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Research and Application of Intelligent Sensing Technology in Three-Sided CNC Punching System for Automotive U-Shaped Longitudinal Beams

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Abstract

In this study, an intelligent sensing system of CNC three-side punching equipment for automotive U-shaped longitudinal beams based on multi-sensor fusion is developed. Kalman filtering, Dempster-Shafer (D-S) evidence theory, and convolutional neural networks (CNNs) are adopted for multi-source data fusion and processing. In addition, Geometric and thermal error models are established based on Chebyshev polynomials and thermoelastic equations, and online error compensation is realized through embedded algorithms in the computer numerical control (CNC) system. This intelligent sensing technology effectively enhances the intelligence level, operational reliability, and machining quality of the system, provides a feasible technical solution for the intelligent upgrading of processing equipment for automotive U-shaped longitudinal beams, and promotes the development of intelligent manufacturing in the automotive industry. The experimental results demonstrate that the developed equipment achieves punching accuracy within ±0.05mm, and reduces the hole spacing error to ±0.03mm.

Keywords

Computer Numerical Control (CNC); Intelligent Sensing Technology; Punching System; U-Shaped Longitudinal Beam.

1. Introduction

With the rapid development of the modern automotive industry, vehicle production has grown steadily. In the CNC three-sided punching system for automotive U-shaped longitudinal beams, the CNC system acts as the core and "intelligent brain" of the equipment. However, various machining errors lead to spatial deviations of the tool tip and deterioration of machining accuracy. In addition, most existing machining parameters are preset relying on engineers' experience and operation manuals, resulting in low processing efficiency. Based on the widely applied Beckhoff CNC system, we adopt intelligent sensing technology to investigate the intelligent upgrading of CNC three-side punching equipment for automotive U-shaped longitudinal beams. Self-perception and self-decision functional modules are integrated to realize intelligent upgrading of the punching system, so as to improve processing accuracy and efficiency. The self-perception module collects equipment error data and performs error compensation to realize precision self-repair, while the self-decision module supports adaptive parameter adjustment to enhance production efficiency and reduce processing costs.

In [1] we used digital twin (DT) technology to accurately simulate the punching process within virtual space, optimize processing parameters and avoid manufacturing defects. Intelligent sensing

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technology supports real-time monitoring of equipment operation and machining conditions as well as automatic parameter calibration. The synergy of these two technologies significantly improves punching efficiency, shortens production cycles, achieves precise quality control, and reduces defect rates. Furthermore, this synergistic framework enables predictive maintenance, reduces operational costs, improves the adaptability to multi-variety production requirements, advances the intelligent renovation of high-end automotive manufacturing equipment, and accelerates the industrial digital transformation of the automotive intelligent manufacturing industry.

In the 1960s the world's first adaptive control system for CNC machine tools with intelligent sensing came out. However, the system requires online measurement of tool wear, and the lack of a widely accepted and practical method for tool wear measurement prevents its widespread application. Huazhong 9, launched in 2021, is the world's first intelligent CNC system equipped with AI chips, possessing four core intelligent capabilities: autonomous perception, autonomous learning, autonomous decision-making, and autonomous execution. Recently, Li et al. develop a novel dynamic data-driven degradation method for monitoring the remaining useful life (RUL) of cutting tools. A rolling HI-RUL mapping is established by employing a historical health indicator curve, which estimates the RUL of cutting tool with a given threshold [2]. Zhou et al. propose a multi-sensor multi-domain feature fusion transformer model that achieves precise tool wear prediction through innovative feature engineering and cross-modal self-attention mechanisms[3].

Nevertheless, most existing research outcomes suffer from limitations in their technical architectures, as they generally adopt a single-core framework for perception, decision-making and control, resulting in fixed information processing workflows when facing complex and variable working conditions. Such architectures fail to rapidly integrate multi-dimensional sensing data to generate comprehensive and accurate control decisions, leading to insufficient response speed for high-speed machining. Moreover, the absence of dynamic parameter adjustment mechanisms causes system overshoot and oscillation due to parameter mismatch during control execution, which seriously degrades machining stability and product quality.

Targeting the above problems, this work investigates an intelligent sensing module with self-perception and self-decision capabilities. The module supports adaptive parameter updating, which can adjust model parameters during operation to ensure real-time consistency between model parameters and physical entity states. The proposed module effectively improves the intelligence level of three-sided CNC punching equipment for automotive U-shaped longitudinal beams, ensures safe and stable operation of CNC equipment, and further enhances machining accuracy and efficiency.

This paper is organized as follows. Section 2 presents the research on relevant technologies, including the development of multi-sensors and mechanical installation methods research(Section 2.1), the design, construction and optimization of the intelligent sensing system (Section 2.2), the thermal-error modeling and compensation for motorized spindles (Section 2.3). Finally, conclusions are drawn in Section 3.

2. Intelligent Sensing Technology Research for CNC Punching System of Automotive U-Shaped Longitudinal Beams

2.1 Research on Multi-Sensor Development and Mechanical Installation Methods

This system consists of high-precision pressure, displacement, and temperature sensors with optimized measuring ranges, accuracy grades, and response frequencies. These sensors are rationally arranged at key positions to realize continuous online real-time monitoring of equipment operating status and dynamic tracking of critical indicators during machining. For instance, pressure sensors are installed near the punch to monitor variations in punching pressure; displacement sensors are placed at die interfaces to detect position offset and positioning errors; temperature sensors are deployed at heat-concentrated positions to monitor the temperature rise of motorized spindles and prevent overheating. To eliminate measurement errors caused by external vibration and mechanical interference, dedicated mechanical installation schemes are designed for different types of sensors to

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ensure firm fixation and stable measurement. For example, displacement sensors are fixed by rigid brackets; temperature sensors adopt optimized contact installation modes based on the thermal conduction characteristics between sensors and measured components.

Combined with the structural features of three-side punching equipment for automotive U-shaped longitudinal beams, finite element analysis (FEA) software, ANSYS, is adopted to identify key monitoring positions such as punches, dies, motorized spindles and feed mechanisms. Modular sensor mounting brackets are designed. Mechanical simulation analysis is carried out for sensor installation positions to evaluate stress distribution characteristics, avoid installation-induced measurement errors, guarantee mounting rigidity and eliminate mechanical interference. A multi-channel parallel acquisition system is developed on the FPGA platform with sampling frequency ≥10kHz and time-synchronization error ≤1μs. In addition, electromagnetically shielded cables are used to mitigate electromagnetic interference from the CNC system.

Data from different sensors differ in physical meaning and dimension. Hence, an effective data-fusion strategy is required to synthesize such information, extract useful features and improve overall system accuracy. The Kalman filter is employed to displacement data for noise elimination. The D-S evidence theory is used to pressure and temperature data for equipment abnormal conditions identification. High-speed data transmission technologies are further investigated. By comparing different data transmission protocols in terms of transmission rate and anti-interference performance, a Gigabit-Ethernet communication protocol is developed to meet industrial practical requirements. Time-sensitive networking enables real-time data transmission with a latency of less than 1ms, satisfying the millisecond-level monitoring demand of high-speed punching processes. Time-domain fusion methods including weighted-average method and Kalman filtering are utilized to process redundant data from sensors of the same type to enhance data accuracy. Feature-level fusion algorithms such as principal component analysis and wavelet transform are used to extract effective feature information. Deep-learning-based data fusion models are constructed using algorithms such as CNNs and long short-term memory networks, and trained with massive experimental datasets to realize adaptive fusion of multi-source heterogeneous data. Furthermore, lossless and lossy data compression algorithms are implemented to reduce data transmission load, and network topology and communication parameters are optimized to minimize transmission latency, and achieve high-speed, stable and timely data transmission.

2.2 Design, Construction and Optimization of the Intelligent Sensing System

This study constructs a distributed system with an "edge computing+cloud storage" architecture. The edge end (industrial personal computer) processes sensor data in real time, while the cloud stores historical data and trains error models. A human-machine interface is developed based on LabVIEW to visualize punching-pressure curves, displacement deviations, and temperature fields. Trigger alarms when thresholds are exceeded. Spatial positioning errors of the equipment are measured by a tracker. Combined with multi-sensor monitoring data, the least square method is adopted to identify 21 key geometric errors including straightness error and roll angle error. Based on kinematic and dynamic analysis, key force-bearing positions, deformation-prone regions and temperature-sensitive points are determined as optimal sensor deployment positions. Particle swarm optimization and genetic algorithm are applied to optimize the sensor layout, which reduces the number of sensors and system cost while achieving full-coverage monitoring of equipment status. The hardware platform of the intelligent sensing system is built, with connection and integration for sensors, data acquisition cards, transmission networks, and data processing servers. System software is developed to implement real-time data acquisition, processing, storage and visualization. System joint debugging and testing are also conducted to verify the stability of communication between functional modules and the accuracy of data acquisition and processing, so as to guarantee reliable operation of the intelligent sensing system. Furthermore, Chebyshev polynomials are used to fit the errors. By adjusting the polynomial order and coefficients, the Runge phenomenon is effectively suppressed, and the error fitting accuracy is significantly improved.

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2.3 Thermal error Modeling and Compensation for Motorized Spindles

We propose a thermal error modeling method for motorized spindle, combining thermoelastic theory and intelligent sensing technology. Specifically, temperature sensors are arranged on the bearing and shell of the motorized spindle, and capacitive displacement sensors are deployed in radial and axial directions. Monitoring experiments are carried out for 4 hours at a rated spindle speed of 12000rpm, with a 10s sampling interval, to collect real-time temperature field distribution data and axial thermal elongation data. Radial and axial thermal deformations are calculated according to thermoelastic mechanics. The radial thermal expansion of the spindle is derived from thermoelastic equations, while multivariate linear regression method is adopted for axial thermal error modeling. On this basis, a linear model for axial thermal error is constructed, and corresponding thermal error compensation strategies are formulated, such as applying preload or adjusting cooling conditions to counteract adverse effects induced by thermal deformation. A thermal error-temperature mapping table is pre-stored in the CNC system. Real-time temperature monitoring data are used to dynamically adjust the Z-axis feed and zero offset of the spindle via PLC (S7-1500). A laser interferometer calibrates sensor measurement errors to ensure system accuracy≤±5μm. The Fanuc FOCAS API is used to revise G-codes online, and compensation values are written into #5000-series variables. Coordinate measuring machine detection results show that the hole spacing error of the equipment is reduced from ±0.1mm to ±0.03mm.

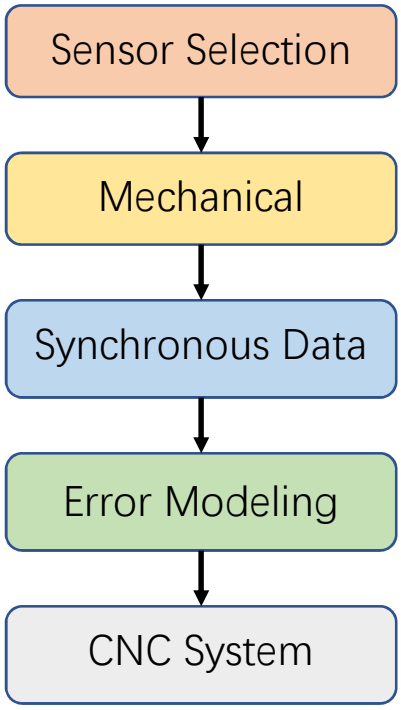


Figure 1. Schematic diagram of the thermal and geometric error compensation strategy

3. Conclusion

High-precision error detection and active compensation are essential to guarantee the machining accuracy and operational reliability of punching equipment. Therefore, it is important to develop a multi-sensor system for error detection of automobile longitudinal beam equipment. Aiming at the high-precision error detection and compensation requirements of three-sided CNC punching system for automotive U-shaped longitudinal beams, this work develops an intelligent sensing system based on multi-sensor fusion. FEA and experimental tests are performed to investigate the influences of sensor installation angles and fixing modes on measurement accuracy, and standardized sensor installation specifications are formulated to ensure the consistency and reliability of multi-sensor monitoring. Based on multi-sensor monitoring results, the least squares method and iterative

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optimization algorithms are adopted to identify key geometric errors. Chebyshev polynomials are applied to fit these errors. Compared with traditional polynomial fitting methods, Chebyshev polynomials can better suppress the Runge phenomenon, so that a high-precision spatial model of geometric errors can be established. Based on this model, specific geometric error compensation strategies are designed. The machining trajectory is corrected via the CNC system to realize geometric error compensation. The thermal deformation mechanism of motorized spindle under different working conditions is analyzed based on thermoelastic theory, and the key factors affecting thermal errors are determined. Multi-sensors are used to monitor real-time parameters such as temperature field distribution and displacement variation, so as to establish high-precision radial and axial thermal error models of the motorized spindle. In addition, a multivariate linear regression model is established for axial thermal error prediction, and corresponding thermal error compensation strategies are proposed. Experimental verification results demonstrate that the developed intelligent punching equipment maintains a punching accuracy within ±0.05mm and reduces the hole spacing error to ±0.03mm, which significantly improves the overall machining precision and stability of the equipment.

Acknowledgments

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