RESEARCH ARTICLE

Design and Performance Evaluation of Flexible CNC Machining Equipment for Panel Furniture Manufacturing

Lizhen Li[1,*] **and Hongying Jin**[1]

[1] Jinhua Institute of Electromechanical Product Simulation Technology, Jinhua, China

Abstract

A flexible CNC machining system is developed for panel furniture manufacturing to improve equipment adaptability and reduce non-machining time in customized production. The proposed system integrates a modular machining structure, multi-axis motion platform, automatic positioning fixtures, and a digital control system to enable flexible drilling and grooving operations. A machining path optimization strategy is introduced to reduce unnecessary tool movements. Experiments on medium-density fiberboard (MDF) panels demonstrate that the optimized method reduces machining time from 986 s to 654 s for 20 machining tasks and from 1248 s to 812 s for 25 tasks. The proposed equipment achieves a positioning error of 0.04–0.06 mm in repeated tests, showing improved machining stability compared with conventional equipment. The results verify the effectiveness of the proposed approach for small-batch and multi-variety panel furniture manufacturing.

Keywords: Panel furniture, flexible CNC machining, modular design, path optimization, positioning accuracy, smart manufacturing.

Submitted: 20 June 2026
Revised: 20 August 2026
Accepted: 03 September 2026
Published: 09 September 2026

Vol. 1, **No.** 3, 2026.
10.62762/TICPS.2026.403794

***Corresponding author:**
Lizhen Li
lizhenli2026@126.com

1 Introduction

With the increasing diversification of consumer demands and the transformation of manufacturing modes, panel furniture production has gradually shifted from large-scale standardized manufacturing toward small-batch and multi-variety flexible production. Therefore, machining equipment is required to achieve not only high accuracy and efficiency but also rapid adaptability to different product specifications and processing tasks. Manufacturing flexibility has become a key factor in advanced manufacturing systems. De Toni and Tonchia [1] analyzed manufacturing flexibility and demonstrated its importance in improving the responsiveness of enterprises to market changes and product diversity requirements.

Flexible manufacturing systems (FMS) provide an effective solution for multi-variety production through computer control, automated coordination, and flexible processing units. Koren [2] highlighted that reconfigurable manufacturing resources can significantly improve system adaptability to different product types. Mehrabi et al. [3] further proposed reconfigurable manufacturing systems and emphasized the importance of structural

Citation
Li, L., & Jin, H. (2026). Design and Performance Evaluation of Flexible CNC Machining Equipment for Panel Furniture Manufacturing. *ICCK Transactions on Intelligent Cyber-Physical Systems*, 1(3), 86–92.

adjustment and functional reconfiguration for future manufacturing equipment. Tolio [4] indicated that flexible equipment design should consider the interaction between equipment structure, production requirements, and operational efficiency.

Recently, advances in the industrial internet, intelligent control, and data-driven technologies have accelerated the development of intelligent computer numerical control (CNC) machining systems. Kusiak [5] pointed out that smart manufacturing enables autonomous optimization through digital sensing, data analysis, and intelligent decision-making. Lu et al. [6] further emphasized that intelligent manufacturing equipment should integrate automation, information interaction, and intelligent control to improve real-time responsiveness. Mourtzis et al. [7] demonstrated that the integration of real-time data acquisition and digital monitoring technologies in manufacturing environments enhances equipment operational visibility and supports process coordination.

In panel furniture manufacturing, CNC cutting machines, drilling machines, and processing centers have improved automation, but most are designed for fixed products or processes [8]. Changes in panel dimensions or machining requirements often require fixture and parameter adjustments, reducing production flexibility. In addition, drilling and grooving usually involve multiple discrete positions, where excessive tool movements increase non-machining time.

Modular design and path optimization provide effective solutions. Bi et al. [9] showed that modular manufacturing systems can improve equipment reconfiguration capability, while Chryssolouris emphasized the integration of automation, computer control, and flexible production strategies [10]. Xu [11] demonstrated that automated tool-path generation can reduce manual intervention. Recent studies have demonstrated that CNC tool-path optimization can effectively eliminate redundant tool movements and reduce machining time while maintaining machining accuracy [12].

However, existing studies still mainly focus on individual functions rather than integrated flexible equipment design and performance optimization. Reconfigurable manufacturing systems provide an effective approach for responding to dynamic market demands by enabling rapid adjustments in production capacity and functionality while supporting high product variety and flexible batch production [13]. Simulation-based methods and digital tools have been widely adopted to support the design and validation of adaptive manufacturing systems [14], while intelligent control strategies and collaborative communication technologies between machining units and control systems further enhance integration and real-time responsiveness [15].

Based on these considerations, this paper proposes a flexible CNC machining system integrating modular machining units, multi-axis motion control, automatic positioning, and machining path optimization. Experimental tests are conducted to evaluate machining efficiency, positioning accuracy, and operational stability.

2 Design of Flexible CNC Machining Equipment

2.1 Design Requirements of the Equipment

To address the issues of frequent product variations, complex processing operations, and insufficient equipment adaptability in panel furniture manufacturing, a flexible CNC machining system is designed in this study. The primary objective of the proposed system is to improve the adaptability of machining equipment to different panel sizes and processing tasks while maintaining high machining accuracy. The proposed equipment enables rapid adjustment and multi-process coordination during customized panel furniture production.

Conventional panel furniture processing equipment is generally designed for specific product structures and fixed machining processes. When product dimensions, hole patterns, or manufacturing requirements change, operators often need to manually adjust fixtures, modify machining parameters, or replace processing modules, resulting in increased preparation time and reduced production flexibility. Therefore, a modular design concept is adopted in this study, where the machining system is divided into a motion control module, a workpiece positioning module, a machining execution module, and an intelligent control module. Standardized interfaces are employed among different functional units to improve equipment reconfiguration capability.

The proposed flexible CNC machining equipment is designed to satisfy the following requirements:

(1) *Multi-task machining capability.* The equipment can perform typical panel furniture operations, including drilling and grooving, by replacing

different machining modules according to specific processing requirements.

(2) *Rapid reconfiguration capability.* For panels with different dimensions and structures, machining programs and positioning parameters can be quickly adjusted without complex mechanical modifications, reducing production preparation time.

(3) *High-precision motion control.* A multi-axis servo motion system is employed to achieve accurate positioning of machining tools and ensure the quality of complex hole and groove processing.

(4) *Digital control capability.* A CNC-based control system is developed to integrate task input, path planning, motion control, and real-time feedback, improving the automation level of the equipment.

2.2 Structural Design of the Flexible Machining Equipment

The overall structure of the proposed flexible CNC machining equipment is illustrated in Figure 1. The system mainly consists of a CNC control system, a multi-axis motion platform, an automatic positioning fixture, and a modular machining unit.

The CNC control system serves as the core unit for program interpretation, motion control, and coordination of functional modules. By integrating an industrial computer and a motion controller, machining tasks are converted into executable commands for automated processing. The multi-axis platform adopts X-, Y-, and Z-axis motion mechanisms. The X/Y axes enable planar tool positioning, while the Z-axis controls machining depth. Servo motors are employed to improve response speed and positioning accuracy.

An adjustable positioning fixture is developed to accommodate panels with different dimensions and ensure stable fixation during machining. The modular machining unit allows rapid replacement of tools for drilling and grooving operations, enabling multi-process integration within a single platform. Through the integration of modular structures, multi-axis control, and flexible machining modules, the proposed equipment improves adaptability for multi-variety panel furniture manufacturing.

2.3 Design of the CNC Control System

A digital control architecture is developed to enable intelligent operation of the flexible machining equipment, consisting of task input, machining planning, motion control, and feedback modules. The system generates machining programs based on panel dimensions, machining positions, and process parameters, and automatically configures the corresponding manufacturing process. During machining, the path planning module optimizes tool movement sequences to reduce unnecessary motions, while the motion control module drives the servo system to execute accurate trajectories. Position sensors provide real-time feedback for closed-loop control and error compensation, improving machining stability.

This digital-driven control strategy transforms traditional manual adjustment-based operation into automated task-oriented manufacturing, enhancing equipment flexibility and automation capability. The integration of real-time sensor feedback, closed-loop motion control, and digital task management constitutes a cyber-physical coupling mechanism that aligns with the core principles of intelligent cyber-physical manufacturing systems. To verify the feasibility of the proposed equipment design, the main technical specifications of the proposed flexible CNC machining equipment are described as follows.

The equipment provides a maximum machining area of 1200 mm × 600 mm and adopts a three-axis motion structure with $X/Y/Z$-axis travels of 1200/600/150 mm, respectively. The machining system is equipped with a 1.5 kW spindle with a maximum rotational speed of 18 000 r/min, and the maximum moving speed reaches 15 m/min. The positioning accuracy is maintained within ±0.05 mm through CNC- and PLC-based control, where PLC denotes a programmable logic controller. The equipment supports typical panel furniture manufacturing operations, including drilling and grooving, enabling flexible processing for multi-variety panel products. The proposed equipment provides a relatively large machining range and high positioning accuracy, which can satisfy typical panel furniture manufacturing requirements. Furthermore, the combination of modular structural design and digital control improves the adaptability of the equipment under small-batch and multi-variety production conditions.

In summary, the proposed flexible CNC machining equipment integrates modular mechanical structures, digital motion control, and intelligent processing strategies, enabling the transition of panel furniture machining equipment from fixed-function systems

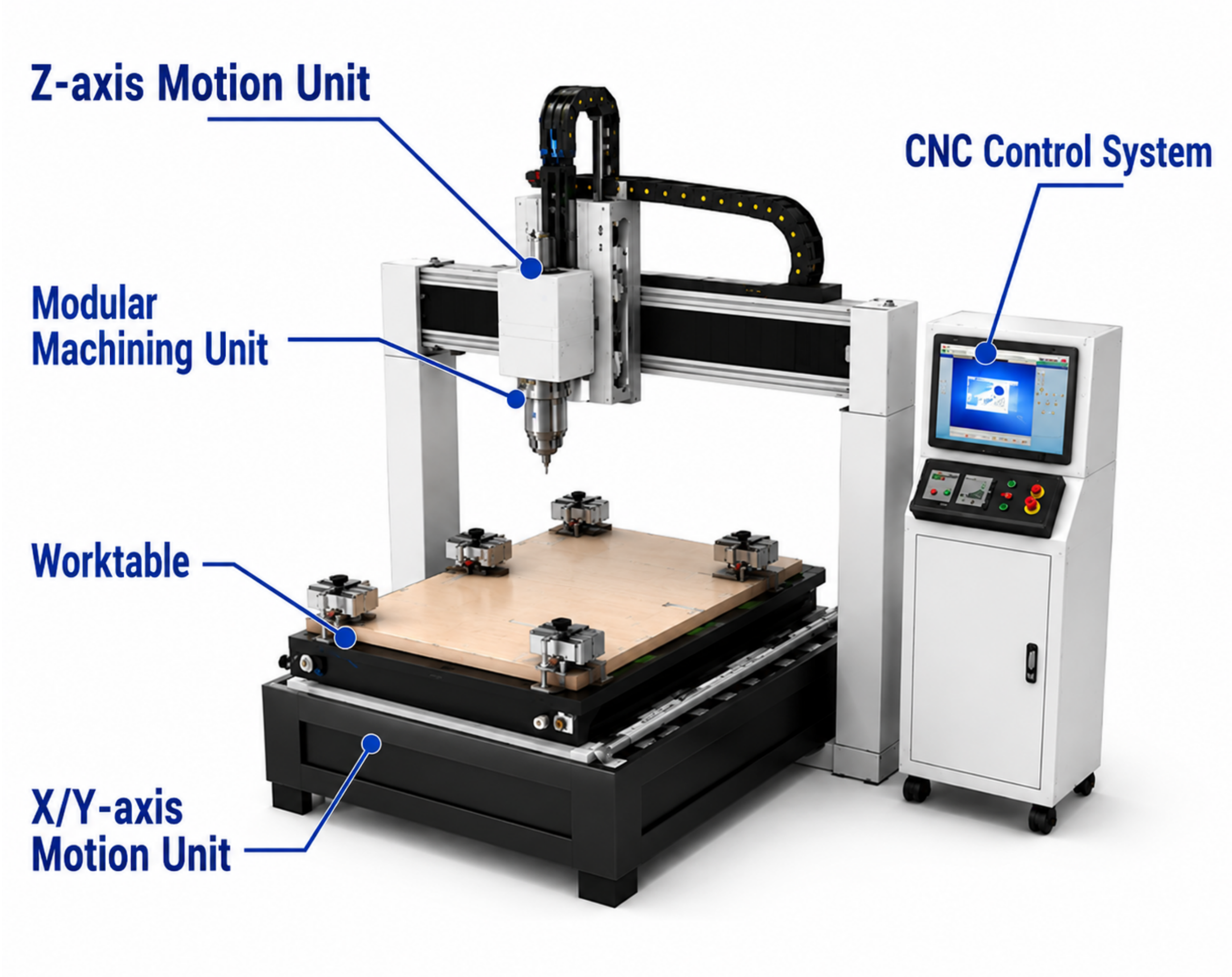

Figure 1. Structural diagram of the flexible CNC machining equipment.

toward flexible manufacturing units. This design provides the foundation for subsequent machining path optimization and experimental performance evaluation.

3 Experimental Results and Performance Evaluation

3.1 Experimental Setup and Evaluation Criteria

To verify the practical performance of the proposed flexible CNC machining equipment in panel furniture manufacturing, machining experiments were conducted using the developed system. Medium-density fiberboard (MDF) with a thickness of 18 mm was selected as the experimental material, which is widely used in panel furniture production due to its stable machining characteristics and dimensional consistency.

The proposed flexible CNC machining equipment was employed to perform typical panel processing tasks, including multi-position drilling and local grooving operations. During the experiments, machining parameters such as spindle speed, feed rate, and machining depth were maintained constant. The performance differences between the conventional machining strategy and the optimized machining strategy were investigated by adjusting the machining path planning method.

To comprehensively evaluate the performance of the proposed equipment, machining efficiency, tool movement distance, and positioning accuracy were selected as the main evaluation indicators. Machining efficiency was used to evaluate the time required to complete machining tasks; tool movement distance was used to characterize unnecessary non-machining motions; and positioning accuracy was used to assess the stability of repeated machining operations. The machining experiments were conducted using an MDF panel with a size of 600 mm $\times$ 400 mm. The proposed equipment was evaluated under typical panel furniture processing operations, including drilling and grooving. The number of machining tasks was varied from 5 to 25 to investigate the influence of task complexity on machining performance. During the experiments, the spindle speed and feed rate were maintained at 12 000 r/min and 10 m/min, respectively. Each experiment was repeated 10 times, and the average value was used for performance evaluation.

3.2 Effect of Machining Path Optimization on Processing Efficiency

During panel furniture machining, multiple discrete processing locations often lead to excessive tool movements and increased non-machining time. Studies on CNC routing optimization for wooden furniture parts have confirmed that sequencing machining operations effectively reduces total processing time [16]. To address this issue, the proposed method optimizes the machining sequence according to the spatial distribution of processing positions. Experiments were conducted using conventional and optimized paths under different numbers of machining tasks.

As shown in Figure 2, the machining time increased with the increase in task number for both strategies. However, the optimized path consistently achieved shorter machining time than the conventional path. For 20 machining tasks, the machining time was reduced from 986 s to 654 s, representing a reduction of 33.7%. When the number of tasks increased to 25, the machining time decreased from 1248 s to 812 s, corresponding to a reduction of 34.9%. These results demonstrate that the proposed path optimization strategy effectively reduces unnecessary tool movements and improves machining efficiency, especially under complex multi-position processing conditions.

The relationship between the number of machining tasks and machining time is presented in Figure 2. The optimized path curve exhibits a lower growth rate compared with the conventional path, demonstrating the advantage of the proposed flexible machining strategy in complex production environments.

3.3 Positioning Accuracy Test of the Equipment

In addition to machining efficiency, positioning accuracy is a critical indicator for evaluating CNC machining performance. In panel furniture manufacturing, positioning accuracy directly affects assembly quality. Therefore, repeat positioning tests were conducted to evaluate the stability of the motion system. A fixed machining position was selected, and the equipment was repeatedly positioned 20 times.

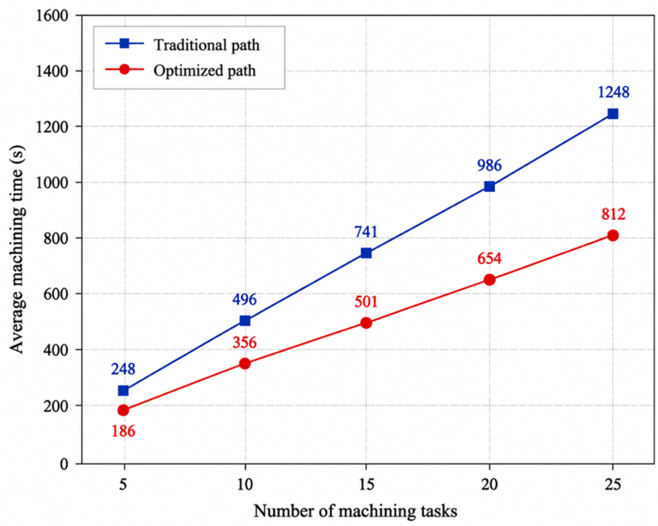

Figure 2. Comparison of machining time under different numbers of machining tasks.

The results were compared with those of conventional machining equipment.

The positioning errors of the conventional equipment ranged from 0.11 mm to 0.14 mm, with an average error of 0.124 mm. In contrast, the proposed flexible CNC equipment maintained an error range of 0.04–0.06 mm, with an average error of 0.050 mm. The positioning error was reduced by approximately 59.7% compared with conventional equipment. These results demonstrate that the integration of multi-axis servo control and adjustable positioning mechanisms improves repeat positioning accuracy and machining stability.

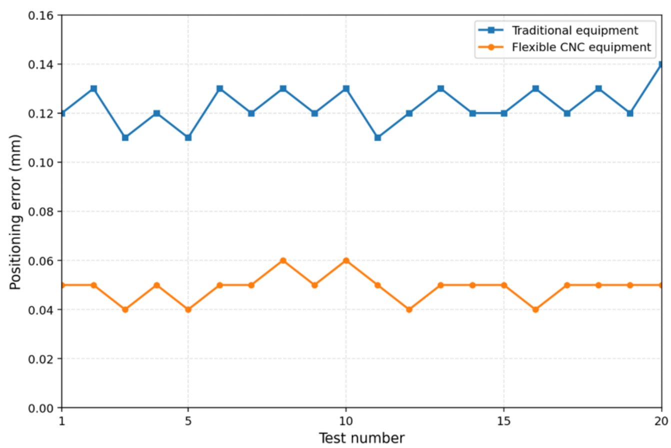

Figure 3. Repeat positioning error of conventional and flexible CNC machining equipment.

The variation trend of positioning errors is shown in Figure 3. The flexible CNC equipment maintains a consistently lower error level throughout the testing process, demonstrating better repeatability and machining reliability.

3.4 Comprehensive Performance Analysis

The experimental results demonstrate that the proposed flexible CNC machining equipment effectively improves machining efficiency and positioning stability compared with conventional machining approaches.

Regarding machining efficiency, the optimized machining path reduces unnecessary tool movements and decreases the machining time from 986 s to 654 s under 20 machining tasks, achieving an improvement of 33.7%. Regarding positioning performance, the integration of multi-axis motion control and automatic positioning mechanisms reduces the average positioning error to 0.050 mm, ensuring stable machining accuracy.

Overall, the proposed equipment provides improved flexibility and machining performance for small-batch and multi-variety panel furniture manufacturing. The experimental validation confirms that the combination of modular equipment design, digital control, and machining path optimization provides an effective solution for the intelligent upgrading of panel furniture manufacturing equipment.

4 Conclusion

In this study, a flexible CNC machining system for panel furniture manufacturing was developed to address the limitations of conventional equipment in adaptability and machining efficiency. The proposed system integrates modular machining units, multi-axis motion control, automatic positioning fixtures, and digital control strategies to enable flexible drilling and grooving operations. Experimental results demonstrated that the proposed path optimization strategy effectively improved machining efficiency. For 20 machining tasks, the machining time was reduced from 986 s to 654 s, achieving a reduction of 33.7%. When the number of tasks increased to 25, the machining time was further reduced from 1248 s to 812 s. In addition, repeat positioning tests showed that the proposed equipment achieved an average positioning error of 0.050 mm, significantly lower than the 0.124 mm of conventional equipment, indicating improved machining stability.

The proposed flexible CNC machining equipment provides an effective solution for small-batch and multi-variety panel furniture manufacturing by balancing machining efficiency, positioning accuracy, and production adaptability. Future work will focus on further validation under diverse materials and industrial production conditions.

Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request.

Funding

This work was supported without any funding.

Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] De Toni, A., & Tonchia, S. (1998). Manufacturing flexibility: a literature review. *International journal of production research*, *36*(6), 1587-1617. [CrossRef]

[2] Y. Koren, *The Global Manufacturing Revolution: Product-Process-Business Integration and Reconfigurable Systems*. Hoboken, NJ, USA: Wiley, 2010. [CrossRef]

[3] Mehrabi, M. G., Ulsoy, A. G., & Koren, Y. (2000). Reconfigurable manufacturing systems: Key to future manufacturing. *Journal of Intelligent manufacturing*, *11*(4), 403-419. [CrossRef]

[4] Tolio, T. (2008). *Design of flexible production systems*. Berlin/Heidelberg, Germany: Springer. [CrossRef]

[5] Kusiak, A. (2018). Smart manufacturing. *International journal of production Research*, *56*(1-2), 508-517. [CrossRef]

[6] Lu, Y., Xu, X., & Wang, L. (2020). Smart manufacturing process and system automation–a critical review of the standards and envisioned scenarios. *Journal of manufacturing systems*, *56*, 312-325. [CrossRef]

[7] Mourtzis, D., Vlachou, E., & Milas, N. J. P. C. (2016). Industrial big data as a result of IoT adoption in manufacturing. *Procedia cirp*, *55*, 290-295. [CrossRef]

[8] Luo, Y., & Xu, W. (2023). Optimization of panel furniture plates rework based on intelligent manufacturing. *Bioresources*, *18*(3), 5198. [CrossRef]

[9] Bi, Z. M., Lang, S. Y., Shen, W., & Wang, L. (2008). Reconfigurable manufacturing systems: the state of the art. *International journal of production research*, *46*(4), 967-992. [CrossRef]

[10] Chryssolouris, G. (2006). *Manufacturing systems: theory and practice*. New York, NY: Springer New York. [CrossRef]

[11] Xu, X. (2009). *Integrating advanced computer-aided design, manufacturing, and numerical control: Principles and implementations*. IGI Global. https://dl.acm.org/doi/10.5555/1538386

[12] Pajaziti, A., Tafilaj, O., Gjelaj, A., & Berisha, B. (2025). Optimization of toolpath planning and CNC machine performance in time-efficient machining. *Machines*, *13*(1), 65. [CrossRef]

[13] Bortolini, M., Galizia, F. G., & Mora, C. (2018). Reconfigurable manufacturing systems: Literature review and research trend. *Journal of manufacturing systems*, *49*, 93-106. [CrossRef]

[14] Mourtzis, D., Doukas, M., & Bernidaki, D. (2014). Simulation in manufacturing: Review and challenges. *Procedia Cirp*, *25*, 213-229. [CrossRef]

[15] Baumann, D., Mager, F., Wetzker, U., Thiele, L., Zimmerling, M., & Trimpe, S. (2020). Wireless control for smart manufacturing: Recent approaches and open challenges. *Proceedings of the IEEE*, *109*(4), 441-467. [CrossRef]

[16] Gawroński, T. (2013). Optimisation of CNC routing operations of wooden furniture parts. *The International Journal of Advanced Manufacturing Technology*, *67*(9), 2259-2267. [CrossRef]

Lizhen Li was born in 1981. He received the B.Eng. degree in Mechanical Engineering from Beijing Institute of Graphic Communication in 2003. He is currently an associate senior engineer at Jinhua Institute of Electromechanical Product Simulation Technology, Jinhua, China. His research interests mainly include woodworking machinery, stamping equipment, lightweight design, and reverse engineering. (Email: lizhenli2026@126.com)

Hongying Jin was born in 1987. She received the B.Eng. degree in Mechanical Engineering. She is currently an intermediate engineer at Jinhua Institute of Electromechanical Product Simulation Technology, Jinhua, China. Her research interests mainly focus on mechanical equipment design and related technologies in electromechanical product development. (Email: 97184258@qq.com)