

Research and Implementation of High-Precision Multi-Axis Collaborative Control Algorithm for Stage Machinery Based on Fuzzy PID Optimization

Xuefeng Guan, Ruixin Yu, Jianjun Chen, Qingsong Kong, Xiaofei Jia

Beijing Bette Technology Development Co., Ltd., Beijing 100028, China

Copyright: © 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: Precise control of stage machinery directly affects the presentation effect and safety of performances. At present, the independent and controllable development of control technology for performing arts equipment has become an urgent demand for industrial development. Based on domestic chips as the hardware foundation, this study designs a fuzzy PID optimization algorithm adapted to stage machinery, builds a corresponding high-precision multi-axis collaborative control system, optimizes parameter tuning logic, and designs a distributed control architecture, high-precision trajectory planning, and error compensation strategies. Simulation verification and practical tests show that the algorithm can achieve motion control accuracy of ± 0.5 mm. This study provides a feasible technical solution based on the axis controller architecture for the localization and intelligent control of stage machinery. Keywords: Stage machinery; Fuzzy PID; Multi-axis collaborative control; Domestic chip; Motion control accuracy

Online publication: Jun 29, 2026

1. Design of special fuzzy PID optimization algorithm for stage machinery

1.1. Principles and limitations of traditional PID control

PID control is the most widely used control method in industrial control, consisting of proportional, integral, and derivative links. It regulates according to the deviation between the actual value and the set value of the controlled object. The proportional link adjusts the control output according to the deviation to improve the response speed; the integral link accumulates the deviation to optimize the overall system operation state; the derivative link regulates according to the change trend of the deviation to reduce overshoot and oscillation of the system^[1].

Traditional PID control has a simple principle and precise adjustment, but has obvious limitations in multi-axis control of stage machinery. First, parameter setting is difficult. The multi-axis linkage system of stage machinery is nonlinear and time-varying, making it hard to establish an accurate mathematical model

^[2]. Second, robustness is poor. When the system is disturbed by load changes, mechanical vibration, etc., fixed PID parameters cannot be adjusted in real time, resulting in reduced control accuracy. Third, single-axis regulation is limited. Traditional PID control only adjusts the position deviation of a single axis without considering the synchronization error between multiple axes.

1.2. Basic principle of fuzzy control

Fuzzy control is an intelligent control method based on fuzzy logic reasoning. Its core is to transform human control experience into fuzzy rules, without establishing an accurate mathematical model of the controlled object, and it has good adaptive ability for nonlinear and time-varying systems. Fuzzy control can conduct adaptive reasoning according to the actual situation of the control process, and is suitable for dealing with nonlinear and uncertain disturbances in stage machinery control. However, it has low steady-state accuracy when used alone. Therefore, combining fuzzy control with PID control to design a fuzzy PID optimization algorithm can take advantage of both to achieve high-precision control of stage machinery ^[3].

1.3. Design of special fuzzy PID controller for stage machinery

The special fuzzy PID controller for stage machinery designed in this study takes the single-axis position deviation and deviation change rate as input variables, and the correction of PID parameters as output variables. It adjusts PID parameters in real time through fuzzy reasoning to realize precise control of single-axis motion.

First, fuzzification of input and output variables is completed. The fuzzy domains of deviation, deviation change rate, and PID parameter correction are all set to {NB, NM, NS, ZO, PS, PM, PB}, and a triangular membership function is adopted to ensure the smoothness and real-time performance of fuzzy reasoning. Second, fuzzy rules are formulated combined with the motion characteristics and control experience of stage machinery, and parameter correction is adjusted according to the actual situation of the control process. Finally, the centroid method is used for defuzzification to convert the fuzzy output into accurate parameter correction, which is superimposed with the initial PID parameters to obtain real-time control parameters, realizing adaptive control of single-axis motion ^[4].

2. Construction of multi-axis collaborative control algorithm based on fuzzy PID optimization

2.1. Design of distributed multi-axis collaborative control architecture

The distributed multi-axis collaborative control architecture is mainly composed of a main controller and multiple axis controllers. The main controller is the core scheduling unit, responsible for high-precision motion trajectory planning based on the timing requirements of stage performances, issuing multi-axis linkage commands, and global monitoring and coordination ^[5]. Each axis controller is an independent control unit equipped with a fuzzy PID optimization algorithm, responsible for single-axis position control, speed adjustment, local fault detection, and real-time data interaction with the main controller through an industrial bus.

2.2. High-precision motion trajectory planning based on time axis

The motion of stage machinery must strictly follow the timing schedule of performances. Therefore, this study designs a high-precision motion trajectory planning algorithm based on the time axis, which converts

the action requirements of stage performances into position-time curves of each axis.

S-curve acceleration and deceleration curves are adopted for trajectory planning, dividing the equipment motion process into three stages: acceleration, constant speed, and deceleration. At the same time, the trajectory curve is smoothed according to the motion characteristics of each axis to make the speed and acceleration of each axis change continuously^[6]. The main controller issues real-time position commands to each axis controller according to the trajectory planning results, and each axis controller tracks the commands through the fuzzy PID optimization algorithm.

2.3. Multi-axis linkage interpolation and synchronization error compensation technology

Multi-axis linkage interpolation is the key for stage machinery to complete complex actions. Combined with the common action forms of stage machinery, linear interpolation and circular interpolation algorithms are designed, and the fuzzy PID optimization algorithm is matched to improve the control accuracy during interpolation^[7]. During interpolation, the main controller calculates the interpolation feed rate of each axis in real time according to the trajectory planning results and issues it to each axis controller; each axis controller follows the feed rate through the fuzzy PID optimization algorithm and adjusts the control parameters in real time according to the single-axis position value to improve the control accuracy during interpolation^[8].

To solve the synchronization error problem in multi-axis linkage, this study adopts the master-slave cooperation plus real-time value correction method. The axis with the most stable operation state is selected as the reference. The main controller obtains the position deviation between each axis and the reference axis in real time, and takes this value as an auxiliary input to conduct secondary adjustment of the PID parameters of each axis^[9]. When the deviation is obvious, the corresponding axis adjusts the operation speed for rapid correction; when the deviation is controlled within ± 0.5 mm, the speed is kept stable to make the system operate more smoothly. After adjustment, the deviation between each axis can be stabilized within ± 0.5 mm, meeting the control requirements of stage machinery.

2.4. Design of auxiliary control algorithms

To improve the stability and safety of the system, vibration suppression algorithm, safety protection algorithm, and fault-tolerant control algorithm are added to the multi-axis collaborative control algorithm.

The vibration suppression algorithm combines the parameter adjustment of fuzzy PID. When mechanical vibration is detected, the differential coefficient is fine-tuned to suppress oscillation and reduce the impact of vibration on control accuracy^[10]. The safety protection algorithm sets multiple protection mechanisms such as position limit, speed limit, and current limit. When the equipment operates beyond the limited range, the system immediately sends an alarm signal and executes an emergency stop^[11]. The fault-tolerant control algorithm designs fault detection and switching logic for common problems such as axis jamming, signal loss, and encoder failure. When a fault is detected, the main controller can quickly isolate the faulty axis from the system to ensure the normal operation of other axes.

3. System implementation and performance test of fuzzy PID multi-axis collaborative control algorithm

3.1. Hardware platform implementation based on domestic chips

This study takes domestic chips as the core to design a special multi-axis motion controller for stage

machinery as the hardware carrier of the fuzzy PID multi-axis collaborative control algorithm. The hardware research adopts the method of “integrated circuit design + EMC test and optimization + wide temperature domain adaptability verification” to solve the problems of dependence on imported chips and insufficient adaptability to complex scenarios.

The hardware circuit of the controller mainly includes five functional modules. The core is a high-performance integrated circuit based on domestic chips, which undertakes the operation of various control algorithms. The supporting high-precision ADC/DAC signal processing circuit completes analog-to-digital and digital-to-analog signal conversion. The redundant power management system realizes a stable power supply and reduces the impact of voltage fluctuation on equipment^[12]. The encoder interface and frequency converter control interface complete the collection of each axis operation data and the speed regulation of driving motors, respectively. At the same time, electromagnetic compatibility optimization and wide temperature domain adaptability verification are carried out on the controller. By adding shielding layers and optimizing circuit wiring, the electromagnetic anti-interference ability is improved to resist electromagnetic interference from surrounding equipment such as stage lighting and audio^[13]. Measured by a high and low temperature test chamber, the controller can operate stably in the temperature range of -20–60°C, fully meeting the environmental adaptation requirements of stage machinery.

3.2. Software implementation of control algorithm

The software implementation of the fuzzy PID multi-axis collaborative control algorithm is based on an embedded operating system, programmed in C language. The software architecture is divided into underlying driver layer, algorithm layer, and application layer. The underlying driver layer is responsible for driving the hardware circuit, including ADC/DAC conversion, encoder signal collection, frequency converter control, etc.^[14]. The algorithm layer is the core of the software, including modules such as fuzzy PID optimization algorithm, trajectory planning algorithm, multi-axis linkage interpolation algorithm, and synchronization error compensation algorithm. Each algorithm module is encapsulated as a subroutine and can be flexibly called according to actual needs. The application layer is responsible for interaction with the host computer, receiving action commands for stage performances, issuing control commands to each axis controller, and displaying the operating status and fault information of the equipment in real time^[15].

3.3. System performance test and result analysis

To verify the effectiveness of the algorithm, this study builds a multi-axis control test platform for stage machinery, selects lifting platforms and suspenders as test objects, conducts simulation tests and practical application tests, tests core indicators, and compares with traditional PID control. The simulation test builds a model based on MATLAB/Simulink to simulate working conditions such as load change and mechanical vibration. The results show that the motion control accuracy of traditional PID control is ± 1.2 to ± 2.0 mm, the command response time is 8–12 ms, and the multi-axis synchronization error is ± 1.0 to ± 1.5 mm. Under the same working conditions, the fuzzy PID optimization algorithm in this study stabilizes the motion control accuracy within ± 0.5 mm, command response time ≤ 5 ms, and multi-axis synchronization error ≤ 0.5 mm, with better robustness.

The practical application test builds a multi-axis linkage platform composed of 4 lifting platforms and 6 suspenders, completing 1000 hours of continuous reliability test and a wide temperature domain environment

test. The results show that the system motion control accuracy is ± 0.3 to ± 0.5 mm, the command response time is 3–5 ms, and the multi-axis synchronization error is ± 0.2 to ± 0.5 mm, all reaching the preset technical indicators. The system MTBF is $\geq 50,000$ hours, and there is no significant decline in performance under extreme temperature environments. Compared with imported controllers, the procurement cost of this domestic controller is reduced by 40%, and the delivery cycle is shortened by 60%.

4. Conclusion

Aiming at the industrial pain points of multi-axis control of stage machinery, the research team designs a special fuzzy PID optimization algorithm for stage machinery, builds a multi-axis collaborative control algorithm system, develops a special multi-axis controller hardware for stage based on domestic chips, and creates a high-precision control scheme for stage machinery integrating software and hardware. Practical tests show that the motion control accuracy, command response time, and multi-axis synchronization error of this scheme all reach the preset core technical indicators. The controller can operate stably in a wide temperature domain environment, the system operation reliability is outstanding, the controller procurement cost is reduced, and the delivery cycle is shortened accordingly. In the future, the research team should continue to integrate technologies such as machine learning and digital twin, optimize the fuzzy PID rule base, expand the application scenarios of multi-axis control, create an intelligent system operation and maintenance mode, and extend the technology to similar cultural equipment fields such as amusement facilities and film and television shooting equipment, helping the localization development of the cultural equipment manufacturing industry.

Funding

This project was supported by the 2025 Special Project for Enterprise Efficiency Improvement in Science and Technology Service Industry (No. 20250467457) of Beijing Municipal Science & Technology Commission.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Deng H, Shi H, Zhu L, et al., 2025, Motion Control of Four-Wheel Differential Robot Based on Optimized Fuzzy Control Algorithm. *Mechanical Research & Application*, 38(02): 7–13.
- [2] Zhai Y, 2025, Multi-Axis Linkage Control Technology of Complex Mechanical System for Intelligent Manufacturing. *Southern Agricultural Machinery*, 56(07): 122–125.
- [3] Luo D, Liu S, 2024, Research on Intelligent Gateway System of Stage Machinery Equipment Based on Edge Computing. *Computer & Digital Engineering*, 52(11): 3258–3263.
- [4] Bai B, Li L, Zhang F, et al., 2024, Design and Application of Control System for Omnidirectional Carriage of Stage Performing Arts. *Mechanical Research & Application*, 37(05): 106–109.
- [5] Liu M, 2024, Discussion on Structural Design of Large-scale Variety Show Stage Machinery. *TV Production*,

30(07): 62–65.

- [6] Zhang Q, 2024, Discussion on Stage Machinery Performance Operation and Safety Maintenance. *China Plant Engineering*, (06): 85–87.
- [7] Lü X, 2023, Analysis of Stage Art from the Perspective of Artificial Intelligence. *Public Communication of Science & Technology*, 15(23): 110–116.
- [8] Liu Y, Yang Q, Wang H, 2023, Research and Analysis on Configuration and Use of Stage Machinery—Taking the Opera House of National Centre for the Performing Arts as an Example. *Entertainment Technology*, (03): 47–51.
- [9] Wu P, Shi J, 2023, Design of Multi-Axis Controller for Multilateral Lifting Stage Based on Embedded System. *Manufacturing Automation*, 45(06): 195–199 + 220.
- [10] Zhu W, Huang J, Zhou Y, 2023, Research on Motion Control of Self-Guided AGV Based on Fuzzy Adaptive PID. *Science and Technology Innovation*, (02): 220–223.
- [11] Shi Y, Wu P, 2023, Motion Error Compensation of Multi-Axis Linkage CNC Machine Tool Based on PID Control. *Computer Simulation*, 40(01): 278–282.
- [12] An H, Wang B, Di J, et al., 2022, Analysis and Optimization of Electromagnetic Compatibility Detection. *Fluid Measurement & Control*, 3(06): 43–45.
- [13] Zhi H, Rao Z, Xiao R, et al., 2021, Series Discussion on Stage Machinery Technology, Craft and Application—Use of Stage Machinery. *Entertainment Technology*, (12): 38–43 + 47.
- [14] Qiang M, Li Y, Bai Y, 2021, Research on Synchronous Control Method of Stage Speed-Regulating Suspender. *Automation & Instrumentation*, (08): 60–64.
- [15] Shen Y, E L, Feng J, 2021, Research on Synchronous Detection Method and Device of Stage Machinery. *China Special Equipment Safety*, 37(07): 41–45.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.