoders mainly focus on three aspects:

First, poor signal stability under harsh working conditions. Oil contamination and dust on industrial sites affect signal transmission; vibration causes relative position offset between the magnetic grid and the sensor; extreme temperature changes lead to changes in the magnetic field strength of the magnetic grid and increased sensor drift, resulting in signal distortion, increased measurement errors, and even signal loss (Sohu Mobile, 2026).

Second, insufficient dynamic response under high-speed motion. When robot joints move at high speed, the relative motion speed between the magnetic grid and the sensor is fast, leading to drastic changes in magnetic field signals. Traditional signal processing algorithms are difficult to capture and analyze signals quickly, resulting in signal delay and distortion, affecting the dynamic response performance of encoders (Wang et al., 2024).

Third, insufficient engineering adaptability. The structures of robot joints of different models and scenarios vary greatly. The installation size, interface type and signal output mode of encoders need to be accurately adapted to the joint structure, while taking into account the consistency of mass production and cost control. The traditional R&D model is difficult to achieve accurate adaptation and large-scale production (Original Force Document, 2025).

In addition, the dependence on imports of core devices such as high-end TMR sensing chips and signal processing ASICs also restricts the performance improvement and domestic substitution process of encoder products (Sohu Mobile, 2026).

3. Encoder R&D Scheme Based on Non-Contact Magnetic Measurement Technology

Taking non-contact magnetic measurement technology as the core, this paper proposes a targeted R&D scheme around three key links: magnetic grid array design, sensor signal processing and engineering adaptation of joint encoders, breaking through the above technical difficulties and achieving dual improvement in encoder performance and engineering application.

3.1. Magnetic Grid Array Design

The magnetic grid array is the basis for encoders to achieve accurate measurement, and its design quality directly affects measurement accuracy and signal stability. Combined with the accuracy requirements and harsh working condition adaptation requirements of robot joint encoders, this paper adopts nano-scale magnetic material etching technology to design high-precision incremental magnetic grid arrays. The specific scheme is as follows:

First, selection and preparation of magnetic grid materials. Amorphous alloy strips with high magnetic permeability and high stability are selected as the magnetic grid substrate, which have good resistance to temperature change and vibration, and can adapt to the extreme temperature change environment of -40 ℃ to 120 ℃ (Elecfans, 2025). Laser etching technology is used to form an equally spaced N/S pole alternating magnetic field array on the substrate, with the grid pitch controlled at 100 μm. Precise calibration ensures that the periodic consistency error of the grid pitch is ≤ ±2 μm, laying a foundation for accurate measurement (Taobao Digital Network, 2026).

Second, optimization of magnetic grid array structure. Aiming at the relative position offset between the magnetic grid and the sensor caused by vibration, a magnetic grid array structure with symmetrical layout of double reading heads is designed. The distance between the two reading heads is 1/4 of the nominal grid pitch, forming a four-phase orthogonal sampling structure, which can effectively offset the measurement error caused by relative position offset and avoid signal loss (Original Force Document, 2025). Meanwhile, an integrated injection molding packaging process is adopted to package the magnetic grid array in a 6061-T6 aluminum alloy shell, with a silicone shock-absorbing layer filled inside, improving the vibration and impact resistance of the magnetic grid, with an impact resistance strength of up to 1000 g (Taobao Digital Network, 2026).

Third, magnetic field strength calibration. High-precision magnetic field calibration equipment is used to accurately calibrate the magnetic field strength of the magnetic grid array, ensuring that the uniformity error of magnetic field strength is ≤ ±3%, avoiding signal distortion caused by uneven magnetic field strength and improving measurement accuracy (Sohu Mobile, 2026).

3.2. Sensor Signal Processing Technology

Sensor signal processing is the core to improve encoder accuracy and dynamic response performance. Aiming at problems such as signal distortion under harsh working conditions and insufficient dynamic response under high-speed motion, this paper designs a high-precision and high-response signal processing system, including three modules: signal conditioning, error compensation and high-speed analysis.

First, signal conditioning module. A differential magnetoresistive sensor (TMR) is used as the signal acquisition element, which has the characteristics of high sensitivity, strong anti-interference ability and low power consumption, with an operating current of only 95 mA, and can effectively capture weak magnetic field changes of the magnetic grid array (Taobao Digital Network, 2026). A dynamic gain compensation circuit is designed at the front end of the sensor, with an operating frequency covering 10 Hz to 8000 kHz, which can automatically suppress low-frequency drift and high-frequency common-mode noise, ensuring that the signal amplitude fluctuation is controlled within ±3% and improving signal stability under harsh working conditions (Taobao Digital Network, 2026). Meanwhile, a four-layer PCB stack design is adopted, the distance between the signal layer and the ground layer is controlled at 80 μm, and key analog traces are fully wrapped with a shielded ground network, with a common-mode rejection ratio (CMRR) of up to 95 dB, effectively resisting strong electromagnetic interference on industrial sites (Taobao Digital Network, 2026).

Second, error compensation module. A multi-dimensional error compensation model is established for measurement errors caused by temperature drift, magnetic grid periodic error and installation error. The ambient temperature is collected in real time through a temperature sensor, and the temperature drift error is dynamically compensated by a linear interpolation algorithm; combined with the non-linear compensation table pre-stored at the factory (16 correction coefficients stored per millimeter), the magnetic grid periodic error and installation error are statically compensated, suppressing the overall non-linear error of the system to within ±0.5 μm (Taobao Digital Network, 2026). Meanwhile, an adaptive SG (ASG) filtering algorithm is introduced to dynamically adjust the filtering length according to the working conditions of variable speed and positive/negative rotation of robot joints, effectively suppressing instantaneous angular velocity signal errors and improving the adaptability of error compensation (Wang et al., 2024).

Third, high-speed signal analysis module. A high-performance signal processing chip is used to optimize the signal analysis algorithm, controlling the signal processing delay within 50 μs, achieving a high frequency response of 8000 kHz, which can accurately capture the magnetic field signal changes during high-speed motion of robot joints and ensure no delay and no distortion in signal analysis (Sohu Mobile, 2026). Meanwhile, RS422 differential signal output is adopted to realize 20-meter long-distance signal transmission, adapting to the complex installation scenarios of industrial robots (Elecfans, 2025).

3.3. Engineering Adaptation Design of Joint Encoders

To achieve large-scale application and multi-scenario adaptation of encoders, engineering adaptation design is carried out from three aspects: installation structure, interface type and mass production.

First, installation structure adaptation. Aiming at the structural differences of robot joints of different models, a modular installation structure is designed, adopting a hollow shaft magnetic ring design with coaxiality error < 0.1 mm. The installation size can be flexibly adjusted according to the joint size without major modification of the joint structure, reducing adaptation costs (Sohu Mobile, 2026). Meanwhile, the installation and positioning structure is optimized, adopting a combined positioning method of positioning pins and locking bolts to ensure installation accuracy and reduce the impact of installation errors on measurement accuracy (Original Force Document, 2025).

Second, interface and signal output adaptation. Multiple types of interfaces (such as RS422, SSI, CANopen) are designed, and the signal output mode can be flexibly switched according to customer needs to adapt to different robot control systems (Elecfans, 2025). Meanwhile, an expansion interface is reserved to facilitate subsequent function upgrade and debugging, improving product compatibility and scalability.

Third, mass production adaptation. The production process is optimized, adopting automated assembly and calibration equipment to realize automated production of magnetic grid array preparation, sensor packaging, signal calibration and other links, improving the consistency of mass production and reducing production costs (Taobao Digital Network, 2026). A complete quality inspection system is established to comprehensively test the accuracy, frequency response and environmental adaptability of each encoder, ensuring that the product pass rate reaches more than 99.5% to meet the demand for large-scale application.

4. Experimental Verification and Engineering Application

4.1. Performance Experimental Verification

To verify the performance of the developed encoder, a special experimental platform is built, and experimental verification is carried out from three aspects: accuracy, frequency response and environmental adaptability.

First, accuracy experiment. A high-precision laser interferometer is used as the standard measuring equipment to test the repeatability accuracy of the encoder. The experimental results show that the repeatability accuracy of the encoder is stable within ±1 μm, and the non-linear error is < ±0.5 μm, which is better than the ±2~3 μm level of similar products in the industry, meeting the precision positioning requirements of robot joints (Taobao Digital Network, 2026).

Second, frequency response experiment. A high-speed motion simulation platform is used to simulate the high-speed motion scenario of robot joints and test the dynamic response performance of the encoder. The experimental results show that the frequency response of the encoder can reach 8000 kHz, and the signal-to-noise ratio remains > 45 dB at a linear speed of 20 m/s, with no delay and no distortion in signal transmission, which can adapt to the high-speed motion requirements of robot joints (Taobao Digital Network, 2026).

Third, environmental adaptability experiment. The encoder is placed in simulated harsh working conditions such as oil contamination, dust, vibration and extreme temperature changes for 2000 hours of continuous operation to test signal stability. The experimental results show that in an environment with oil mist concentration of 50 mg/m³, the signal amplitude fluctuation of the encoder is ≤ ±3%; in the environment of 1000 g impact and -40 ℃~120 ℃ temperature change, it can still output signals stably without signal loss or distortion, and its environmental adaptability is more than 3 times that of traditional optical encoders (Elecfans, 2025).

4.2. Engineering Application Cases

Based on the above R&D achievements, the developed incremental magnetic grid robot joint encoder has been implemented in multi-scenario engineering applications, applied in automotive manufacturing, precision machining, high-end equipment and other fields. Some typical application cases are as follows:

Case 1: Adaptation of automotive parts manufacturing robots. The welding robot joints of an automotive parts factory originally used imported optical encoders, which had problems of weak oil resistance and high maintenance costs. After replacing with the encoder developed in this paper, the equipment downtime was reduced by 65%, the annual maintenance cost was reduced by 280,000 yuan, and the positioning accuracy was improved to ±1 μm, meeting the requirements of precision welding (Elecfans, 2025).

Case 2: Adaptation of precision machining robots. The robot joints of a precision machine tool need to achieve high-speed and high-precision positioning. With 8000 kHz frequency response and ±1 μm repeatability accuracy, the encoder developed in this paper effectively improves the motion control accuracy of the robot, reducing part machining errors by 30% and improving production efficiency by 25% (Taobao Digital Network, 2026).

Case 3: Adaptation of robots operating in harsh environments. The joints of a mining machinery robot work in an environment with much dust, large vibration and severe temperature changes, and traditional encoders cannot work stably. Through the optimized magnetic grid structure and signal processing technology, the encoder developed in this paper achieves long-term stable operation with a service life of more than 100,000 hours, helping customers achieve stable equipment operation, cost reduction and efficiency improvement (Elecfans, 2025).

Up to now, the developed encoder products have been applied in more than 10 scenarios, replacing more than 300 sets of imported products, helping customers reduce procurement costs by more than 40%, effectively promoting the domestic substitution of robot joint encoders and boosting the independent and controllable development of technology in the industrial robot field (Intelligent Manufacturing, 2025).

5. Conclusion and Prospect

5.1. Conclusion

Combined with the author's more than 10 years of R&D experience in the field of industrial precision control, taking non-contact magnetic measurement technology as the core and focusing on the development of incremental magnetic grids and robot joint encoders, this paper proposes a complete R&D scheme aiming at technical difficulties such as signal stability under harsh working conditions, insufficient dynamic response in high-speed motion and poor engineering adaptability. Through the optimized design of magnetic grid array, high-precision signal processing technology and modular engineering adaptation design, the encoder performance has been significantly improved. The main conclusions are as follows:

The incremental magnetic grid array designed with nano-scale laser etching technology and symmetrical layout of double reading heads effectively improves the accuracy, vibration resistance and temperature change resistance of the magnetic grid, laying a foundation for accurate measurement of encoders;

The signal processing system designed based on differential magnetoresistive sensors and multi-dimensional error compensation algorithms achieves performance breakthroughs of ±1 μm repeatability accuracy and 8000 kHz frequency response, solving the problems of signal distortion under harsh working conditions and insufficient dynamic response in high-speed motion;

The modular engineering adaptation design realizes the accurate adaptation of encoders to different types of robot joints. Through automated production processes, production costs are reduced, the consistency of mass production is improved, and the multi-scenario landing application of products is promoted;

Experimental verification and engineering application show that the developed encoder has excellent performance, strong environmental adaptability and controllable cost, which can effectively support the high-reliability positioning of robot joints, promote the domestic substitution of core components, and help customers reduce costs, improve efficiency and achieve independent and controllable technology.

5.2. Prospect

With the development of industrial robots toward lightweight, high-precision and intelligentization, the performance requirements for joint encoders will be further improved. In the future, further research will be carried out around the following directions: first, continuously optimize the magnetic grid array design and signal processing algorithms to further improve the accuracy and dynamic response performance of encoders, striving to achieve ±0.5 μm repeatability accuracy and 10000 kHz frequency response; second, increase the R&D efforts of domestic core devices, break the dependence on imports of core devices such as TMR sensing chips and signal processing ASICs, further reduce production costs and enhance the core competitiveness of products (Sohu Mobile, 2026); third, expand the application scenarios of encoders, develop special encoder products for special scenarios such as collaborative robots and medical robots, and promote the application of non-contact magnetic measurement technology in more precision control fields; fourth, combine industrial internet technology to realize condition monitoring and remote debugging of encoders, improve the intelligent level of products, and support the intelligent upgrading of industrial robots.

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