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# Intelligent Absolute Magnetic Grating and Rotary Encoder System Based on TMR Sensing and Embedded Signal Processing for Industrial Automation Applications

Lujie Ren [1,*], Jianming Mao [1], Haijun Lei [1], Dengcheng Lu [1], Shishui Zhou [1], Chaohui Zhang [1]

[1] Hopo Technology (Ningbo) Co., Ltd., Ningbo 315000, China

*** Correspondence:**

Lujie Ren

renlj200812@163.com

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**Abstract**

With the rapid advancement of intelligent manufacturing, industrial robotics, digital motion-control systems, and high-end automated equipment, position sensing technologies have become fundamental components for precision motion control and intelligent industrial feedback systems. Absolute magnetic gratings and rotary encoders are increasingly employed in industrial robots, servo drives, CNC machine tools, logistics systems, and automated production equipment due to their advantages in non-contact measurement, anti-contamination capability, wide-temperature adaptability, and power-off position retention. However, conventional encoder systems still face several engineering challenges, including insufficient resistance to electromagnetic interference, unstable operation under vibration and oil contamination, limited multi-turn memory capability, and reduced measurement consistency in harsh industrial environments. To address these challenges, this paper presents a systematic study on intelligent absolute magnetic grating and rotary encoder technologies based on tunnel magnetoresistance (TMR) sensing, adaptive signal processing, magnetic circuit optimization, embedded decoding algorithms, and industrial reliability verification. A complete engineering framework integrating magnetic measurement principles, magnetic circuit structure optimization, absolute coding algorithm development, interpolation subdivision methods, wide-temperature compensation, anti-vibration optimization, multi-turn power-off memory, and automated calibration technologies is proposed. The system employs high-sensitivity TMR sensing bridges, low-noise signal-conditioning circuits, adaptive digital filtering algorithms, and embedded decoding architectures to improve position resolution, environmental robustness, and operational reliability. A high-precision multi-turn absolute encoder system is developed as an engineering validation platform. Experimental results demonstrate that the optimized encoder achieves stable high-resolution position output under industrial environments involving vibration, electromagnetic interference, oil contamination, and thermal fluctuation. The proposed system supports multiple industrial communication interfaces including RS422, SSI, CANopen, and incremental pulse output, enabling compatibility with industrial servo systems and intelligent motion-control platforms. Reliability tests including vibration testing, thermal cycling, electromagnetic compatibility evaluation, waterproof verification, and long-term aging experiments further confirm the engineering stability of the developed system. Compared with conventional encoder products, the proposed optimization framework significantly improves measurement consistency, anti-interference capability, environmental adaptability, and industrial deployment efficiency. The research provides a practical technical solution for intelligent industrial sensing systems and contributes to the development of high-precision motion-control technologies in intelligent manufacturing environments.

**Keywords:** Absolute Magnetic Grating; Rotary Encoder; TMR Sensing; Embedded Signal Processing; Industrial Automation; Intelligent Sensing Systems; Motion Control

## 1. Introduction

With the rapid development of intelligent manufacturing, industrial automation, digital production systems, and precision motion-control technologies, position sensing systems have become indispensable components in modern industrial equipment. Absolute rotary encoders and magnetic grating systems are widely used in industrial robots, CNC machine tools, servo motors, automated logistics equipment, semiconductor manufacturing platforms, and intelligent assembly systems, where they are responsible for position feedback, speed monitoring, angular measurement, and precision motion coordination. The measurement accuracy and operational stability of encoder systems directly affect motion-control precision, response speed, system reliability, and production efficiency.

In recent years, the increasing demand for high-speed motion control and intelligent equipment has significantly raised the technical requirements for industrial position sensing systems. Modern industrial environments require encoders to maintain stable operation under harsh conditions involving electromagnetic interference, vibration, oil contamination, dust exposure, humidity variation, and wide-temperature fluctuation. Traditional optical encoders often suffer from contamination sensitivity and environmental instability because their measurement accuracy heavily depends on optical cleanliness and precise alignment conditions. Under complex industrial conditions, optical contamination and vibration may lead to signal distortion, position drift, and decoding errors.

Compared with optical encoder systems, absolute magnetic gratings and magnetic rotary encoders provide significant engineering advantages. Magnetic measurement systems rely on non-contact magnetic field detection rather than optical imaging, allowing stable operation under oil pollution, dust contamination, vibration, and moisture conditions. Furthermore, magnetic encoder systems exhibit strong anti-interference capability, compact structural design, low maintenance requirements, and improved environmental adaptability. These advantages make magnetic encoder systems particularly suitable for industrial robots, automated production lines, heavy industrial machinery, and harsh manufacturing environments.

Tunnel magnetoresistance (TMR) sensing technology has recently become an important research direction in high-precision magnetic measurement systems due to its high magnetic sensitivity, low power consumption, low temperature drift, and strong signal stability. Gao et al. (2020) demonstrated that TMR-based encoder systems significantly improve magnetic signal resolution and environmental adaptability compared with conventional Hall-based sensing structures. Kim et al. (2019) further analyzed the performance advantages of TMR position sensors in harsh industrial environments and highlighted their suitability for high-vibration and high-temperature applications. In addition, magnetic circuit optimization, interpolation algorithms, and adaptive compensation technologies have become critical for improving measurement accuracy and long-term operational stability.

Although significant progress has been achieved in magnetic encoder technologies, several engineering challenges still exist in practical industrial deployment. First, magnetic field consistency and decoding accuracy are highly affected by installation eccentricity, air-gap fluctuation, and magnetic material stability. Second, electromagnetic interference and mechanical vibration may introduce signal distortion and phase jitter, reducing measurement reliability during high-speed operation. Third, multi-turn power-off memory and high-resolution interpolation algorithms remain difficult to implement in low-cost embedded systems while maintaining real-time response capability. Furthermore, large-scale industrial deployment requires stable manufacturing processes, automated calibration systems, and long-term reliability verification.

Extensive research has been conducted on magnetic encoder systems and intelligent sensing technologies. Zhang et al. (2019) investigated magnetic circuit optimization methods for absolute magnetic gratings and demonstrated that optimized magnetic field distribution significantly improves signal consistency. Li et al. (2020) proposed wide-temperature compensation algorithms for magnetic encoders and reduced temperature-induced measurement drift through adaptive correction methods. Chen et al. (2022) studied anti-interference optimization technologies for industrial robot encoders and demonstrated the effectiveness of electromagnetic compatibility design in harsh industrial environments. Meanwhile, multi-turn memory technologies and interpolation subdivision methods have also become important research topics for improving industrial encoder performance (Wang et al., 2021; Park et al., 2018).

Despite these advancements, existing studies often focus on isolated technical aspects such as magnetic sensing, interpolation algorithms, or anti-interference structures, while lacking a systematic engineering framework integrating magnetic circuit design, embedded decoding algorithms, industrial communication, reliability verification, and mass-production optimization. In practical industrial applications, encoder systems must satisfy not only high measurement precision but also long-term operational reliability, manufacturing consistency, and compatibility with industrial control platforms.

Based on practical engineering development and industrial deployment experience, this paper presents a comprehensive study on intelligent absolute magnetic grating and rotary encoder technologies for industrial automation applications. The proposed framework integrates TMR sensing technology, magnetic circuit optimization, adaptive signal processing, interpolation subdivision algorithms, multi-turn power-off memory, embedded communication architecture, and reliability verification into a unified industrial sensing system. A high-precision industrial encoder platform is developed and experimentally validated under practical industrial environments involving vibration, thermal fluctuation, electromagnetic interference, and oil contamination.

The major contributions of this research can be summarized as follows:

(1) A complete engineering framework integrating magnetic sensing, signal processing, embedded decoding, and industrial communication is proposed.

(2) A high-stability magnetic circuit structure and adaptive compensation strategy are developed to improve measurement consistency under harsh industrial conditions.

(3) Multi-turn power-off memory and embedded interpolation algorithms are optimized for high-resolution industrial motion-control applications.

(4) Comprehensive reliability verification and mass-production optimization methods are established to improve industrial deployment capability.

(5) A practical engineering implementation platform is developed for industrial robots, servo systems, and intelligent manufacturing equipment.

The remainder of this paper is organized as follows. Section 2 introduces the fundamental principles and system architecture of absolute magnetic gratings and rotary encoders. Section 3 presents key technological optimization methods including magnetic circuit design, embedded signal processing, and interpolation algorithms. Section 4 discusses engineering implementation and industrial reliability verification. Section 5 analyzes industrial deployment results and application performance. Finally, Section 6 concludes the paper and outlines future research directions.

## 2. Fundamental Principles of Absolute Magnetic Gratings and Rotary Encoders

### 2.1. Magnetic Measurement Principles

Absolute magnetic gratings and rotary encoders operate based on magnetic field detection and position decoding technologies. Compared with optical sensing systems, magnetic encoder systems utilize magnetic code arrays or magnetic drums to generate periodic magnetic fields, which are detected by magnetic-sensitive elements to obtain displacement or angular position information.

During operation, magnetic-sensitive elements continuously collect magnetic field intensity, polarity distribution, and magnetic phase information generated by the magnetic code rail or magnetic drum. After signal conditioning, amplification, analog-to-digital conversion, and decoding processing, the system outputs absolute position information. The measurement accuracy mainly depends on magnetic field consistency, sensing resolution, interpolation algorithms, and signal-processing capability.

Modern magnetic encoder systems commonly employ AMR, GMR, and TMR sensing technologies. Among these sensing methods, TMR sensing technology provides the highest magnetic sensitivity and the lowest temperature drift. TMR sensors exhibit strong signal linearity, high signal-to-noise ratio, and low power consumption, making them particularly suitable for high-precision industrial motion-control systems.

The proposed encoder system adopts a differential TMR sensing bridge combined with low-noise signal-conditioning circuits. Differential magnetic field acquisition effectively suppresses common-mode noise and improves signal stability during high-speed operation. In addition, adaptive filtering algorithms are integrated into the signal-processing framework to reduce phase fluctuation caused by vibration and electromagnetic interference.

Single-turn absolute position measurement is achieved through magnetic code detection and interpolation subdivision. To realize multi-turn position sensing, a low-power counting mechanism combined with non-volatile memory is integrated into the embedded control architecture. The multi-turn memory system retains position information after power interruption and enables immediate position recovery during restart without homing initialization.

### 2.2. System Architecture of Intelligent Magnetic Encoder Platforms

The proposed encoder system adopts a layered architecture integrating magnetic sensing, embedded processing, communication management, and industrial reliability optimization. The complete system mainly consists of a magnetic sensing layer, signal-conditioning layer, embedded decoding layer, industrial communication layer, and reliability protection layer.

The magnetic sensing layer includes the magnetic code rail, TMR sensing bridge, and magnetic field guidance structure. The magnetic code rail generates periodic magnetic field distribution according to the designed coding sequence, while the TMR sensing bridge converts magnetic field variation into analog electrical signals.

The signal-conditioning layer performs amplification, filtering, offset correction, and analog-to-digital conversion. Low-noise operational amplifiers and high-precision ADC modules are employed to improve signal stability and reduce quantization error. Differential transmission structures and electromagnetic shielding are also integrated to improve anti-interference capability.

The embedded decoding layer is responsible for interpolation subdivision, absolute code decoding, error compensation, multi-turn counting, and communication coordination. Adaptive digital filtering algorithms are introduced to suppress signal jitter while maintaining dynamic response speed.

The industrial communication layer supports multiple industrial interfaces including SSI, RS422, CANopen, and incremental pulse outputs, enabling compatibility with industrial robots, servo systems, PLC platforms, and CNC motion controllers.

The reliability protection layer integrates vibration resistance, thermal compensation, waterproof sealing, and fault-detection mechanisms to ensure stable operation under harsh industrial conditions.

### 2.3. Magnetic Circuit Structure Optimization

The magnetic circuit structure directly determines magnetic field consistency, signal strength, and measurement stability. Uneven magnetic field distribution may lead to decoding ambiguity, interpolation nonlinearity, and position fluctuation.

To improve magnetic field stability, extensive optimization is conducted for magnetic substrate materials, magnetic code arrangement, magnetic shielding structures, and air-gap distribution. Different magnetic substrate materials are analyzed according to temperature stability, coercivity, residual magnetism, and mechanical strength.

The proposed system adopts segmented absolute coding structures combined with Gray-code optimization to improve decoding reliability. Pseudo-random coding structures are also integrated into specific application scenarios to improve fault tolerance and signal robustness.

Magnetic shielding and magnetic field guidance structures are optimized to reduce external magnetic interference and improve magnetic field consistency. Finite-element simulation and prototype testing demonstrate that the optimized magnetic circuit significantly improves signal stability and reduces sensitivity to installation eccentricity.

### 2.4. Embedded Signal Processing and Interpolation Algorithms

Embedded signal processing is critical for improving measurement resolution and operational stability in industrial encoder systems. Traditional interpolation methods often suffer from phase distortion and harmonic interference under high-speed operation.

The proposed system employs adaptive interpolation subdivision algorithms combined with synchronous sampling and phase compensation. The original sinusoidal magnetic signals are subdivided through digital interpolation processing to achieve high-resolution angular output.

To reduce signal distortion caused by vibration and electromagnetic interference, adaptive digital filtering algorithms are introduced into the embedded signal-processing architecture. The filtering parameters are dynamically adjusted according to signal amplitude and noise intensity.

Error compensation algorithms are also integrated to reduce position errors caused by temperature drift, magnetic field non-uniformity, and installation eccentricity. Experimental results demonstrate that the optimized interpolation framework significantly improves dynamic measurement stability.

## 3. Key Technological Optimization and Engineering Implementation

### 3.1. High-Precision Position Sampling Technology

To achieve stable high-resolution position output, the complete signal acquisition chain from magnetic sensing to digital decoding is optimized. The TMR sensing bridge is combined with low-noise amplification circuits and high-speed ADC modules to improve magnetic signal fidelity.

Synchronous sampling technology is introduced to reduce phase delay and improve signal consistency during high-speed operation. Dynamic calibration algorithms continuously compensate offset variation and phase fluctuation.

Experimental validation demonstrates that the optimized system achieves stable sampling performance under vibration and electromagnetic interference conditions.

### 3.2. Multi-Turn Power-Off Memory Technology

Multi-turn memory capability is one of the most important features of absolute rotary encoders. The proposed system adopts a low-power counting architecture combined with non-volatile memory storage.

During normal operation, the embedded controller continuously records rotation counts and position information. When external power is interrupted, backup power modules maintain low-power counting operation while writing key position data into memory.

Long-term storage verification demonstrates that the encoder retains accurate multi-turn position information after extended power interruption and immediately restores absolute position output during restart.

### 3.3. Anti-Vibration and Anti-Contamination Optimization

Industrial robots and CNC systems often operate under harsh conditions involving vibration, oil contamination, and dust exposure. Therefore, structural sealing and anti-vibration optimization are critical for industrial deployment.

The proposed encoder adopts reinforced structural supports, vibration-resistant PCB mounting, waterproof sealing structures, and resin protection technologies to improve environmental adaptability.

Signal-processing algorithms are further optimized to suppress vibration-induced phase fluctuation and transient signal jitter. Industrial testing confirms stable operation under high-vibration machine tool environments.

### 3.4. Wide-Temperature Compensation Technology

Industrial encoder systems are often required to operate within wide temperature ranges from −40°C to 85°C. Temperature variation may significantly affect magnetic sensitivity, signal amplitude, and interpolation stability.

To reduce thermal drift, temperature compensation algorithms are integrated into the embedded decoding framework. Temperature-sensitive parameters are dynamically corrected according to real-time thermal conditions.

Thermal cycling tests demonstrate that the optimized encoder maintains stable measurement accuracy throughout the full operating temperature range.

### 3.5. Industrial Communication and Embedded Integration

Modern industrial motion-control systems require encoder platforms to support high-speed communication and intelligent integration capability. Therefore, the proposed system supports multiple industrial communication interfaces.

The embedded communication architecture integrates SSI, RS422, CANopen, and incremental pulse outputs to improve compatibility with industrial servo systems and PLC platforms.

Communication fault-detection and packet-verification mechanisms are also introduced to improve transmission reliability under electromagnetic interference conditions.

## 4. Engineering Verification and Industrial Deployment

### 4.1. Prototype Development and Debugging

After completing theoretical design and algorithm optimization, a prototype encoder platform is established for engineering validation. Joint debugging is conducted for magnetic sensing structures, signal-conditioning circuits, embedded firmware, and industrial communication interfaces.

Repeated optimization is carried out for signal distortion, phase fluctuation, zero drift, and communication stability problems. Through multiple rounds of parameter iteration, stable signal output is achieved.

The optimized prototype successfully passes environmental adaptability verification and enters small-batch industrial testing.

### 4.2. Automated Calibration and Manufacturing Optimization

To improve manufacturing consistency, automated calibration systems are introduced into the production process. High-precision turntables and standard encoders are employed for error calibration and compensation generation.

Automated calibration equipment significantly improves production efficiency and reduces manual calibration errors. Statistical analysis demonstrates strong consistency among different production batches.

Standardized manufacturing procedures are further established for SMT assembly, magnetic code calibration, signal testing, and aging verification.

### 4.3. Reliability Verification

Comprehensive reliability tests are conducted according to industrial standards. The encoder system undergoes vibration testing, impact testing, waterproof evaluation, thermal cycling, electromagnetic compatibility verification, and long-term aging experiments.

Under high-vibration and oil-contamination conditions, the encoder maintains stable signal output without position loss or communication interruption.

Long-term operation tests further demonstrate strong environmental adaptability and engineering reliability.

## 5. Industrial Application Results and Discussion

The developed encoder system has been successfully applied in industrial robots, servo systems, precision machine tools, and automated logistics equipment. Industrial users report stable operation and low maintenance requirements. In industrial robot applications, the encoder significantly improves positioning stability and startup efficiency because multi-turn absolute position information can be recovered immediately after power restoration. Machine tool applications demonstrate strong vibration resistance and contamination tolerance. Compared with optical encoder systems, the magnetic encoder maintains stable operation under oil-pollution environments. The integration of TMR sensing technology, adaptive interpolation algorithms, and industrial communication architectures significantly improves system performance. Experimental results demonstrate that the proposed framework effectively balances high precision, environmental adaptability, and engineering cost. Compared with conventional encoder products, the proposed system improves operational reliability, reduces maintenance frequency, and shortens equipment recovery time during restart. However, several limitations still exist. Further optimization is required for ultra-high-speed interpolation processing and ultra-miniaturized encoder structures. In addition, intelligent predictive maintenance and cloud-based monitoring technologies remain future research directions.

## 6. Conclusion and Future Work

This paper presents a comprehensive study on intelligent absolute magnetic grating and rotary encoder technologies for industrial automation applications. A complete engineering framework integrating TMR sensing, magnetic circuit optimization, adaptive signal processing, interpolation subdivision algorithms, multi-turn memory technology, embedded communication architecture, and reliability verification is proposed. Experimental and industrial validation demonstrate that the developed encoder system achieves stable high-resolution position output under harsh industrial environments involving vibration, oil contamination, electromagnetic interference, and thermal fluctuation. The proposed optimization framework significantly improves measurement consistency, anti-interference capability, environmental adaptability, and industrial deployment efficiency. The developed system provides practical technical support for intelligent manufacturing, industrial robotics, servo motion control, and digital industrial sensing systems.

Future research will focus on higher-speed interpolation algorithms, intelligent self-diagnosis technologies, AI-based predictive maintenance, edge computing integration, and chip-level localization optimization. These technologies are expected to further improve industrial encoder intelligence and support the development of next-generation intelligent manufacturing systems.

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