Journal of Computer Science and Digital Technology, 2025, 1(2), 8-16
https://doi.org/10.71204/5z5xmw25

# Design and Implementation of an Intelligent Motion Control and Automatic Detection System for Magnetic Grid Manufacturing

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*Received: 1 October 2025 / Accepted: 27 December 2025 / Published online: 29 December 2025*

## Abstract

Magnetic grid sensors are widely used in industrial robots, CNC machine tools, and intelligent manufacturing systems due to their high precision and strong environmental adaptability. However, conventional magnetic grid production still suffers from low assembly consistency, inefficient manual inspection, weak process traceability, and insufficient integration between motion control and quality management systems. To address these challenges, this paper proposes an intelligent automatic detection and motion control system for magnetic grid manufacturing. The proposed system integrates high-precision motion control algorithms, multi-axis coordinated control, automatic signal acquisition, human–machine interaction (HMI), and software–hardware collaborative integration into a unified production platform. A modular system architecture consisting of equipment execution, control management, and data application layers is designed to realize automated assembly positioning, precision calibration, real-time signal analysis, and digital quality control. To improve positioning stability and trajectory tracking accuracy, feedforward compensation and friction compensation strategies are introduced into the motion control framework. In addition, a real-time data acquisition and traceability mechanism is established to support process monitoring, defect analysis, and production optimization. Experimental verification and mass-production deployment demonstrate that the proposed system significantly improves assembly consistency and inspection efficiency. The positioning repeatability reaches ±0.01 mm, the single-station inspection time is reduced by more than 50%, and the product defect rate decreases from 12% to below 3%. The developed system provides an effective technical solution for intelligent upgrading of precision sensor manufacturing and offers practical references for industrial automation, intelligent quality control, and digital manufacturing applications.

**Keywords:** Magnetic Grid Manufacturing; Automatic Detection; Motion Control; Intelligent Quality Control; Software－Hardware Integration; Industrial Automation

## 1. Introduction

With the rapid advancement of intelligent manufacturing and industrial automation, the demand for high-precision displacement sensors continues to grow. Featuring strong pollution resistance, high measurement accuracy, good environmental adaptability and moderate cost, magnetic grid sensors have become core measuring components for robot joints, linear motors, precision transmission mechanisms, intelligent logistics equipment and so on. Magnetic grid products are mainly composed of magnetic scales, magnetic heads, signal processing circuits and mechanical structures. Their production process involves multiple key processes such as magnetic signal writing, geometric dimension assembly, signal acquisition and detection, and precision calibration, which impose extremely high requirements on assembly positioning accuracy, motion stability and signal detection repeatability.

At present, most magnetic grid manufacturing enterprises in China still adopt semi-manual assembly and manual detection modes, which result in problems including inconsistent assembly positioning benchmarks, large manual operation errors, untraceable detection data, low production efficiency and difficult guarantee of batch consistency. These problems not only restrict the improvement of product quality, but also fail to meet the downstream customers' demand for large-batch and high-stability supply (Chen & Zhou, 2020; Li & Zhao, 2022). Against this background, the research and development of automatic equipment and special control systems for magnetic grid production technology to realize the integration of assembly, detection and quality control is of great engineering value for promoting the technological upgrading of the magnetic grid industry and enhancing the market competitiveness of enterprises.

This study is based on long-term engineering research and development experience in magnetic grid production automation and software-assisted manufacturing systems, with a focus on motion control algorithms, dedicated control systems, human–machine interaction (HMI), and software–hardware integration technologies. The paper systematically presents the overall architecture, key technology implementation, system integration strategy, engineering debugging process, and industrial application results of an intelligent automatic detection and control system for magnetic grid manufacturing. Through practical production-line deployment and verification, the proposed system demonstrates significant improvements in assembly consistency, inspection efficiency, and digital quality management. The research provides a practical technical reference for the intelligent transformation of precision sensor manufacturing and contributes to the development of industrial automation and intelligent manufacturing technologies.

## 2. Analysis of Pain Points and Technical Requirements in Magnetic Grid Production Process

### 2.1. Typical Production Process of Magnetic Grid

The large-scale production of magnetic grids mainly includes: substrate pretreatment → magnetic signal magnetization writing → mechanical structure assembly → relative position debugging between magnetic head and magnetic scale → signal output detection → precision calibration → appearance and dimension inspection → packaging and warehousing. Among them, mechanical assembly and signal detection are the key links affecting product accuracy and consistency, as well as the core objects of automatic transformation. The process quality directly determines the final measurement accuracy and service life of magnetic grids.

### 2.2. Core Pain Points of the Existing Production Mode

Poor consistency of assembly accuracy: Manual assembly relies on the experience and hand feel of operators, and the positioning accuracy of tooling fixtures is insufficient. The gap, parallelism and perpendicularity between magnetic head and magnetic scale are difficult to control stably, leading to large fluctuations in signal amplitude and high precision dispersion of products in the same batch, as well as a high defect repair rate (exceeding 12% in some enterprises).

Low detection efficiency and great human influence: Traditional detection depends on manual data reading with universal instruments such as multimeters and oscilloscopes. There are many detection items and cumbersome operation steps, with the single detection time exceeding 30s, which is difficult to adapt to the large-batch production rhythm. Meanwhile, the manual judgment standards are inconsistent, prone to misjudgment and missed judgment, further affecting the stability of product quality (Zhou & Li, 2023).

Lack of digital quality control in the production process: Production data are only recorded manually, failing to realize real-time collection, storage and traceability, and making it difficult to carry out process capability analysis, defect cause statistics and process parameter optimization. Quality control stays at the post-inspection level and cannot reduce the defect rate from the source.

Low integration of software and hardware systems: General motion controllers and detection equipment have inconsistent protocols and poor data interaction, failing to realize the integrated operation of motion control, signal acquisition, logic judgment and data uploading, with low automation degree and difficulty in exerting the collaborative efficiency of equipment.

### 2.3. Summary of Technical Requirements

To solve the above problems, combined with the characteristics of magnetic grid production process and large-scale production demand, the system needs to meet the following core technical requirements: high-precision positioning and motion control, high repeat positioning accuracy of special tooling fixtures, automatic signal acquisition and intelligent judgment, friendly human-computer interaction, real-time uploading of production data and quality control, stable and reliable system for mass production introduction, as well as the ability of rapid switching of multi-variety products to adapt to the flexible production demand of enterprises.

## 3. Overall Scheme Design of Automatic Detection and Control System

### 3.1. Overall System Architecture

The automatic detection and control system for magnetic grid production designed in this paper consists of a mechanical execution mechanism, a tooling fixture module, a motion control system, a data acquisition module, a human-computer interaction system and quality control software, forming a three-tier architecture of "hardware execution + software control + data management" to realize the collaborative linkage and efficient operation of each module.

Equipment layer: Including servo motors, linear modules, sliding tables, pneumatic actuators, high-precision sensors, signal acquisition cards, etc., serving as the execution terminal of the system to complete the core actions of magnetic grid assembly, positioning and detection, which is the basis for ensuring system accuracy and efficiency (Liu & Wang, 2021; Zhao & Chen, 2022).

Control layer: Taking a special motion controller as the core, running self-developed control algorithms to realize multi-axis coordinated motion, logic interlocking, signal processing and abnormal protection, acting as the "brain" of the system responsible for coordinating the orderly operation of each equipment.

Application layer: Composed of human-computer interaction interface and quality control software to realize parameter setting, process monitoring, data display, report generation, historical query and other functions, providing a convenient operation entrance for operators and data support for managers.

### 3.2. Main Function Design

Combined with the demand of magnetic grid production process, the system designs the following core functions:

Automatically complete the assembly positioning and gap adjustment of magnetic head and magnetic scale without manual intervention.

Automatically collect the output signal of magnetic grid, and conduct accurate analysis and judgment on the signal amplitude, period and stability.

Automatically complete precision calibration and qualification judgment, automatically distinguish good products from defective products, and realize automatic sorting of defective products.

Record production data, process parameters and detection results in real time, supporting data traceability and historical query.

Support rapid switching of multi-variety magnetic grid products, with configurable and storable parameters to adapt to flexible production.

Equipped with abnormal alarm, emergency stop protection and fault self-diagnosis functions to ensure the safety of equipment and operators.

### 3.3. Key Technical Indicators

Combined with the accuracy requirements of magnetic grid products and large-scale production demand, the key technical indicators of the system are determined as follows:

Positioning repeat accuracy $\leq \pm 0.01$mm;

Assembly gap control accuracy $\leq 0.02$mm;

Single-station detection time ≤ 15s, improving detection efficiency by more than 50% compared with manual detection;

Continuous trouble-free operation time of the system ≥ 720h;

Data acquisition frequency ≥ 1kHz to ensure the accuracy of detection data;

Product qualification rate increased by ≥ 15%, effectively reducing enterprise production costs.

## 4. Research and Implementation of Key System Technologies

### 4.1. Design of High-Precision Tooling Fixtures

Tooling fixtures are the basis for ensuring the consistency of magnetic grid assembly. Aiming at the insufficient positioning accuracy of existing fixtures, a modular and quick-change structure design is adopted, and the specific implementation is as follows:

Adopt precision positioning pins and elastic clamping mechanisms to realize rapid clamping and benchmark unification of magnetic scales and magnetic heads, avoiding deformation during clamping (Wang & Li, 2022; Zhang & Liu, 2021).

Select high-rigidity and low-deformation alloy for fixture materials, and conduct aging treatment to reduce stress deformation and ensure stable accuracy for long-term use.

Design a micro-gap adjustment mechanism that can be precisely fine-tuned within the range of 0–0.5mm, adapting to different specifications of magnetic grid products and improving system versatility.

Optimize the fixture structure through multiple tests, making the clamping repeat positioning accuracy better than 0.008mm and effectively eliminating manual clamping errors.

### 4.2. Development of Motion Control Algorithm and Control System

Control platform selection: A high-performance motion controller is adopted, matched with servo drives and linear modules to build a multi-axis coordinated motion platform. The platform features fast response speed, high positioning accuracy and stable operation, which can meet the high-precision requirements of magnetic grid assembly and detection.

Optimization of motion control algorithm: Aiming at the requirements of low-speed stability and high-precision positioning for magnetic grid assembly, feedforward control and friction compensation are added on the basis of traditional PID control, effectively reducing low-speed crawling and overshoot, improving trajectory tracking accuracy and controlling positioning error within the allowable range. Meanwhile, logics such as limit protection, overload protection and abnormal emergency stop are added to ensure the safe operation of equipment and avoid product damage and potential safety hazards caused by misoperation or equipment failure.

Multi-axis coordinated control: Realize X/Y/Z three-axis linkage and pneumatic fixture timing control through programming to complete the whole process of automatic loading, positioning, pressing, detection and unloading, optimize process connection, ensure no interference and no waiting between processes, improve system operation rhythm and meet large-batch production demand.

### 4.3. Development of Human-Machine Interface (HMI)

A special human-machine interface is developed based on industrial configuration software, optimizing the interface layout and improving operation convenience combined with the operation habits of workshop operators. The core functions include:

Visual setting of process parameters such as motion speed, positioning coordinates, detection thresholds and product models, supporting parameter saving and calling.

Real-time monitoring of equipment operation status, axis coordinates, signal waveforms, output counting and defect rate, facilitating operators to grasp production status in a timely manner.

Providing operation guidance and alarm prompts, clarifying operation steps and fault causes, and reducing operators' learning cost.

Supporting authority management to distinguish operator, technician and administrator levels, ensuring parameter security and preventing misoperation.

The interface is simple to operate and responsive, adapting to the workshop site environment, and realizing one-key start, pause, reset and data export on the touch screen.

### 4.4. Collaborative Integration of Software and Hardware Systems

System integration involves the collaborative work among motion controller, data acquisition card, sensor, pneumatic component and upper computer software, which is the key to realize the automatic operation of the system. Specific measures are as follows:

Adopt standard industrial communication protocols to realize high-speed data interaction between the controller and acquisition equipment, ensuring stable and accurate data transmission.

Adopt a modular structure for software development, divided into motion control module, signal processing module, data storage module and alarm module. Each module operates independently and cooperates with each other, facilitating later maintenance and upgrading.

Establish a unified data format to synchronously store motion parameters, detection data and production results into the database, supporting subsequent statistical analysis and process optimization.

### 4.5. Automatic Quality Control in Production Process

The quality control system realizes the data closed-loop of the whole production process and improves the level of quality control:

Automatically collect the detection data of each product, compare with the preset standards, and automatically judge qualified/unqualified products, reducing manual intervention.

Real-time statistics of OEE (Overall Equipment Effectiveness), production capacity, defect types and distribution, facilitating managers to grasp production status.

Generate production reports and quality traceability tables, which can be queried by time, shift and product model to realize traceable production data.

Analyze weak links of the process based on historical data, guide the optimization of process parameters, form a continuous improvement mechanism, and improve product quality from the source.

## 5. Prototype Debugging and Mass Production Engineering Implementation

### 5.1. Prototype Development and Laboratory Debugging

After completing the mechanical assembly, hardware wiring and program writing of the equipment, multiple rounds of debugging are carried out in the laboratory to ensure that all system indicators meet the standards:

Calibration of axis motion accuracy to ensure that positioning accuracy meets design requirements through repeated optimization of control parameters.

Clamping test of tooling fixtures to verify repeat positioning accuracy by clamping magnetic grid products of different specifications for many times.

Debugging of signal acquisition and judgment logic, tested with standard qualified products and defective products to ensure accurate and stable detection results.

Continuous operation reliability test, running continuously for 72 hours to troubleshoot program vulnerabilities and mechanical interference problems and ensure stable system operation.

### 5.2. Trial Production and Optimization on Production Line

After laboratory verification, the prototype is introduced into the actual production line for trial operation, and targeted optimization is carried out for problems such as on-site environmental vibration, temperature and humidity changes and product specification differences:

Add equipment shock absorption structure to improve the anti-interference ability of the system and avoid environmental factors affecting detection accuracy.

Improve the parameter library of multi-specification products to realize rapid model change of different product models and enhance production flexibility.

Optimize alarm logic and prompt information, clarify fault troubleshooting methods and improve on-site maintainability.

Adjust the operation rhythm to balance automatic efficiency and production rhythm, ensuring coordinated operation with the whole production line.

### 5.3. Mass Production Introduction and Operation Effect

The system finally realizes stable mass production introduction with remarkable application effects:

The consistency of magnetic grid assembly accuracy is significantly improved, and the product defect rate is reduced from 12% to below 3%.

Replacing manual detection and assembly processes, the single-station labor is reduced from 3 to 1 person, and production efficiency is increased by more than 60%.

Realize full-process traceability of production data, shifting quality control from post-inspection to process control and improving the level of quality control.

The equipment operates stably with a failure rate lower than 2%, meeting the demand of large-scale production and bringing significant economic and social benefits to enterprises.

## 6. Conclusion and Prospect

Aiming at the pain points of poor assembly accuracy consistency, low manual efficiency and weak quality control in the magnetic grid production process, this paper develops a set of magnetic grid production automation system integrating automatic detection, special motion control, tooling fixtures, human-computer interaction and quality control. Through high-precision motion control algorithms, modular tooling design and software-hardware collaborative integration, the automation of magnetic grid assembly and detection processes is realized, which significantly improves product consistency, production efficiency and digital management level. The system has been successfully implemented in engineering and applied in mass production, providing a feasible technical solution for the intelligent upgrading of the magnetic grid industry and practical references for the application of mechanical and electrical engineering technology in the field of precision manufacturing.

Future research will further introduce machine vision detection, AI quality prediction and production line interconnection technology to promote the upgrading of magnetic grid production to a higher degree of intelligence, networking and flexibility, and continuously provide technical support for cost reduction and efficiency improvement in the precision manufacturing industry. Meanwhile, I will continue to deeply cultivate the fields of mechanical and electrical engineering and automatic control, constantly improve the ability of technology research and development and engineering application, tackle more industry technical pain points, and contribute more practical achievements to the technological progress of the industry.

**Author Contributions:**

All authors have read and agreed to the published version of the manuscript.

**Funding:**

This research received no external funding.

**Institutional Review Board Statement:**

Not applicable.

**Informed Consent Statement:**

Not applicable.

**Data Availability Statement:**

Not applicable.

**Conflict of Interest:**

The authors declare no conflict of interest.

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