

Design and Development of a Laser-Based Measurement and Control System for Machining of Shaft-Type Components

Bin Hu, Hongchang Sun, Heng Su, Nianyu Xia, Meiling Ma, Zixu Wang,
Yongxiang Jiang

School of Mechanical Engineering, Tianjin University of Technology and Education, Tianjin
300000, China

Abstract

Shaft-type components are critical in mechanical manufacturing. Online inspections using laser measurement technologies allow real-time data acquisition during machining, enhancing quality inspection efficiency. This study focuses on the design of a laser-based measurement system for shaft-type component machining. The research includes the construction of the hardware architecture and an investigation of laser measurement principles. In addition, data processing algorithms are developed, enabling precise processing of measurement data of machining error information.

Keywords

Shaft-type components; laser measurement system; online inspection; least squares method.

1. Introduction

Shaft components are fundamental parts in mechanical manufacturing, widely used in automotive, aerospace, and CNC machine tools, and responsible for torque transmission and support. Their machining accuracy is crucial. Traditional offline inspection requires removing parts for testing, which is time-consuming and prone to errors, making it difficult to meet the demands of high-precision and efficient production. Online inspection technology captures data in real-time, seamlessly integrating machining and inspection while dynamically adjusting parameters to improve quality consistency. Laser inspection technology, with its non-contact, high-precision, and rapid-response features, serves as an ideal solution. This project designs a laser inspection control system for shaft components, achieving high-precision real-time inspection and control through hardware, algorithm, and software development, advancing intelligence, and enhancing manufacturing competitiveness.

In developed countries such as Europe and the United States, laser detection technology has long remained at the forefront. Research institutions and enterprises in the U.S. have developed high-precision online inspection systems for roundness measurement of shaft components based on the laser triangulation principle. These systems are widely used in automotive parts processing production lines, enabling real-time monitoring and compensation control of roundness errors in shaft components through multi-sensor layouts and complex algorithm integration, significantly improving product qualification rates [1]. Germany has achieved notable advancements in laser interferometry for measuring shaft straightness, with its commercialized products playing a pivotal role in precision machine tool manufacturing. By utilizing ultra-high-precision laser interferometry, these systems provide reliable high-accuracy inspection for critical shaft components like machine tool lead screws, ensuring machine motion accuracy reaches internationally leading levels [2]. Domestic research on laser detection technology for online inspection of shaft component machining has also made significant progress. Universities and research institutions have actively conducted related

studies. For instance, Tsinghua University has achieved breakthroughs in laser sensor integration technology, enabling the coordinated operation of multiple laser sensors at shaft component machining sites, thereby enhancing the reliability and comprehensiveness of detection systems [3]. Harbin Institute of Technology has focused on optimizing data processing algorithms, proposing improved filtering and feature extraction algorithms tailored to the characteristics of laser detection data, effectively enhancing detection accuracy and anti-interference capabilities [4]. However, existing technologies still face challenges in practical applications at shaft component machining sites. Issues such as the need to improve the stability of laser detection accuracy under complex processing conditions (high temperatures, high humidity, and strong electromagnetic interference), as well as the limited adaptability of certain inspection systems to shaft components of varying specifications, hinder their ability to meet diverse production demands.

This project focuses on the laser detection and control system for machining spindle parts, specifically including constructing the hardware architecture of the laser detection and control system, conducting in-depth research on the principles of laser detection and measurement, optimizing the measurement optical path and model based on the characteristics of spindle part machining to enhance measurement accuracy and reliability; designing efficient data processing algorithms, with a focus on developing data fitting and error compensation algorithms based on the least squares method to precisely process detection data and obtain accurate machining error information of the parts.

2. Overall Design of the Laser Measurement and Control System for Shaft Components

The hardware configuration of the laser measurement and control system is illustrated in Figure 1. The system consists of a laser emission module, a photoelectric receiving module, a data acquisition module, a main control and computation module, and a machine tool linkage control module. The laser emission module employs a highly stable semiconductor laser to generate a coherent laser beam as the measurement signal. The photoelectric receiving module uses a photodiode array to capture the reflected laser signal and convert it into electrical signals. The data acquisition module utilizes a high-speed acquisition card to sample and digitize the electrical signals. The main control and computation module serves as the core of the system, responsible for real-time analysis of the acquired data, calculation of machining parameters, and generation of control commands. The machine tool linkage control module communicates with the machine tool through a motion control card and executes control commands to achieve coordinated operation between machining and measurement, thereby ensuring machining accuracy.

The cooperative operation principle of the sensors in the measurement system is shown in Figure 2. A laser displacement sensor measures the outer surface of the workpiece along the X-axis direction, providing information on instantaneous radius variations at different angular positions. A high-resolution photoelectric encoder is mounted at the spindle end to acquire spindle rotation angle information, enabling angular positioning of the workpiece circumference. During measurement, the spindle drives the shaft component to rotate continuously, while the photoelectric encoder outputs real-time angular signals. Simultaneously, the laser displacement sensor collects radial displacement data corresponding to each angular position. The data processing module synchronizes and temporally aligns the two signal types, establishing a correspondence between angular position and radial displacement. This enables accurate reconstruction of the workpiece contour along the circumferential direction.

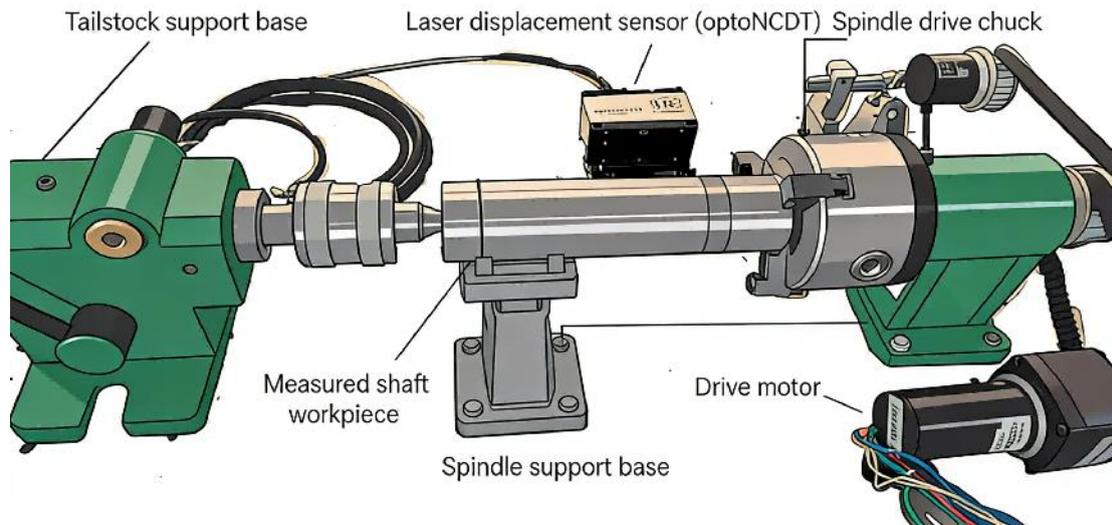


Fig. 1 Hardware layout of the laser measurement system

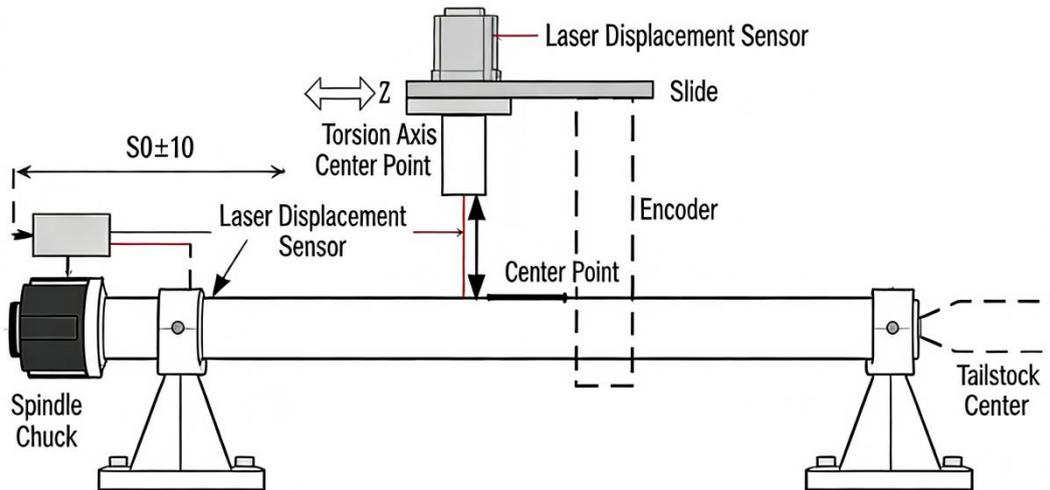


Fig. 2 Cooperative measurement principle of the detection system sensors

3. Laser Measurement Principle for Rolling Machine Tool

The laser measurement system performs high-precision measurement of shaft components based on the laser triangulation principle, as illustrated in Figure 3. The core concept of this method is to utilize the high directionality and monochromaticity of laser beams in combination with reflection laws and geometric triangulation to accurately determine dimensional and geometric parameters of shaft components.

In practical measurement, a semiconductor laser emits a laser beam at a specific inclination angle θ toward the surface of the rotating shaft component. Due to the micro-geometric features of the shaft surface, the laser beam undergoes reflection and scattering, carrying positional information of the measured surface. The reflected light is received by a photoelectric sensor positioned at an angle α relative to the laser emission direction. This sensor is composed of a high-sensitivity photodiode array.

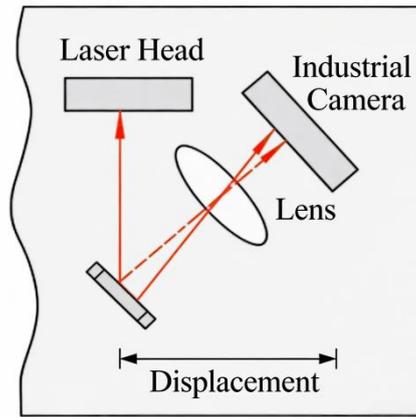


Fig. 3 Principle of laser triangulation measurement

According to geometric optics, when the surface position of the shaft component changes, the image position of the reflected light on the photodiode array shifts accordingly. Let the baseline distance between the laser emitter and the receiver be L , the perpendicular distance from the measured surface point to the baseline be h , and the image displacement on the photodiode array be x . The relationship can be expressed as:

$$h = \frac{L \cdot x}{x \cdot \sin(\theta + \alpha) + L \cdot \sin\alpha} \tag{1}$$

By accurately measuring the image displacement x and using the known structural parameters L , θ , and α , the radius of the shaft component at the measured point can be calculated. As the shaft rotates continuously, measurements are taken at multiple angular positions, forming a set of radius data that enables calculation of shape parameters such as roundness and cylindricity.

4. Data Processing Algorithms for Laser Measurement

During laser measurement of shaft components, the acquired raw data inevitably contain errors and noise caused by environmental disturbances, laser speckle effects, and surface roughness. Therefore, efficient data processing algorithms are required to enhance data accuracy and reliability. The least squares method, a classical data fitting and error processing technique, plays a crucial role in this system.

The principle of least squares curve fitting is illustrated in Figure 4. The fundamental idea of the least squares method is to determine the best-fitting function by minimizing the sum of squared errors. In shaft roundness measurement, assume that the measured discrete contour points are (x_i, y_i) , where $i = 1, 2, \dots, n$. The goal is to find an ideal circular equation $(x - a)^2 + (y - b)^2 = r^2$ such that the sum of squared distances from all measured points to the circle is minimized. The error function

$E(a, b, r)$ is defined as:

$$E(a, b, r) = \sum_{i=1}^n [(x_i - a)^2 + (y_i - b)^2 - r^2]^2 \tag{2}$$

By taking partial derivatives of $E(a, b, r)$ with respect to a , b , and r , and setting them to zero, a system of nonlinear equations is obtained. Solving this system yields the optimal circle center coordinates (a, b) and radius r . In practice, iterative numerical methods such as the Gauss–Newton algorithm can be employed to obtain the solution.

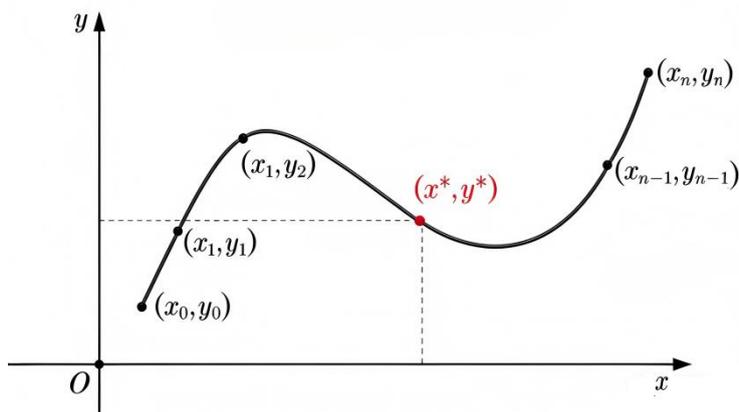


Fig. 4 Principle of least squares curve fitting

For cylindricity measurement, the shaft is divided into multiple axial cross-sections, and least squares circle fitting is applied to each section. The cylindricity error is then evaluated based on the distribution of fitted circle centers and radius variations along the axial direction. This least squares-based data processing approach effectively suppresses noise and measurement errors, significantly improving the accuracy of dimensional and geometric measurements and providing reliable data for subsequent error compensation and control.

5. Experimental Verification and Analysis

By monitoring the outer contour of the workpiece, the measured data were preprocessed and analyzed using least squares fitting. Figure 5 presents the least squares fitting results of the shaft outer contour, which show high consistency with the actual measurement data, demonstrating the effectiveness of the proposed data processing method.

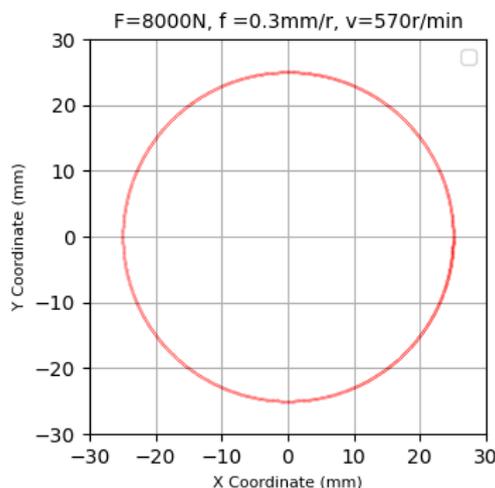


Fig.5 Least squares fitting result

6. Conclusion

This study presents the design and development of a laser-based measurement and control system for shaft-type component machining. The proposed system effectively addresses the limitations of traditional inspection methods and provides a high-performance, intelligent solution for online measurement and control. At the hardware level, an integrated system architecture comprising laser emission, photoelectric reception, data acquisition, main control computation, and machine tool linkage control modules was constructed, enabling efficient coordination among system components. At the measurement principle level, high-precision measurement of shaft parameters such as radius and roundness was achieved based on the

laser triangulation method, considering the rotational characteristics of shaft machining. At the data processing level, least squares fitting and error compensation algorithms were applied to enhance measurement accuracy.

Overall, the developed system realizes real-time online inspection and coordinated control during shaft machining, providing strong technical support for high-precision manufacturing of shaft-type components.

Acknowledgements

Undergraduate Innovation and Entrepreneurship Project

Project Title: Design and Development of Intelligent Rolling Machine Tool Based on Laser Detection

Project Number: 202510066120

Tianjin Science and Technology Program — Cooperation Project between Tianjin and the Chinese Academy of Sciences (CAS)

Project Title: Development of Posture Variation Mechanism and Precision Intelligent Control Technology for Ultra-Minimally Invasive Robotic Puncture Components

Project Number: 25YFYSHZ00250

Tianjin Science and Technology Program — Cooperation Project between Tianjin and the Chinese Academy of Sciences (CAS)

Project Title: R&D of an Embodied Intelligent Mobile Robot Machining and Inspection System for Large-Scale Complex Components

Project Number: 24YFYSHZ00180

References

- [1] Jurko J, Miškiv-Pavlík M, Hladký V, et al. Measurement of the Machined surface diameter by a laser triangulation sensor and optimization of turning conditions based on the diameter deviation and tool wear by GRA and ANOVA[J]. *Applied Sciences*, 2022, 12(10): 5266.
- [2] Budzyn G, Rzepka J, Kaluza P. Laser interferometer based instrument for 3D dynamic measurements of CNC machines geometry[J]. *Optics and Lasers in Engineering*, 2021, 142: 106594.
- [3] Ding D, Ding W, Huang R, et al. Research progress of laser triangulation on-machine measurement technology for complex surface: A review[J]. *Measurement*, 2023, 216: 113001.
- [4] Zheng Y, Dong X, Liang Z, et al. Research on the Preprocessing Method of Laser Ranging Data with Complex Patterns Based on a Novel Spline Function[J]. *Remote Sensing*, 2025, 17(6): 1043.