DESIGN AND SIMULATION OF A CNC POSITION CONTROL SYSTEM USING PID AND FUZZY-PID CONTROL

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Abstract

This paper presents the design and simulation of a position control system for a two-axis CNC machine using PID and fuzzy-PID control strategies. The study focuses on the mathematical modeling of the positioning loop, including the derivation of the transfer function of the CNC servo system, and its implementation in MATLAB/Simulink for dynamic analysis. A conventional PID controller was first applied to regulate the positioning system and evaluate the closed-loop response. In order to improve tracking accuracy and dynamic performance, a fuzzy logic block was then introduced for adaptive tuning of the PID parameters. Simulation results showed that the PID controller achieved stable control of the system, while the fuzzy-PID approach provided improved positioning performance and higher control precision. The presented methodology demonstrates the usefulness of simulation-based control design for CNC positioning systems and offers a practical framework for improving motion-control performance in mechatronic applications.

Keywords: CNC machine; Position control; PID; fuzzy-PID; MATLAB/Simulink;

Introduction

Computer Numerical Control (CNC) machines are a central part of modern manufacturing because they enable accurate, repeatable, and automated motion control in machining processes. The quality of CNC machining depends strongly on the dynamic performance of the feed drive and position control system, since tracking errors and axis-coupling effects can directly influence contour accuracy and final part quality. In this context, the design of effective motion-control strategies remains an important topic in CNC research and mechatronic system development. [1]

Classical PID control is still widely used in motion-control applications because of its simple structure, reliability, and practical effectiveness. However, CNC servo systems are influenced by nonlinear effects, parameter uncertainty, and external disturbances, which can reduce the performance of fixed-parameter PID control, especially when higher positioning accuracy is required. For this reason, fuzzy logic has often been combined with PID control in order to improve adaptability and dynamic response. [1]

This paper focuses on the modeling and simulation of a two-axis CNC position control system. The system transfer function was derived and implemented in MATLAB/Simulink in order to analyze the dynamic behavior of the servo loop. A conventional PID controller was first applied as a baseline solution, after which a fuzzy-PID controller was introduced to improve the positioning performance of the system. The objective of the study is to evaluate, through simulation, the extent to which fuzzy-assisted tuning can improve control precision compared with a standard PID-based approach. [2]

Related Work

The control performance of CNC machine tools has long been recognized as a key factor affecting machining accuracy, contour quality, and dynamic response. Reviews of machine-tool control emphasize that servo loops, interpolation behaviour, and compensation strategies are central elements in achieving accurate motion in CNC systems. This makes the modeling of the feed drive and position-control loop an important step in the design and analysis of CNC machines. [3]

Among the available control approaches, PID control remains one of the most widely used solutions in CNC servo systems because of its simple structure, practical implementation, and stable closed-loop behavior. At the same time, recent work notes that conventional PID control can become insufficient when higher motion-control accuracy is required in the presence of nonlinear friction, parameter variation, and time-varying disturbances. For this reason, many studies continue to investigate improved PID-based strategies for CNC positioning systems. [4]

One of the most common improvements is the integration of fuzzy logic with PID control. In CNC servo applications, fuzzy-PID strategies are used to adapt controller behavior according to the magnitude and rate of the control error, with the goal of improving transient response, robustness, and positioning precision. Prior simulation work on CNC servo systems has reported that fuzzy-PID control can outperform conventional PID control in terms of robustness and disturbance rejection, while more recent studies continue to show the value of fuzzy-assisted PID tuning for nonlinear CNC motion systems. [2] [5]

Motivated by these findings, the present paper focuses on the modeling and simulation of a two-axis CNC position control system using PID and fuzzy-PID control strategies. In contrast to broad survey work, the emphasis here is placed on deriving the transfer function of the positioning loop, implementing the model in MATLAB/Simulink, and comparing the control response of a conventional PID controller with a fuzzy-PID alternative for the studied CNC configuration.

System Modeling and Control Design

This section describes the mathematical modeling of the two-axis CNC positioning system, the derivation of the transfer function of the control loop, and the implementation of PID and fuzzy-PID controllers in MATLAB/Simulink. The objective is to evaluate the dynamic response of the positioning system and compare the performance of the two control approaches under the same simulation conditions.

Methodology

This section presents the modeling and simulation procedure used for the analysis of the CNC position control system. In this paper we design the positioning control circuit of a CNC machine was designed by deriving the transfer function of a two-axis servo system and implementing the model in MATLAB/Simulink. The control performance was then evaluated using a conventional PID controller and an enhanced fuzzy-PID approach.

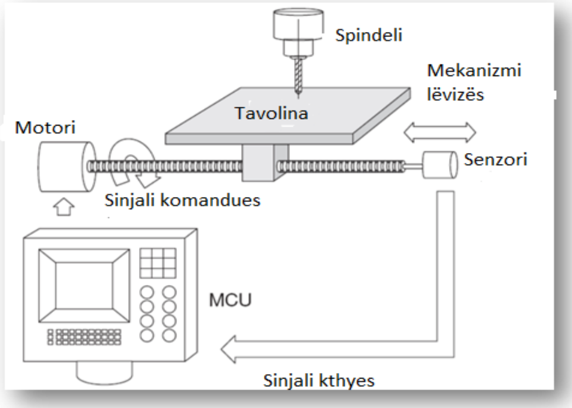

Figure 1. Operation principle of CNC milling machine.

System Modeling

The CNC machine was modeled as a two-axis positioning system in which translational motion along the machine axes is generated through servo-driven actuation and mechanical transmission elements. In the adopted control structure, the actuator, transmission mechanism, and feedback element form the core of the positioning loop, while the controller determines the dynamic response and positioning accuracy of the system. Based on this representation, the position-control problem was treated as a closed-loop servo-system suitable for mathematical modeling and simulation in MATLAB/Simulink.

Transfer function

The mathematical model of the two-axis CNC positioning system was developed from the physical structure of the servo-driven feed mechanism. For the purposes of simulation, the machine was represented as a two-axis system with translational motion along the X and Y axes, driven by two DC servo motors and ball-screw transmission elements. In the model, the mechanical part of the system was represented through the equivalent inertia of the moving table and transmission mechanism, while the damping contribution of the motor rotor and ball-screw system was retained.

In this paper, the working table was assumed to be made of aluminium with dimensions of 496 mm × 496 mm and thickness 10 mm, from which its mass and moment of inertia were calculated. The table inertia was calculated together with the ball-screw inertia and combined with the electrical and mechanical parameters of the selected DC servo motor.

These quantities were then substituted into the analytical model of the positioning loop in order to derive the transfer function used in simulation.

$$J_{xy} = \frac{1}{12} M(a^2 + c^2) \qquad (1)$$

where □ is the table mass and □ and □ are the table dimensions. Using the calculated table mass □ = *6.67* □□, the paper obtained the table inertia as:

$$J_{xy} = 0.1372 kgm^2 (2)$$

while the ball-screw inertia was also calculated:

$$J_b = 0.00122 kgm^2 \quad (3)$$

The DC servo motor parameters used in the model were presented in table 1.

Table 1. parameters of servo motor used in the paper.

$\boldsymbol{K_t}$	$\boldsymbol{K_b}$	$\boldsymbol{J_m}$	$\boldsymbol{R_a}$	$\boldsymbol{D_m}$	$\boldsymbol{L_a}$
0.352	12.7	$1 * 10^{-5}$	2.2	$1 * 10^{-3}$	$3.8 * 10^{-4}$

After substitution of the model parameters, the transfer function of the simulated CNC positioning system was obtained as:

$$G(s) = \frac{5.664}{s^2 + 14.82s} \quad (4)$$

This transfer-function model was used as the basis for controller design and closed-loop simulation in MATLAB/Simulink

PID controller design

After deriving the transfer function of the CNC positioning system, a conventional PID controller was adopted as the baseline control strategy. The PID controller was selected because of its simple structure, practical applicability, and widespread use in industrial motion-control systems. In the closed-loop configuration, the controller generates the control signal based on the position error, its integral, and its derivative, thereby enabling improvement of the transient response and reduction of steady-state error.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (5)$$

where □(□) is the position error, $□_□$ is the proportional gain, $□_□$ is the integral gain, and $□_□$ is the derivative gain. The PID controller was implemented in MATLAB/Simulink and used as the reference controller for comparison with the fuzzy-PID approach.

Fuzzy-PID controller design

In order to improve the control performance of the positioning system, a fuzzy-PID controller was introduced as an enhanced alternative to the conventional PID approach. The purpose of the fuzzy logic block was to adapt the PID parameters according to the instantaneous control error and the change of error, thereby making the controller more flexible in the presence of varying dynamic conditions. This approach was adopted in the paper to improve position accuracy and overall dynamic performance of the simulated CNC system.

The fuzzy-PID structure preserved the basic PID control law, while the fuzzy inference mechanism was used to modify the controller action in a rule-based manner. In this way, the advantages of classical PID control were retained, but additional adaptability was introduced through fuzzy logic. The resulting controller was implemented in MATLAB/Simulink and tested under the same simulation conditions as the conventional PID controller in order to enable a direct performance comparison.

MATLAB/Simulink simulation

The derived transfer-function model of the CNC positioning system was implemented in MATLAB/Simulink in order to evaluate the dynamic response of the closed-loop servo system under different control strategies. The simulation environment was used to compare the performance of the conventional PID controller and the fuzzy-PID controller under the same operating conditions, using the derived plant model as the common basis for both cases.

For the fuzzy-PID implementation, the fuzzy inference structure was defined using the control error □(□) and the change of error □□(□) as input variables, while the controller outputs were associated with the PID gain adjustment. The placement of the membership functions and the formulation of the fuzzy rules were based on the reference study used in this work and then adapted to the present simulation model. In particular, the adopted reference describes the fuzzy self-tuning PID structure and presents membership functions for error, change of error, and controller gains, together with rule tables for □□, □□, and □□. [6]

A comparative simulation was then carried out in MATLAB/Simulink in order to examine the position-control response of the system under PID and fuzzy-PID control. The resulting responses were evaluated in terms of transient behavior and positioning performance, and the comparison is presented in the following section.

Results and Discussion

This section presents the simulation results obtained for the two-axis CNC positioning system under PID and fuzzy-PID control. The comparison was carried out in MATLAB/Simulink using the same plant model and identical reference conditions, so that the effect of the control strategy could be evaluated more clearly. The main objective of the analysis was to examine the dynamic response of the system and determine whether the fuzzy-PID approach provided an observable improvement in positioning performance over the conventional PID controller.

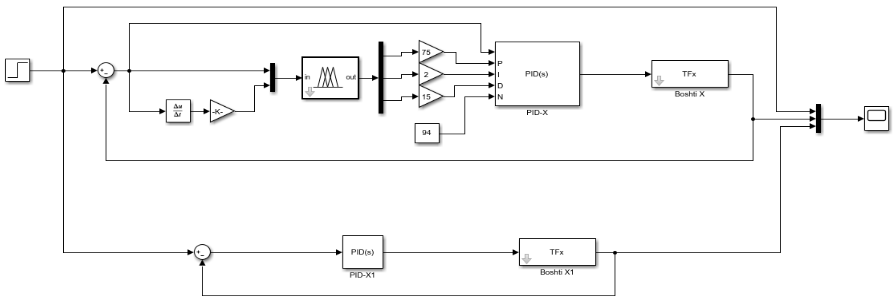

Figure 2. Schematic of the system with fuzzy logic (top) and with only the PID regulator (bottom).

The evaluation focused primarily on transient-response characteristics, since these provide a direct indication of control quality in positioning systems. In particular, the comparison considered the shape of the step response, the speed of convergence toward the reference position, and the overall smoothness of the response. From a motion-control perspective, these aspects are important because they influence positioning accuracy, tracking quality, and the suitability of the controller for CNC applications where stable and precise axis motion is required.

The MATLAB/Simulink implementation of the control loop can be shown in the methodology section as a separate figure, while the step-response plots should be presented here in the results section. In this way, the methodology explains how the model was built, whereas the results section demonstrates how the model behaved under the two control approaches. For the present paper, the most important results figure is therefore the step-response comparison between the conventional PID controller and the fuzzy-PID controller.

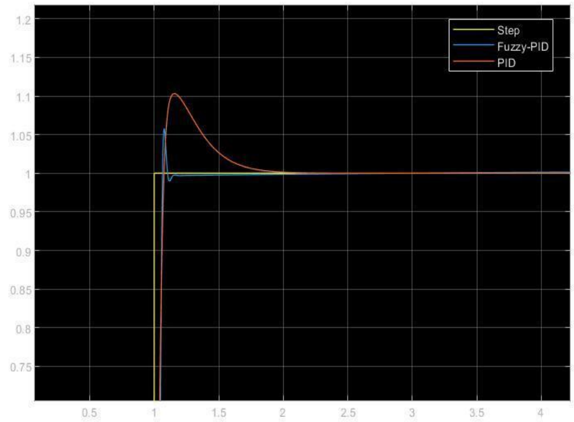

Figure 3. Step response comparison between just the PID controller and the Fuzzy-PID controller.

Figure 3 shows the simulated step responses of the CNC positioning system under PID and fuzzy-PID control. The responses were compared in order to evaluate the influence of fuzzy-based gain adjustment on the transient behaviour of the servo system. Particular attention was given to the speed of response, overshoot tendency, and the ability of the system to approach the reference position in a stable and accurate manner.

Tabel 2. Comparison of the PID values against Fuzzy-PID values

	PID	**Fuzzy-PID**
Rise time	49.889 ms	46.218 ms
Overshoot	10.556 %	5.851 %
Settling time	538.50 ms	53.879 ms

Discussion

The results summarized in Table 2 show that both controllers were able to stabilize the simulated CNC positioning system, but the fuzzy-PID controller achieved better overall dynamic performance than the conventional PID controller. In particular, the rise time decreased from **49.889 ms** for the PID controller to **46.218 ms** for the fuzzy-PID controller, indicating a slightly faster response to the reference input. A more noticeable improvement was observed in the overshoot, which was reduced from **10.556%** to **5.851%**, showing that the fuzzy-PID controller provided a much smoother transient response with less deviation beyond the desired position.

The most significant difference between the two control approaches was observed in the settling time. While the conventional PID controller required **538.50 ms** to settle, the fuzzy-PID controller reduced this value to **53.879 ms**. This result suggests that the fuzzy-PID strategy was able to bring the system to its steady operating region much faster than the fixed-parameter PID controller. From a CNC motion-control perspective, this is especially important, since shorter settling times and lower overshoot are directly related to improved positioning quality and more stable axis motion.

The observed improvement can be explained by the adaptive nature of the fuzzy-PID controller. Unlike the classical PID controller, which uses fixed gains throughout the response, the fuzzy-PID approach adjusts the controller action according to the instantaneous error and

the change of error. As a result, it is better able to respond to different phases of the transient process, leading to faster convergence and reduced oscillatory behavior.
At the same time, it should be noted that the presented comparison is based on simulation results obtained in MATLAB/Simulink rather than on experimental implementation on a physical CNC machine. Therefore, the findings should be interpreted as simulation-based validation of the control strategy. Nevertheless, the results clearly indicate that the fuzzy-PID controller offers a more effective control solution for the modeled CNC positioning system than the conventional PID controller under the same simulation conditions.

Conclusion

This paper presented the modeling and simulation of a two-axis CNC position control system using PID and fuzzy-PID control strategies. A mathematical model of the positioning loop was developed, and the corresponding transfer function was derived and implemented in MATLAB/Simulink for dynamic analysis. On the basis of this model, a conventional PID controller was used as the baseline control approach, while a fuzzy-PID controller was introduced in order to improve the dynamic performance of the system.
The simulation results showed that both controllers were able to stabilize the CNC positioning system, but the fuzzy-PID approach achieved better overall performance. In particular, the rise time was reduced from **49.889 ms** to **46.218 ms**, the overshoot was reduced from **10.556%** to **5.851%**, and the settling time decreased from **538.50 ms** to **53.879 ms**. These results indicate that the fuzzy-PID controller provided a faster and smoother response than the conventional PID controller under the same simulation conditions.
Overall, the study demonstrates that MATLAB/Simulink provides a practical environment for the analysis and comparison of CNC motion-control strategies, and that fuzzy-assisted PID tuning can significantly improve the positioning performance of the modeled servo system. The presented approach can serve as a useful basis for future work involving experimental validation and implementation on a physical CNC platform.

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