Advances and Emerging Trends of PID and Intelligent Control Strategies in CNC Machine Tools

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Abstract. In contemporary manufacturing, high precision, efficiency, and stability in control systems are crucial. It is relatively simple and reliable, and therefore, proportional-integral-derivative (PID) control has continued to be widely used. Standard PID controllers are challenging to adapt to nonlinear and time-varying or tightly decoupled systems. This paper encompasses the new trend on the use of PID and PID variants, particularly fuzzy and adaptive PID, in the Computer Numerical Control (CNC) machine tools to ensure that these issues are solved. These approaches have dynamic response, reductions in overshoot, and stability in the processes of spindle drives, servo motors, and feed mechanism applications. The paper classifies mainstream PID techniques, compares their performance in different CNC subsystems, and summarizes their advantages in practical machining environments. This study also includes representative CNC machining examples to demonstrate how various PID methods are applied in practice and how they improve machining accuracy and system stability. This work provides a technical reference for the development and implementation of high-performance PID control strategies in modern CNC machine tools and supports continued research toward more accurate and stable control solutions in precision machining systems.

Keywords: CNC machine tool, PID control, Adaptive control, Fuzzy control.

1. Introduction

Computer Numerical Control (CNC) machine tools will have to be able to provide high precision and quick response in a more complex environment that occurs in the era of smart manufacturing. The most common type of control used with servo systems is the Proportional-Integral-Derivative (PID) controller, which is a simple and straightforward control type that is well-known to do well with real-time feedback control [1]. Increased acceleration, multiaxis interaction, nonlinear friction, backlash, time-dependent loads, and thermal effects are modern-day challenges facing machine tools. Conventional PID controllers are unable to monitor and react rapidly under such circumstances [2, 3].

To address these issues, numerous works have come up with better and smarter PID-based controllers, such as fuzzy PID [4], model reference adaptive PID [5], evolutionary algorithm-based optimization of PID [6], and AI-based PID tuning [7]. In the case of the CNC feed servo system, Dong et al. designed a fuzzy-adaptive PID controller, which showed a higher transient responsiveness and stability as compared to that of the conventional PID [4]. The sparse-rule fuzzy PID controller proposed by Yu et al. minimized the overshoot and maximized the disturbance rejection of a CNC ball-screw servo drive [8]. The model reference adaptive PID controller developed by Gai et al. reduced the speed reversal error in CNC feed due to nonlinear friction [5].

The current research is largely concerned with individual axes or systems, whereas the transfer of intelligent PID control to complete machine tool systems, in particular the multi-axis coordination and practical production, is only marginally researched [9, 10]. The concepts of digital twins, large-scale AI models, and big data analysis are assisting researchers to create PID controllers, which can tune themselves and predict control behavior. These observations mean that PID control can go hybrid with adaptive systems, where real-time optimization and computer-guided modeling can be used to deliver the contemporary requirements of a production process.

Against this background, the paper will survey the key technologies of PID in CNC machine tools, examine its application in important elements, like spindle drives, feed servos, ball-screw

transmissions, and tool changers, and plot the way forward. The goal is to provide a clear and structured reference for researchers and engineers working on advanced machine tool control.

2. Mainstream PID Techniques

2.1. Classical PID Control

PID control remains the most fundamental and extensively applied feedback mechanism in industrial automation. It generates a control signal from the present, cumulative, and rate-of-change values of the system error $e(t)$ to achieve stable and accurate responses.

The parallel form of the PID controller is defined as equation (1) [11]:

$$u(t) = K_c \left(e(t) + \frac{1}{T_i} \int e(t)dt + T_d \frac{de(t)}{dt} \right) \tag{1}$$

And the series form as equation (2):

$$\begin{aligned} e_1(t) &= e(t) + T_d \frac{de(t)}{dt} \\ u(t) &= K_c \left(e_1(t) + \frac{1}{T_i} \int e(t)dt \right) \end{aligned} \tag{2}$$

Figure 1 presents the closed-loop control scheme. The error signal successively passes through the proportional, integral, and derivative parts, and the resulting control output is applied to the actuator.

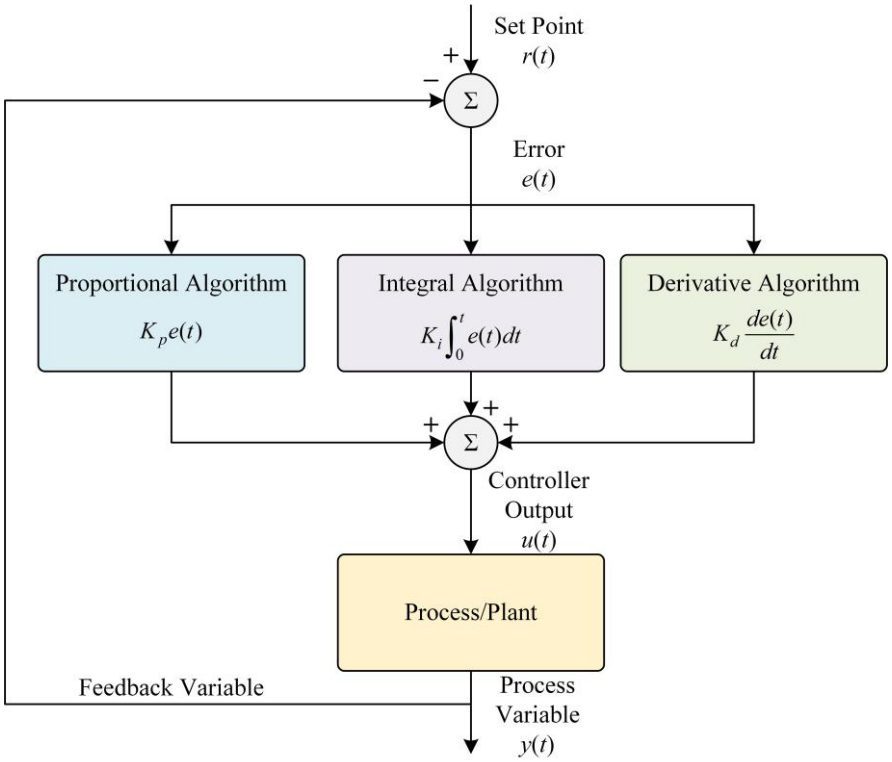


Figure 1. Block diagram of process control using PID [11]

Classical PID controllers are still widely applied in CNC machine tools for servo drives, spindle speed regulation, and hydraulic systems because of their simple structure and strong reliability [12]. However, using fixed parameters often causes performance decline when the system operates under nonlinear or time-varying conditions [13]. To enhance this, Kristiansson and Lennartson came up with a frequency-domain optimization method that ensures enhancement in the degree of phase margin and height of robustness [14]. Ho et al. studied the gain and phase margin requirements in order to come up with PID tuning rules [15, 16].

Although numerous fuzzy and intelligent control methods were produced recently, the classical PID controller can be used as the underlying structure and performance standard of both the industries and CNC control systems.

2.2. Fuzzy PID Controller

Traditional PID controllers are thought to dominate industry, but they cannot handle complex processes that have nonlinearities, time lags, and changing parameters. The fuzzy PID controllers are more appropriate in complex systems due to the fact that the control technology of fuzzy-fused PID controllers has been integrated with the normal PID controllers [17]. This approach effectively translates the operator's heuristic knowledge into an automatic control strategy, providing a robust means for handling uncertain dynamics [18].

The fundamental structure of a fuzzy logic controller is shown in Figure 2:

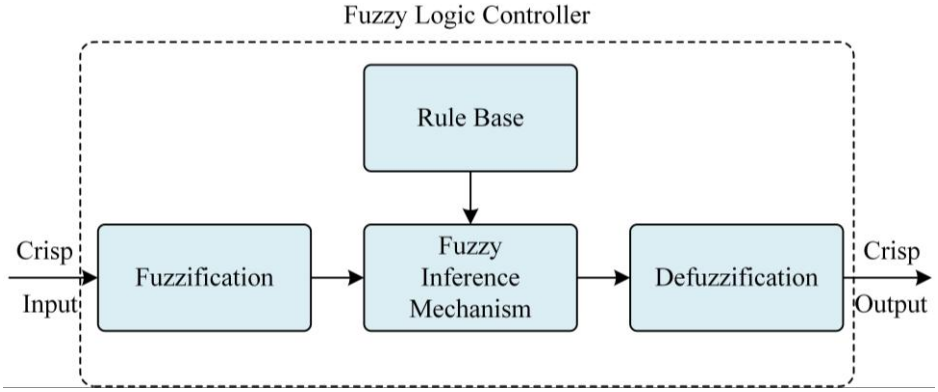


Figure 2. The structure of a fuzzy logic controller [16]

The majority of Fuzzy PID controller designs focus on the conventional two-input PI or PD type controller [19]. A common configuration of a fuzzy PID controller is depicted in Figure 3:

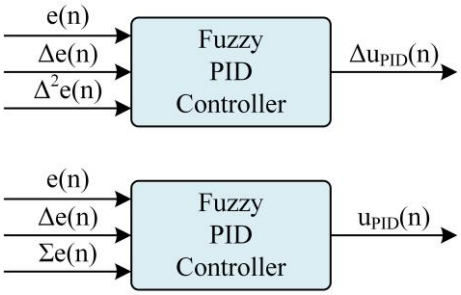


Figure 3. Fuzzy PID structure [20]

The discrete-time version of a classical PID controller in its positional form is given by equation (3) [16]:

$$u_{PID}(n) = K_C e(n) + \frac{K_C}{\tau_I}\sum_{j=0}^{n} e\,(j)T_S + (K_C\tau_D/T_S)\Delta e(n) \tag{3}$$

Index n refers to time instant and TS sampling time. Its incremental form is expressed by equation (4):

$$\Delta u_{PID}(n) = K_C\Delta e(n) + \frac{K_C}{\tau_I}T_S e(n) + (K_C\tau_D/T_S)\Delta^2 e(n) \tag{4}$$

Where:

$$u_{PID}(n) = u_{PID}(n-1) + \Delta u_{PID}(n) \tag{5}$$

Which is often preferred to mitigate integral wind-up.

Research has shown that Fuzzy PID controllers can outperform classical PID controllers; for instance, a fuzzy PI + fuzzy PD controller has been proven to demonstrate superior performance in

real-time liquid flow process control compared to a conventional controller [20]. Their design flexibility and ability to handle nonlinearities make Fuzzy PID controllers a powerful solution for a wide range of applications, from robotic manipulators to industrial process control [21].

2.3. Adaptive PID Controller

The adaptive PID control is an automatic online controller parameter adjustment used to maintain the activity of the plant when the parameters vary over time or are uncertain. It is split into direct and indirect adaptation.

Direct adaptive control adjusts parameters of PID and does not utilize a model of a plant through input/output signals. Methods include: Rule-based adaptation uses preset rules that reflect the experience of human operators; Gain scheduling uses several pre-tuned PID parameter sets for different operating points and switches between them according to measured scheduling variables.

Nevertheless, indirect adaptive control initially identifies the parameters of the plant model online and recomputes PID parameters using this information. Frequency adaptive control is one of the promising indirect methods because it is disturbance tolerant.

It begins with the injection of a dual-frequency sinusoidal test signal, as shown in equation (6) [22]:

$$v(t) = \rho_1 \sin\omega_1 t + \rho_2 \sin\omega_2 t \tag{6}$$

The plant input $u(t)$ and output $y(t)$ are processed by a Fourier filter to extract amplitude and phase information at frequencies ω_1 and ω_2, yielding estimates of the plant's frequency parameters $\hat{\alpha}_k$, $\hat{\beta}_k$. The frequency parameters are used to calculate the estimates $\hat{k}_o$, $\hat{T}$, $\hat{\tau}$for a plant model (typically a first-order plus time delay model $\frac{k_o}{Ts+1}e^{-\tau s}$). The detailed computation procedure is illustrated in equation (7).

$$\begin{aligned} &\hat{T}^2 = \frac{(\hat{\alpha}_2^2+\hat{\beta}_2^2)-(\hat{\alpha}_1^2+\hat{\beta}_1^2)}{\omega_1^2(\hat{\alpha}_1^2+\hat{\beta}_1^2)-\omega_2^2(\hat{\alpha}_2^2+\hat{\beta}_2^2)}, \hat{k}_o^2 = \left(\hat{\alpha}_2^2+\hat{\beta}_2^2\right)\left(\hat{T}^2\omega_2^2+1\right), \\ &\hat{\tau} = -\frac{1}{\omega_1}\arctan\frac{\hat{\beta}_1+\hat{T}\hat{\alpha}_1\omega_1}{\hat{\alpha}_1-\hat{T}\hat{\beta}_1\omega_1}. \end{aligned} \tag{7}$$

The estimated model parameters $\hat{k}_o$, $\hat{T}$, $\hat{\tau}$ are substituted into Internal Model Control (IMC)-based tuning rules, as given in equation (8) [23, 24], to update all parameters of the PID controller online.

$$k_c = \frac{2\hat{T}+\hat{\tau}}{2\hat{k}_o(\lambda+\hat{\tau})}, T_I = \frac{2\hat{T}+\hat{\tau}}{2}, T_D = \frac{\hat{T}\hat{\tau}}{2\hat{T}+\hat{\tau}}, T_f = \frac{\lambda\hat{\tau}}{2(\lambda+\hat{\tau})}, \tag{8}$$

Figure 4 illustrates the closed-loop process of signal injection. Fourier filtering, parameter estimation, and controller update.

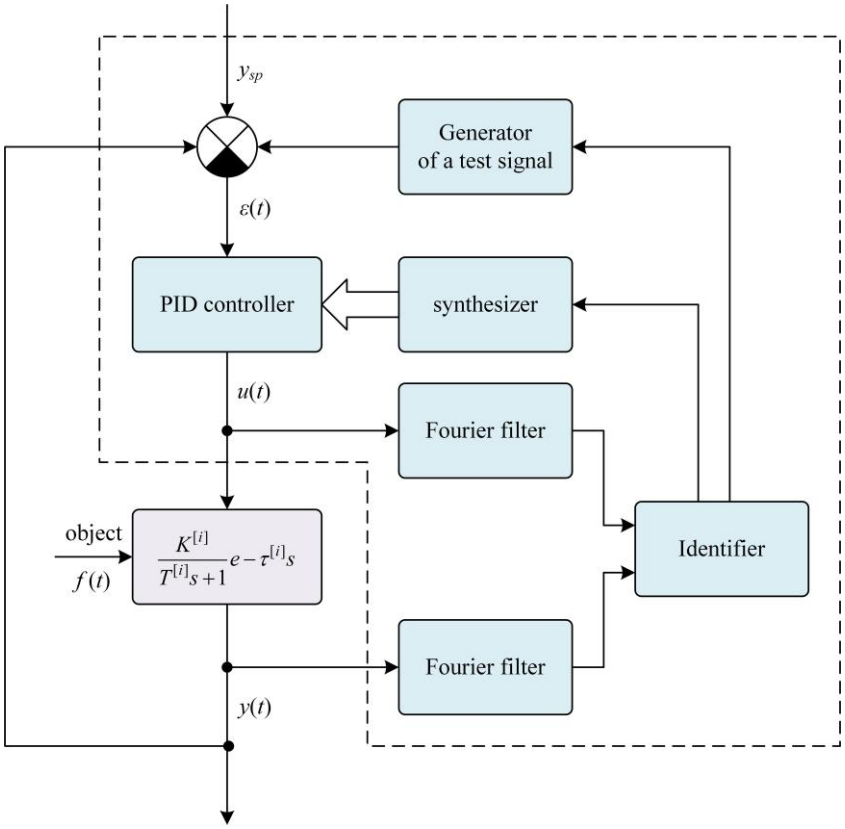


Figure 4. Structural scheme of a system with frequency adaptive PID controller [25]

3. Application of PID Technology in CNC Machine Tools

3.1. Spindle System

In the spindle system of CNC machine tools, PID control is utilized to perform adaptive torque regulation during deep-hole drilling. The control scheme estimates real-time cutting torque indirectly and non-invasively by measuring the three-phase current of the spindle motor with Hall sensors and calculating its root mean square (RMS) value. The estimated torque is then compared with a predefined threshold through a PID controller, which dynamically adjusts the federate override signal of the CNC system. In this way, the drilling torque is precisely maintained at the desired level by continuously controlling the feed rate. Experimental validation showed that, even in challenging drilling conditions where the hole depth reached eight times the tool diameter, the proposed PID strategy effectively suppressed torque fluctuations. Under dry cutting, flank wear was reduced by 65%, and under wet cutting, it was reduced by 84%, as well as the elimination of drill fracture in hard-to-cut materials. All these changes significantly enhanced reliability in machining and the life of tools [23].

3.2. Servo Motor and PMSM

In Permanent Magnet Synchronous Motor (PMSM) types of systems, the speed control loop takes the PID controller as its central element. It checks the difference between reference and actual speed and forms a control signal to track the actual speed properly [24]. Nevertheless, load disturbances and variations of parameters usually restrict the performance of conventional fixed-gain PID controllers because of the nonlinear characteristics of PMSM [26]. In order to enhance this, complicated fine-tuning is employed. A fuzzy PID controller can change parameters (K_p,K_i,K_d) in response to the error of speed and speed rate of change online through a fuzzy inference rule [24]. It has been found that experimental findings indicate that a fuzzy-tuned PID controller possesses superior dynamic behavior in comparison to the traditional Ziegler-Nichols tuning. It eliminates steady-state speed ripple to

0.0001 rps and torque ripple to 0.114 $N \cdot m$, which makes the operation of CNC machine tool servo drives smoother and more focused [24].

3.3. Feed and Positioning Servo Control

In the feed servo system of CNC machine tools, PID control is extensively employed because of its structural simplicity and strong reliability. Nevertheless, traditional PID controllers have difficulties in addressing nonlinear behaviors, changeable factors over time, and disturbances in the loads [6]. A Fuzzy PID (FPID) controller is a self-adaptive controller that dynamically changes control parameters ($\Delta K_p, \Delta K_i, \Delta K_d$) in real time to consider implicit system uncertainties [4]. Experimental and simulation data indicate that the FPID controller reduces step response overshoot and transient performance as well as disturbance rejection compared to the PID controller [4]. High computational efficiency results are achieved with the Sparse-Rule-Base Fuzzy PID (S-FPID) controller, reducing the runtime of the fuzzy logic by 81.25% with robustness similar to that of the FPID and improving CPU consumption in a CNC control system [6].

3.4. Cutting Force and Surface Quality Control

With the 3A CNC machining, the response of the feed servo system to cutting forces and surface quality is highly sensitive. Real-time control of feed rate and cutting depth with a PID controller reduces vibration and changes in force [3]. It has been observed that PID control for the feed servo drive decreases the transient errors and stabilizes tool load to increase the smoothness of the surface [2]. Experimental findings further reveal that, with a composite PID control scheme incorporating input feedforward and dynamic compensation, the machining tracking error decreased from ± 14 μm to less than ± 2 μm [27]. Demir Polat et al. observed a strong correlation between the cutting force and tool wear, indicating that PID-controlled feed servos have the potential to maintain the same primary cutting forces to prolong tool life and minimize heat [27]. Recent studies by Kiswanto et al. centered on a digital-twin-based monitoring system in which the output of the PID was automatically adjusted on the basis of the results of an Extended Kalman Filter (EKF) to offset the wear of the tool [28]. On the whole, PID control is essential in the stability of processes, enhancement of surface integrity, tensile perseverance of tools, and machining productivity.

3.5. Vibration Suppression and Torsional Control in Gear/Transmission Systems

The CNC transmission system incorporates gears. Gears were important in storing the torque and in an external timing signal. Shaft elasticity and backlash cause periodic and torsional vibrations. The effects reduce mechanical integrity and precision in movement. PID-based control is largely utilized in suppressing disruptions [29]. The model of Chen et al. is a vibration model of four degrees of freedom of a vector propulsion shaft system. They used a fuzzy adaptive PID controller to regulate torsional vibration. The results showed a reduction of more than 70% in vibration amplitude and over 90% in transient response time. The control strategy greatly improved the stability and safety of the underwater propulsion system [30]. Mendil et al. proposed a hybrid sliding–PID controller for rotary drilling systems. The controller predicted torsional oscillations and adjusted the PID output in advance. This method effectively reduced high-frequency vibration peaks and enhanced the overall dynamic performance [31].

3.6. Thermal Control and Deformation Compensation

Thermal loads produced during long or high-power machining cause spindle and structural deformation. These effects lower machining accuracy. Real-time temperature control and thermal-error compensation for the spindle and other key parts are therefore important for precision improvement [32]. Li et al. combined a cooling loop with an STM32-based PID controller. The system used closed-loop control of coolant inlet and outlet temperatures and compressor frequency. Cooling capacity was automatically adjusted according to the spindle load. The method reduced spindle thermal deformation by up to 25% under dynamic conditions and shortened the time to reach

steady state [32]. Mareš et al. developed a temperature-sensor-based modeling and compensation method for five-axis machine tools. The system implemented online thermal error prediction and correction, which improved the accuracy of compensation and provided a practical basis for cooling control [25]. Weng et al. used transient thermal analysis to verify that combining thermal models with active cooling control reduces thermal response time. The adaptive PID controller stabilized the temperature field and improved positioning and dimensional stability [33]. The applications of PID control in various CNC machine tool components are summarized in Table 1.

Table 1. Performance Improvements of PID Control in CNC Machine Tool Components

System	Control Objective	Control Method	Key Performance Improvement
Spindle System	Adaptive torque control to prevent tool wear and fracture.	PID compares estimated real-time cutting torque (from motor current) with a threshold to adjust federate.	Drill flank wear reduced by 65% (dry) and 84% (wet); drill fracture entirely prevented.
Servo Motor and PMSM	Precise speed tracking and reduction of speed & torque ripple.	Fuzzy PID dynamically adjusts parameters (Kp, Ki, Kd) online.	Steady-state speed ripple reduced to 0.0001 rps, torque ripple to 0.114 $N \cdot m$.
Feed and Positioning Servo	Reduce overshoot, improve response speed and anti-interference.	Fuzzy PID with real-time parameter adjustment; Sparse Fuzzy PID (S-FPID).	Significant overshoot reduction; S-FPID reduced fuzzy logic runtime by ≈81.25%.
Cutting Force and Surface Quality	Stabilize cutting force, suppress vibration, improve surface finish.	Composite PID with input feedforward & dynamic compensation; digital twin with EKF.	Machining tracking error improved from $\pm$14 μm to $<$ $\pm$2 μm; longer tool life.
Transmission System	Suppress torsional vibration and oscillations.	Fuzzy Adaptive PID; Hybrid Sliding-PID control.	Torsional vibration amplitude reduced by $>$70%, transient response time shortened by $>$90%.
Thermal Control and Compensation	Reduce thermal deformation and shorten settling time.	STM32-based PID for closed-loop cooling; sensor-based online compensation.	Spindle thermal deformation reduced by ≈25%, positioning stability improved.

4. Conclusion

This paper gives an overview of how PID and its improved forms are used in CNC machine tool control systems. Through classical PID, fuzzy PID, adaptive PID, and intelligent optimization methods, it demonstrates that PID control is an essential algorithm used in the machine tools since it is a simple, reliable, and applicable method. Its strengths include spindle speed control, servo drives, feed motion, cutting force control, vibration reduction, and temperature correction. The parameters of conventional PID controllers are fixed in advance, and they slow when acting in a nonlinear or time-driving system, whereas fuzzy logic, adaptive tuning, and intelligent optimization significantly improve their stability and performance rate.

In the future, CNC control systems will likely become more intelligent and capable of self-learning, with better integration of data from multiple sensors. PID controllers can utilize automatic tuning and data prediction from AI and large-scale models, significantly enhancing accuracy and response time as these technologies continue to advance. Moreover, PID strategy testing and optimization in virtual systems will provide Digital Twin technology that can improve temperature, vibration, and cutting control during machining. In the future, deep reinforcement learning can also be integrated with PID frameworks to ensure that it becomes more adaptive and flexible to operate in very complicated machining environments.

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