

Design and Implementation of a High-Precision Grating Measurement System Based on Optical Signal Processing and Absolute Coding Algorithms

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Abstract

Precision grating sensors are critical components in intelligent manufacturing systems, precision motion control, and high-end automated equipment, where measurement accuracy and signal stability directly affect system positioning performance and operational reliability. However, conventional grating measurement technologies still face challenges related to signal interference, environmental adaptability, coding accuracy, and long-term engineering stability. To address these issues, this paper presents the design and engineering implementation of a high-precision grating measurement system integrating optical sensing, coding signal processing, anti-interference optimization, and absolute coding algorithms. The proposed system establishes a complete technical framework covering grating scribing accuracy control, optical system optimization, coding signal processing, interpolation subdivision algorithms, and full-process accuracy calibration. To improve measurement resolution and environmental robustness, multi-stage digital filtering, automatic gain calibration, electromagnetic compatibility optimization, and temperature compensation strategies are introduced. In addition, a high-resolution absolute coding algorithm based on Gray-code and segmented coding mechanisms is developed to achieve stable absolute position output and power-off position retention. The proposed algorithms and signal-processing methods can be deployed on embedded MCUs and dedicated ASIC platforms for industrial applications. Experimental verification and industrial deployment demonstrate that the developed system achieves high measurement stability, strong anti-interference capability, and reliable long-term operation under harsh industrial conditions. The proposed technology has been successfully applied in CNC machine tools, servo systems, and automated equipment, providing an effective technical solution for domestic substitution and intelligent upgrading of precision displacement measurement systems.

Keywords: Precision Grating Sensor; Optical Signal Processing; Absolute Coding Algorithm; Intelligent Measurement System; Anti-Interference Optimization; Industrial Automation

1. Introduction

With the rapid advancement of intelligent manufacturing, industrial automation, and high-end equipment systems, high-precision displacement and angle measurement technologies have become critical components for improving positioning accuracy, motion stability, and real-time control performance. Precision grating sensors are widely employed in CNC machine tools, industrial robots, servo systems, and automated production equipment due to their advantages of high resolution, fast dynamic response, non-contact measurement capability, and strong environmental adaptability (Wang, 2018; Zhao & Jiang, 2019). As core sensing devices in precision motion-control systems, grating sensors play an essential role in achieving micron- and submicron-level positioning accuracy.

However, conventional grating measurement systems still face several technical challenges in practical industrial applications, including insufficient scribing precision, signal instability under electromagnetic interference, environmental sensitivity, and limited long-term operational reliability. Studies have shown that grating scribing accuracy, structural consistency, and signal stability directly affect the measurement resolution and engineering reliability of precision grating systems (Li & Zhang, 2020). In industrial environments, vibration, oil contamination, temperature fluctuation, and electromagnetic interference can easily lead to signal distortion, counting errors, and long-term measurement drift (Huang & Wu, 2022). In addition, high-performance grating sensors require complex optical structures, high-resolution coding methods, and robust signal-processing algorithms, which significantly increase system design complexity and manufacturing cost.

To address these issues, extensive research has been conducted on grating scribing accuracy control, optical system optimization, coding signal processing, anti-interference techniques, and precision calibration methods. Recent advances in embedded signal processing, digital filtering, optical sensing, and absolute coding algorithms have further improved the measurement resolution, environmental robustness, and engineering stability of grating sensors (Liu & Chen, 2021). In particular, the integration of interpolation subdivision algorithms, automatic gain compensation, and error-correction strategies provides effective solutions for enhancing measurement consistency and long-term reliability in industrial environments. Meanwhile, relevant industrial standards and testing specifications have also promoted the standardization and reliability evaluation of rotary encoder systems in engineering applications (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2012).

In recent years, precision grating technologies have gradually evolved toward higher integration, intelligent signal processing, and large-scale industrial deployment. Process optimization, automatic calibration, and reliability verification technologies have become increasingly important for ensuring batch consistency and long-term operational stability in mass-production environments (Zhang & Li, 2021). Based on practical engineering research and industrial deployment experiences, this paper presents the design and implementation of a high-precision grating measurement system integrating optical sensing, coding signal processing, anti-interference optimization, and absolute coding technologies. The proposed framework

systematically covers key stages including grating structure optimization, optical-path matching, signal acquisition and processing, absolute coding algorithm development, and full-process accuracy calibration. Experimental validation and industrial applications demonstrate that the proposed system achieves stable high-resolution measurement performance under complex industrial conditions, providing a practical technical solution for intelligent manufacturing, precision motion control, and digital measurement systems.

2. Technical Principles and R&D Framework of Precision Grating Measurement

2.1. Basic Principles of Grating Measurement

Grating sensors operate based on the optical interference principle of Moiré fringes and are widely used in precision displacement and angle measurement systems. A typical grating measurement system mainly consists of a light source module, an index grating, a scale grating, a photoelectric receiving unit, and a signal-processing circuit. During operation, relative motion between the index grating and the scale grating causes periodic changes in the transmitted or reflected light intensity, thereby generating Moiré fringe signals with stable spatial periodicity. The optical signals are converted into electrical signals through photoelectric devices and subsequently processed by amplification, filtering, interpolation subdivision, waveform shaping, and digital decoding circuits to obtain high-resolution displacement or angular position information.

The measurement accuracy of a grating sensor is closely related to grating pitch precision, optical-path stability, signal contrast, and interpolation subdivision capability. In practical industrial applications, environmental factors such as temperature fluctuation, vibration, electromagnetic interference, oil contamination, and installation eccentricity can directly affect signal quality and measurement stability. Therefore, modern grating systems not only rely on high-precision optical structures, but also require advanced signal-processing algorithms and anti-interference strategies to ensure reliable long-term operation.

Incremental gratings realize relative displacement measurement through periodic pulse outputs, typically including quadrature signals A and B together with a reference zero signal Z. By detecting the phase relationship between A and B signals, the moving direction and displacement increment can be determined in real time. Incremental grating systems feature fast dynamic response, simple hardware structure, and convenient signal acquisition, making them suitable for high-speed servo control, motion feedback, and real-time positioning systems. However, because the position information is stored incrementally, the system requires homing initialization after power interruption, and accumulated counting errors may occur under severe interference conditions.

Compared with incremental gratings, absolute gratings utilize multi-track coding structures to generate unique position codes corresponding to each measurement location. Common coding methods include Gray-code encoding, pseudo-random coding, and hybrid segmented coding structures. Absolute grating systems can directly output absolute position information without reference-point resetting, thereby improving startup efficiency and operational safety in complex

industrial environments. In addition, absolute coding significantly enhances resistance to signal loss and interference, making it more suitable for applications involving power-off restart, long-distance transmission, and high-reliability motion-control systems.

In recent years, with the rapid development of embedded processing technology and intelligent manufacturing systems, grating measurement systems have gradually evolved from traditional optical sensing devices toward integrated intelligent sensing platforms. Advanced technologies such as digital interpolation subdivision, adaptive gain control, temperature compensation, and real-time error correction have been increasingly introduced into grating signal-processing systems, significantly improving measurement resolution, environmental adaptability, and engineering stability under harsh industrial conditions.

2.2. Overall R&D Framework

To satisfy the practical requirements of high-end manufacturing equipment for high precision, high stability, fast dynamic response, and strong environmental adaptability, a complete research and development framework for precision grating systems is established. The framework follows a full engineering process consisting of principle analysis, structural optimization, algorithm development, prototype verification, industrial testing, and mass-production implementation, aiming to improve both measurement performance and engineering applicability.

At the principle design stage, the optical measurement mechanism and coding strategy of the grating system are analyzed according to application requirements such as displacement resolution, response speed, environmental adaptability, and installation constraints. Different technical routes are evaluated for incremental and absolute grating systems to balance measurement accuracy, hardware complexity, and industrial cost.

In the structural optimization stage, emphasis is placed on grating substrate selection, optical-path matching, thermal stability, and mechanical rigidity. Low-expansion materials and precision machining processes are adopted to reduce deformation caused by temperature variation and installation stress. Meanwhile, the compact integration of optical components is optimized to improve resistance to vibration, eccentricity, and external contamination in industrial environments.

For signal-processing and control design, dedicated algorithms are developed for signal amplification, digital filtering, interpolation subdivision, automatic gain adjustment, and error compensation. Multi-stage filtering and anti-interference strategies are introduced to suppress signal distortion caused by electromagnetic noise and mechanical vibration. In addition, absolute coding algorithms and real-time decoding mechanisms are optimized to improve coding reliability and high-speed data-processing capability.

During the prototype development and verification stage, integrated testing of optical modules, signal-acquisition circuits, embedded processing units, and communication interfaces is carried out. Key performance indicators including signal contrast, interpolation accuracy, thermal drift, repeatability, and dynamic response are evaluated under different environmental conditions. Reliability tests such as vibration testing, temperature cycling, continuous operation, and electromagnetic compatibility verification are also conducted to ensure engineering robustness.

To achieve industrial deployment and large-scale production, the R&D framework further incorporates manufacturing process optimization, automatic calibration systems, and batch consistency control. Standardized assembly procedures and automated testing equipment are introduced to improve production efficiency and reduce human-induced errors. At the same time, engineering adaptation is completed for practical application scenarios including CNC machine tools, industrial robots, automated production lines, and servo motion-control systems, enabling the developed grating products to maintain stable operation under long-term industrial conditions.

The proposed framework establishes an integrated technical route covering optical sensing, embedded signal processing, precision calibration, and industrial deployment, providing practical support for the intelligent development of high-precision measurement systems and advanced manufacturing equipment.

3. Key Technological Breakthroughs and Performance Improvement

3.1. Grating Scribing Accuracy Control Technology

Grating scribing accuracy is the core link determining measurement resolution and basic error. Aiming at the problems of poor scribing uniformity, spacing fluctuation and surface defects in traditional processes, multi-dimensional optimization is carried out:

Substrate optimization: Select low-expansion glass and metal substrates to improve thermal stability and mechanical strength, reducing the impact of temperature deformation and installation stress;

Scribing process upgrading: Adopt high-precision photolithography and ion etching technologies, optimize scribing speed, energy and depth parameters to achieve sub-micron scribing accuracy;

On-line closed-loop detection: Introduce laser interferometers and visual inspection systems to monitor the straightness and uniformity of scribing in real time and dynamically compensate errors;

Surface protection treatment: Improve optical transmittance and scratch resistance through coating to extend service life.

After optimization, the grating scribing accuracy is significantly improved, providing hardware support for stable Moiré fringe generation and high-quality signal output.

3.2. Optical System Matching and Structure Optimization

The optical system is one of the most critical parts of a precision grating measurement system, directly determining signal quality, interpolation stability, and long-term measurement reliability. In practical industrial applications, factors such as installation eccentricity, air-gap variation, vibration, thermal deformation, and stray-light interference can significantly affect optical signal contrast and lead to measurement fluctuation or counting instability. Therefore, the optical structure design not only needs to satisfy theoretical optical requirements, but also needs to maintain stable operation under complex industrial conditions.

To improve the rigidity and environmental adaptability of the system, a compact optical-path structure is adopted during the structural design stage. The relative distance between the light source, grating pair, and photoelectric receiver is reduced as much as possible while ensuring sufficient optical-path integrity. This compact arrangement effectively improves structural stability and reduces signal fluctuation caused by vibration and mechanical resonance during high-speed motion. Meanwhile, finite-element analysis and repeated vibration testing are used to optimize the mechanical support structure, avoiding local deformation and optical-axis deviation during long-term operation.

For the light source module, high-stability LED devices with low thermal drift characteristics are selected. Compared with traditional light-emitting structures, the optimized LED source provides better brightness consistency and longer service life under continuous industrial operation conditions. To improve optical energy utilization and signal uniformity, collimating lenses and focusing structures are introduced into the optical path. The beam divergence angle is carefully controlled to ensure that the generated Moiré fringe signals maintain stable contrast across the entire effective measurement range.

Installation eccentricity and air-gap fluctuation are common engineering problems during equipment assembly and field deployment. Excessive eccentricity may lead to uneven signal amplitude, phase distortion, and local interpolation errors. To improve installation tolerance and reduce assembly difficulty, the optical-path matching structure is optimized through adjustable alignment mechanisms and tolerance-relaxation design. The relative position between the index grating and the scale grating is optimized to maintain stable signal coupling even under slight mechanical deviation conditions. Experimental results show that the optimized structure significantly improves signal stability under vibration and repeated installation conditions.

In industrial environments such as CNC machine tools and automated production lines, oil mist, dust, water vapor, and external stray light can seriously affect optical signal transmission. Therefore, sealing and shading structures are integrated into the optical module design. Multi-layer protective structures and anti-pollution coatings are adopted to improve environmental resistance and reduce optical contamination. At the same time, external light interference is effectively suppressed through directional optical shielding and internal stray-light absorption treatment. After structural optimization, the signal contrast ratio is significantly improved, and signal fluctuation under complex operating conditions is effectively reduced, ensuring stable long-term output in harsh industrial environments.

3.3. Coding Signal Processing and Anti-interference Optimization

In industrial applications, grating signal quality is highly susceptible to external disturbances such as electromagnetic interference, mechanical vibration, temperature fluctuation, grounding noise, and transmission attenuation. These disturbances may cause signal distortion, counting errors, phase jitter, and communication instability, especially under high-speed motion and long-distance transmission conditions. Therefore, signal conditioning and anti-interference optimization are essential for ensuring the reliability of precision grating systems.

To improve weak-signal acquisition capability, a low-noise analog front-end circuit is designed for signal conditioning. Differential signal transmission and high-common-mode-rejection amplifiers are adopted to suppress external electromagnetic interference and improve signal integrity during long-distance transmission. In addition, high-precision operational amplifiers with low offset drift and low temperature sensitivity are selected to ensure stable signal amplification under wide-temperature operating conditions.

For digital signal processing, a multi-stage filtering strategy combining hardware filtering and software filtering is introduced. The hardware stage mainly suppresses high-frequency noise and transient interference through low-pass filtering and signal shaping circuits, while the software stage further removes phase jitter and random noise using digital filtering algorithms. The filtering parameters are dynamically adjusted according to signal frequency and motion speed to maintain both response speed and signal stability during high-speed operation.

To address signal attenuation caused by temperature variation, optical aging, and environmental contamination, an automatic gain calibration mechanism is developed. The system continuously monitors the real-time amplitude and contrast of the grating signal and dynamically adjusts amplification parameters to maintain stable signal output. Compared with fixed-gain systems, the adaptive gain strategy significantly improves long-term measurement consistency and reduces maintenance frequency under industrial operating conditions.

Electromagnetic compatibility optimization is also carried out throughout the hardware design process. Shielded transmission cables, independent grounding structures, isolated power modules, and surge-protection circuits are introduced to improve immunity to industrial electromagnetic disturbances. Particular attention is given to grounding-loop suppression and signal isolation between motion-control units and sensor modules to reduce coupled interference generated by servo drives and high-power switching devices.

During reliability verification, the system is tested under high-vibration and strong-electromagnetic-interference environments. Continuous operation tests demonstrate that the optimized signal-processing system maintains stable pulse output without counting jumps, phase loss, or communication interruption, meeting the operational requirements of high-end industrial equipment and precision motion-control systems.

3.4. Absolute Coding Algorithm Development

Absolute coding technology is one of the key technologies determining the performance of high-precision grating systems. Compared with incremental measurement methods, absolute coding systems can directly output unique position information without reference-point initialization, thereby improving system startup efficiency, operational safety, and resistance to power interruption. The core technical challenges mainly involve coding uniqueness, decoding efficiency, interpolation resolution, and long-term operational reliability.

To improve coding reliability and anti-interference capability, multiple coding strategies are analyzed and optimized during algorithm development. Gray-code structures are adopted as the primary coding method because adjacent positions differ by only one bit, effectively reducing decoding errors caused by transition jitter. Meanwhile, pseudo-random coding and segmented

coding structures are introduced in specific application scenarios to improve fault tolerance and coding redundancy under complex industrial conditions.

To further improve measurement resolution, high-resolution interpolation subdivision algorithms are developed based on periodic grating signals. The original sinusoidal signals generated by the optical system are subdivided through phase interpolation and digital calculation, significantly improving position resolution beyond the physical grating pitch limitation. The interpolation algorithm is optimized to reduce phase nonlinearity and harmonic distortion, thereby improving dynamic positioning accuracy during high-speed motion.

For multi-turn absolute position measurement, a low-power counting mechanism combined with non-volatile storage technology is introduced. Even under power-off conditions, the system can retain the current position information and immediately restore absolute position data after restart without additional homing operations. This function is particularly important for industrial applications requiring uninterrupted positioning continuity and rapid system recovery.

In addition, compensation and fault-tolerance algorithms are introduced to reduce measurement errors caused by installation eccentricity, optical non-uniformity, thermal drift, and vibration disturbance. The system continuously monitors signal amplitude, phase consistency, and decoding status during operation. When abnormal signal conditions are detected, the algorithm automatically performs fault diagnosis and compensation processing to prevent output instability and counting errors.

The developed coding and decoding algorithms can be flexibly deployed on embedded MCUs, FPGA platforms, and dedicated ASIC chips according to different application requirements. The algorithm architecture balances computational efficiency, hardware resource consumption, and real-time response capability, making it suitable for both cost-sensitive industrial products and high-performance precision measurement systems.

3.5. Full-process Accuracy Calibration Technology

To ensure measurement consistency and long-term operational reliability, a full-process calibration and verification system is established throughout the entire product development and manufacturing process. The calibration framework covers R&D verification, prototype testing, batch production calibration, environmental compensation, and reliability evaluation, enabling comprehensive control of measurement accuracy and engineering stability.

During the R&D calibration stage, laser interferometers are used as high-precision reference standards for collecting displacement-error data and generating compensation parameters. Multiple groups of calibration curves are obtained under different operating conditions to analyze systematic errors, interpolation deviation, and thermal drift characteristics. Based on the collected data, compensation tables and correction algorithms are generated to improve overall measurement accuracy.

To improve environmental adaptability, wide-temperature calibration tests are carried out under simulated industrial operating conditions. High- and low-temperature chambers are used to evaluate signal stability, thermal expansion characteristics, and drift behavior across different

temperature ranges. A temperature-error compensation model is then established to dynamically correct measurement deviation during operation, effectively reducing thermal influence on positioning accuracy.

For mass-production implementation, automatic calibration equipment is introduced to improve calibration efficiency and batch consistency. The automatic testing platform integrates motion-control systems, standard reference modules, signal-acquisition units, and database-management software to complete batch accuracy detection, parameter compensation, and data recording automatically. Compared with manual calibration methods, the automated process significantly improves production efficiency while reducing human-induced calibration errors.

In addition to accuracy calibration, comprehensive reliability verification is also conducted to evaluate long-term operational stability. The products undergo vibration testing, mechanical shock testing, thermal cycling, salt-spray testing, continuous-operation aging tests, and electromagnetic compatibility verification according to industrial standards. The test results demonstrate that the developed grating system maintains stable signal output and measurement performance under harsh industrial conditions, meeting the reliability requirements of precision manufacturing equipment and intelligent motion-control systems.

4. Engineering Implementation and Industrial Application

4.1. Prototype Development and Performance Verification

After completing the theoretical design and system architecture analysis, a prototype development platform was established to verify the feasibility of the optical structure, signal-processing scheme, and embedded control framework. The prototype integrated optical modules, signal-conditioning circuits, embedded processing units, communication interfaces, and precision mechanical structures into a unified experimental platform. During the initial debugging stage, signal instability and phase inconsistency were observed under high-speed motion conditions, mainly caused by optical-path deviation and insufficient anti-interference capability in the analog front-end circuit. To address these issues, repeated optimization was carried out on optical alignment accuracy, signal amplification parameters, grounding structures, and filtering algorithms.

Joint debugging of optics, electronics, algorithms, and mechanical structures was then conducted under different operating conditions. Particular attention was given to engineering problems commonly encountered in industrial environments, including signal distortion, zero drift, interpolation fluctuation, communication packet loss, and thermal drift during continuous operation. Through multiple rounds of parameter adjustment and structural optimization, the stability of Moiré fringe signals and the consistency of interpolation outputs were significantly improved. In addition, long-duration continuous-operation testing was performed to evaluate system reliability under vibration, temperature variation, and high-frequency motion conditions.

After several prototype iterations, the overall performance of the system gradually met the expected technical indicators. The optimized prototype demonstrated stable signal output, high

positioning repeatability, and reliable communication performance under practical operating conditions. Environmental adaptability tests further verified that the system maintained stable operation in industrial environments involving oil contamination, vibration, and electromagnetic interference. Based on the verification results, the prototype successfully passed the engineering evaluation stage and entered small-batch trial production for further industrial validation.

4.2. Mass Production Process Optimization

Following prototype verification, the project entered the mass-production optimization stage, focusing on improving manufacturing consistency, production efficiency, and long-term product reliability. Considering the high precision requirements of grating systems, the production process was systematically optimized across SMT mounting, optical assembly, calibration, signal testing, and reliability aging procedures. Automated production equipment and standardized process management were gradually introduced to reduce manual intervention and improve batch consistency during large-scale manufacturing.

To improve production stability and reduce process fluctuation, key manufacturing procedures were automated wherever possible. Automatic dispensing equipment, precision alignment platforms, optical inspection systems, and batch calibration devices were introduced into the production line to improve assembly accuracy and testing efficiency. Compared with manual assembly methods, automated production significantly reduced human-induced positioning errors and improved the consistency of optical alignment and signal output among different product batches. At the same time, automated testing systems enabled rapid collection and storage of calibration data, improving traceability and quality management capability.

In addition to production automation, standardized operating procedures and quality-control specifications were established throughout the manufacturing process. Detailed operating instructions were formulated for critical procedures such as grating installation, optical adjustment, signal calibration, and aging verification to ensure process consistency among different operators and production lines. Furthermore, localization of key components and structural parts was promoted during mass production to reduce manufacturing costs and improve supply chain stability. Through continuous optimization of process management and component integration, the production cycle was shortened while maintaining stable product quality and engineering reliability.

4.3. Industrial Application Results

The developed incremental and absolute grating systems have been successfully deployed in various industrial applications including CNC machine tools, automated production equipment, servo-control systems, and precision motion platforms. Practical operating results demonstrate that the developed products achieve stable high-resolution measurement performance under long-term industrial conditions. In high-speed motion-control scenarios, the grating systems provide reliable displacement feedback with good dynamic response capability, effectively meeting the positioning accuracy requirements of high-end manufacturing equipment.

Environmental adaptability tests and field applications further verify the robustness of the developed products. Under industrial conditions involving vibration, oil contamination, dust, and

electromagnetic interference, the system maintains stable signal output without significant phase fluctuation or counting errors. The optimized sealing structure and anti-interference design effectively improve operational stability in harsh environments. In addition, the absolute grating system demonstrates reliable power-off position retention capability, enabling immediate position recovery after restart and reducing system initialization time in automated equipment applications.

From an engineering application perspective, the developed products provide a practical alternative for high-performance grating measurement systems in industrial environments. Compared with traditional imported products, the proposed system achieves competitive measurement performance while offering advantages in production cost, technical support responsiveness, and engineering adaptability. Feedback from industrial users indicates that the products exhibit good operational stability, low maintenance frequency, and strong compatibility with existing automation systems. The successful deployment of the developed grating systems demonstrates their application value in intelligent manufacturing and precision motion-control industries, providing practical support for the development of high-end industrial measurement technologies.

5. Conclusion and Prospect

Based on years of R&D and engineering practices, this paper systematically carries out research on key technologies of incremental gratings and absolute gratings, breaking through core technologies such as grating scribing accuracy control, optical system matching, coding signal processing, absolute coding algorithm, anti-interference optimization and full-process accuracy calibration, forming a complete R&D system from principle design, prototype development and performance testing to mass production optimization, and successfully realizing product engineering implementation and domestic substitution. The products are stably applied in industrial scenarios such as precision machine tools, automated equipment and servo systems, effectively solving the technical pain points of core precision measurement components and supporting the independent and controllable development of equipment.

In the future, we will continue to upgrade towards higher precision, higher speed, smaller size and higher integration. Combined with technologies such as domestic chip, intelligent algorithm and edge computing, we will further enhance product competitiveness, expand applications in high-end scenarios such as semiconductor equipment, aerospace and medical devices, continuously promote the localization of core precision grating components, and provide more reliable technical support for the development of intelligent manufacturing and high-end equipment.

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