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Design and Implementation of PLC-Based Closed-Loop Control Strategy for Hydraulic Systems

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ABSTRACT This paper addresses the issues of insufficient control accuracy and decreased stability in hydraulic systems, where fluctuating loads and nonlinear characteristics often compromise positioning precision in high-speed industrial applications. As modern intelligent manufacturing increasingly depends on electromagnetic sensing and reliable industrial signal transmission, robust closed-loop control architectures are essential for ensuring stable real-time operation. A PLC-based closed-loop control strategy is therefore designed and implemented. First, a hardware control platform is constructed by integrating a programmable logic controller (PLC) with sensors for real-time monitoring of oil pressure, flow rate, and displacement signals. A digital PID control algorithm is then developed, with parameter tuning and optimization performed using a hydraulic system model, followed by implementation of the closed-loop logic through PLC programming and system debugging. Experimental results show that the proposed system achieves a steady-state error of 0.15 mm, an overshoot of 4.55%, and a settling time of 0.518 s under step response testing. Under a 500 N step load disturbance, the maximum dynamic deviation remains below 0.72 mm and the recovery time does not exceed 0.45 s. These results demonstrate that the PLC-based strategy significantly improves control precision, dynamic response, and disturbance rejection capability, providing an effective solution for high-reliability hydraulic actuation while offering valuable references for electromagnetic sensing-assisted industrial automation and intelligent motion control.

INDEX TERMS hydraulic system, closed-loop control, programmable logic controller, electromagnetic sensing, industrial automation

I. INTRODUCTION

As the core power and control unit of modern industrial equipment, the performance of hydraulic systems directly determines the production efficiency and quality of machinery, where precise pressure and motion control are essential for ensuring uniformity and processing consistency. However, due to the inherent nonlinearity, time-varying parameters, and susceptibility to external load disturbances in hydraulic systems, traditional open-loop or simple proportional control methods often face problems such as insufficient control accuracy, slow dynamic response, and poor stability, making it difficult to meet the control requirements of high-end equipment manufacturing for high precision, high reliability, and strong adaptability [1,2]. Therefore, researching and implementing an efficient and stable closed-loop control strategy for hydraulic systems is of great significance for improving the level of industrial automation.

Regarding the advanced control of hydraulic systems, existing research mainly focuses on intelligent algorithms such as fuzzy control, adaptive control, and sliding mode variable structure, aiming to improve the dynamic performance and robustness of the system. For example, Li et al. analyzed the research status and development trend of hydraulic synchronous control systems, studied three control modes and related control algorithms of closed-loop hydraulic synchronous control systems, and predicted their future development [3]. Zhang et al. proposed a repetitive control strategy by modeling electro-hydraulic servo systems, designing stable controllers, and developing plug-in repetitive controllers, which improved the system's position tracking performance [4]. Mahato and Ghoshal reviewed strategies to improve the energy efficiency of power hydraulic systems, classifying them into three categories: system design, component improvement, and loss reduction, and presented the time development of different energy-saving potentials in a table [5]. Li et al. proposed a nonlinear valve flow model, which simulates the nonlinear flow curve by compensating the dead zone with a static inverse function and a polynomial projection function, and combined it with an adaptive robust control method [6]. Wang introduced programmable logic controller technology and applied it to design a control system for a hydraulic robotic arm. A digital incremental PID algorithm was implemented within the PLC, enabling stable and precise control of the hydraulic system [7]. However, the practical deployment of these algorithms is often constrained by their computational complexity and the associated challenges in parameter tuning and real-time implementation, particularly on standard industrial PLC platforms. In contrast to the implementation challenges associated with advanced algorithms, digital PID control offers a practical alternative due to its simple structure, high reliability, and ease of engineering implementation and debugging, making it well-suited for PLC-based industrial applications. However, traditional PID control suffers from limitations in handling the strong nonlinearity and abrupt load changes in hydraulic systems, including fixed parameters and limited adaptive capabilities. Therefore, this paper proposes constructing a closed-loop control architecture on a mature PLC hardware platform by tuning a digital PID control algorithm to optimize the hydraulic pressure and speed synchronization required for processing. This approach effectively improves control accuracy and anti-interference capability while ensuring the system reliability and engineering practicality necessary for continuous production lines.

II. PLC HARDWARE PLATFORM AND SIGNAL LINK CONFIGURATION

To achieve high-performance closed-loop control of the hydraulic system, this study constructed a hardware platform with a programmable logic controller (PLC) as its core. The platform adopts a modular design approach and selects the Siemens S7-1200 series PLC as the main controller, which features high reliability, fast instruction execution speed, and support for multiple industrial communication protocols, making it suitable as the core of real-time control. The signal link of the system is as follows: First, the piston rod displacement of the hydraulic cylinder and the working pressure of the system are collected in real time by a magnetostrictive linear displacement sensor with a measuring range of 150 mm, a resolution of 0.001 mm, and an analog output of 0–10 V, along with a pressure transmitter. The standard analog voltage/current signals are sampled by the PLC's analog input module (Siemens SM1231 AI 4×U/I), which offers a 16-bit resolution and a configurable sampling rate of up to 1 kHz. Second, according to the internally running digital PID control algorithm, the CPU calculates the corresponding control quantity and converts it into an analog voltage signal of -10V ~ +10V through the analog output (AO) module. This signal directly drives the valve core of the electro-hydraulic proportional directional valve, and adjusts the flow into the hydraulic cylinder by changing the valve opening, thereby realizing continuous control of the piston rod displacement or speed. The entire signal link forms a complete closed loop from "detection → processing → output → execution → re-detection", ensuring the real-time performance and control accuracy of the system. In addition, all hardware components are integrated into the same network through the industrial Ethernet PROFINET, and unified hardware configuration and logic programming are performed using Siemens TIA Portal programming software, providing stable and efficient underlying support for the implementation of the control strategy [8]. To clearly illustrate the system hardware configuration, the specific selection of key components used in this study is detailed in Table 1.

TABLE 1. Selection Table of Main Hardware Components for Control System

Components	Key Models/Specifications	Main functions
PLC controller	Siemens S7-1215C	The core of the system is the execution control algorithm and logic.
Analog input module	Siemens SM1231 AI 4xU/I	Collect analog signals from displacement and pressure sensors
Analog output module	Siemens SM1232 AQ 2xU	Output analog control signal to proportional valve
Displacement sensor	Magnetostrictive type, measuring range 150 mm	Real-time feedback of hydraulic cylinder piston rod position
Electro-hydraulic proportional directional valve	Rexroth 4WRKE, 16 L/min	Receive electrical signals to adjust the flow and direction of the hydraulic cylinder.
Hydraulic power unit	Variable displacement pump, rated pressure 16 MPa	Provide a stable hydraulic oil source for the system
Hydraulic cylinder	Double-acting cylinder, 100 mm stroke	The system actuator, as the controlled object

III. CLOSED-LOOP CONTROL CIRCUIT DESIGN

With the hardware platform established, the design of the closed-loop control circuit is crucial for ensuring the effective implementation of the control strategy. This system's control circuit uses the linear displacement of the hydraulic cylinder piston rod as the controlled variable, constructing a typical negative feedback closed-loop structure.

The loop workflow is as follows: First, the operator sets the target position of the hydraulic cylinder in the human-machine interface (HMI) or host computer, and the set value is transmitted to the PLC. At the same time, the high-precision displacement sensor installed on the hydraulic cylinder detects the actual position of the piston rod in real time and sends this measurement value as a feedback signal to the PLC. In the control program inside the PLC, the set value and the feedback value are compared in each scanning cycle, and the difference is the position deviation $e(t)$. The deviation signal is used as input and sent to the digital PID control algorithm module for calculation. The PID algorithm calculates the deviation according to the preset proportional (P), integral (I), and derivative (D) coefficients and generates the corresponding control quantity $u(t)$ in real time. The control quantity is converted into an analog voltage signal that matches the control port of the electro-hydraulic proportional valve through the analog output module of the PLC. The electro-hydraulic proportional valve adjusts its valve core opening linearly according to this voltage signal, thereby accurately controlling the flow rate and direction of the hydraulic oil flowing into the hydraulic cylinder and driving the piston rod to move in the direction of eliminating the position deviation. The displacement change of the piston rod is captured by the sensor and forms a new feedback value, thus forming a closed loop that is continuously acting and dynamically adjusting [9].

The key to this loop design lies in discretizing the continuous control process into periodic scanning tasks executable by the PLC. By rationally configuring the PLC's cyclic interrupt organization block (OB), the PID calculations and signal input/output are ensured to be executed at a fixed and sufficiently high frequency (e.g., 10 ms), meeting the basic real-time control requirements of the hydraulic system. The entire design organically integrates the controller (PLC and algorithm), actuators (proportional valves and hydraulic cylinders), detection devices (displacement sensors), and the controlled object (hydraulic cylinder displacement), forming a well-structured and timely closed-loop automatic control system, laying a solid foundation for the subsequent implementation of control algorithms and performance optimization.

IV. IMPLEMENTATION OF DIGITAL PID CONTROL ALGORITHM IN PLC

After completing the hardware architecture and closed-loop design, the core of the control strategy—the digital PID control algorithm—needs to be implemented in the PLC's software environment. As an industrial computer operating in a cyclic scanning manner, the PLC's algorithm execution is inherently discrete. Therefore, the continuous-time classical PID control law first needs to be discretized. This study adopts the widely used incremental PID algorithm. The advantages of choosing the incremental algorithm are that its output is the change in the control quantity, resulting in less impact on the system. Furthermore, the program implementation does not require handling complex historical accumulation of integral terms, exhibiting stronger resistance to integral saturation and better meeting the requirements for stable and reliable PLC operation. The algorithm was programmed within the Siemens TIA Portal development environment. Utilizing its structured programming approach, the PID algorithm was encapsulated as a single function block. Within this function block, the core calculation code was written in Structured Text (ST) language, clearly implementing the discrete formulas described above, including reading the deviation, storing and updating historical deviations, and summing the products of each coefficient and its corresponding deviation. The function block's input interfaces include the setpoint, process value, and online adjustable parameters; the output interface is the calculated control variable.

To ensure the real-time performance of the control, the PID function block is called in a fixed cycle interrupt organization block (Cyclic Interrupt OB) with an interrupt cycle of 10 ms. This means that regardless of the main program scan cycle, the PID operation will be executed precisely once every 10 ms, thus providing stable and timely control instructions for the hydraulic system. In addition, the program also integrates engineering measures such as manual/automatic bumpless switching, output limiting, and integral separation (temporarily canceling integral action to prevent saturation when the deviation is too large), which enhances the practicality and reliability of the algorithm in industrial field applications. Through this series of software designs, the classical PID control theory is effectively transformed into executable code that can run stably and efficiently in the PLC, becoming the "intelligent brain" of the entire closed-loop control system [10].

V. CONTROL PARAMETER TUNING AND PROGRAM DEBUGGING

After completing the programming of the control algorithm, on-site tuning and system debugging of the digital PID controller parameters (K_P, K_I, K_D) are crucial practical steps to ensure that the closed-loop control performance meets the design requirements. Parameter tuning was conducted in two stages. First, a simulation model of the hydraulic system was established in the MATLAB/Simulink environment, and initial PID parameters were obtained through model-based tuning using the Ziegler-Nichols method. These initial parameters were then implemented on the physical experimental platform as a starting point for further refinement. On the physical platform, the engineering trial-and-error method combined with the critical proportional gain method was applied, following the principle of "proportional first, then integral, then derivative," to fine-tune the parameters and achieve optimal control performance.

First, set the integral coefficient K_I and derivative coefficient K_D to zero and retain only the proportional control. Start with a small value and gradually increase it to observe the system's response to a step input. When K_P is increased until the system exhibits continuous, constant-amplitude oscillations, record the critical proportional gain K_c and the corresponding oscillation period T_c. Then, based on the Ziegler-Nichols empirical formula, calculate the baseline values of the PID parameters. Using this baseline value as the center, conduct fine engineering trial debugging on-site. During the debugging process, focus on the dynamic response of the system: adding K_P can speed up the response but may lead to increased overshoot; introducing K_I can eliminate steady-state error but may slow down the system response and introduce the risk of integral saturation; adding K_D helps to suppress overshoot and improve stability, but is sensitive to measurement noise [11]. During parameter tuning, comprehensive program debugging and system integration were conducted. Utilizing the PLC's online monitoring function, the changing trends of key variables were observed in real time, verifying the correctness of data sampling, PID calculation, and control signal output. During debugging, issues such as valve dead zone and minor signal fluctuations were addressed by adding a small bias voltage to the control output in the program and incorporating first-order digital filtering for the feedback signal. Ultimately, the system achieved seamless switching from manual to automatic control, and the hydraulic cylinder was able to smoothly and accurately track the target position command, laying a stable and reliable operational foundation for subsequent performance verification experiments.

VI. PERFORMANCE VERIFICATION OF THE CONTROL STRATEGY

A. OVERALL EXPERIMENTAL SETUP

This experiment utilizes the PLC-based closed-loop control system for hydraulic cylinder position constructed in Chapter 2, employing an S7-1200 series PLC as the control core to test an electro-hydraulic proportional valve-controlled hydraulic cylinder unit. The control strategy is executed using a digital incremental PID algorithm implemented through PLC programming. The tests are divided into two main scenarios: first, evaluating the system's step response characteristics under no-load conditions; and second, evaluating the system's anti-interference capability and steady-state recovery performance under conditions of applied external step load disturbance. By collecting and analyzing the time-domain response curves of the actual displacement of the hydraulic cylinder, its static accuracy, dynamic response speed, and robustness are quantitatively evaluated.

B. STEP RESPONSE CHARACTERISTIC TEST EXPERIMENT

To verify the actual effectiveness of the control strategy, an experimental platform for valve-controlled hydraulic cylinders based on an S7-1200 PLC was built. The experiment included two typical working conditions: step response test under no-load conditions and load change disturbance test. High-precision displacement sensors were used to collect hydraulic cylinder position data in real time to quantitatively analyze the dynamic and static control quality of the system.

Figure 1 presents the step response test results. Figure 1(a) shows the actual position response curve under a 100 mm step command, with the target position indicated by the red dashed line and the ±2% error band by the black dotted lines. Figure 1(b) illustrates the corresponding position error curve over time. Experimental results show that the PLC-based closed-loop control strategy effectively improves the control performance of the hydraulic system. The steady-state error of the system under a 100 mm step command is 0.15 mm, and the relative error is 0.15%, proving its high steady-state accuracy; the dynamic response is rapid, with a rise time of 0.186 s and an overshoot of 4.55%, exhibiting good damping characteristics and response speed; the system converges quickly, with a settling time of 0.518 s (based on entering the ±2% error band). The data verify that the designed digital PID control strategy achieves the control objectives of high precision, fast response, and strong stability.

C. ANTI-LOAD DISTURBANCE PERFORMANCE TEST EXPERIMENT

During the uniform speed operation of the hydraulic cylinder, a step load disturbance with an amplitude of 500 N is applied to its piston rod through a loading device to simulate a sudden load in actual working conditions. The actual position change curve of the hydraulic cylinder measured by the displacement sensor under this disturbance is recorded to evaluate the anti-interference capability and steady-state recovery characteristics of the closed-loop control system. Details are shown in Table 2.

TABLE 2. Evaluation of Load Disturbance Resistance Performance

Test conditions	Load disturbance amplitude	Maximum dynamic deviation	Time to recover to ±0.3 mm tolerance zone
Running at a constant speed (50 mm/s)	500 N	0.72 mm	0.45 s
Position held (100 mm)	500 N	0.68 mm	0.41 s

The load disturbance test results show that the designed closed-loop control system exhibits good robustness under a 500 N step load. Under both constant velocity and position hold states, the maximum dynamic position deviations are 0.72 mm and 0.68 mm, respectively, and both can quickly recover and stabilize within the allowable error range of ±0.3 mm within 0.45 seconds. These results demonstrate that the PLC-based PID control strategy can effectively suppress external load disturbances and maintain the stability of the system output.

D. COMPARATIVE ANALYSIS

To validate the improvement achieved by the proposed closed-loop control strategy, a comparative experiment was

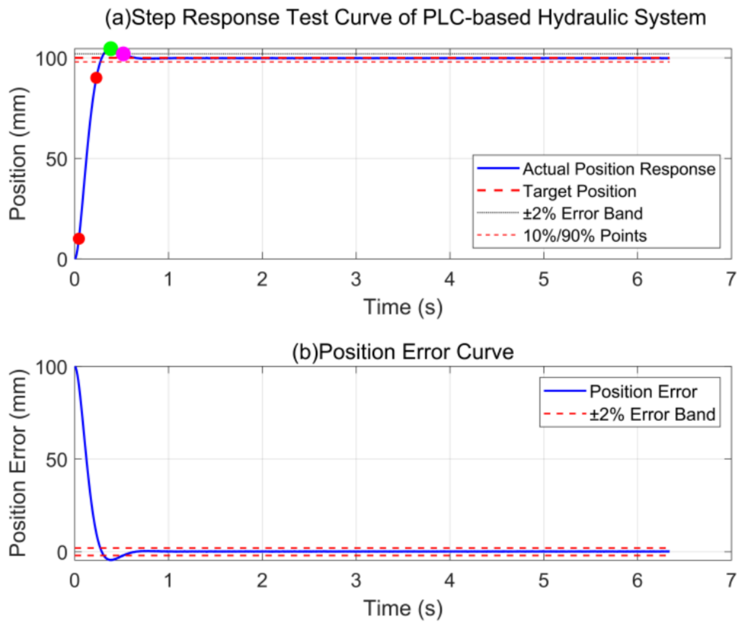

FIGURE 1. Step response characteristic test evaluation

conducted under identical conditions using traditional open-loop control and simple proportional control (P-only). As shown in Table 3, the proposed PID-based closed-loop strategy significantly outperforms the traditional methods across all key performance metrics.

TABLE 3. Performance Comparison of Different Control Strategies

Control Strategy	Steady-State Error (mm)	Overshoot (%)	Settling Time (s)	Recovery Time under 500 N Load (s)
Open-Loop Control	2.85	12.3	1.42	–
Proportional (P-only) Control	0.68	8.7	0.96	0.82
Proposed PLC-Based PID	0.15	4.55	0.518	0.45

The comparative results demonstrate that the proposed strategy reduces steady-state error by 78% compared to P-only control and achieves a 47% reduction in settling time, confirming the effectiveness of the closed-loop PID approach in addressing the limitations of traditional methods.

E. EXPERIMENTAL DISCUSSION

The comparative analysis above quantitatively demonstrates the performance gains of the proposed PLC-based closed-loop PID strategy relative to conventional open-loop and proportional-only control. The improvement can be attributed to the following factors: the closed-loop feedback mechanism continuously compensates for system nonlinearities and external disturbances; the integral action eliminates steady-state error that persists in proportional-only control; and the derivative action provides predictive damping, effectively suppressing overshoot while maintaining rapid response.

Furthermore, the results from the step response and load disturbance tests collectively confirm that the designed control strategy achieves a favorable balance between dynamic responsiveness and steady-state precision. The system exhibits a rapid rise time of 0.186 s with a moderate overshoot of 4.55%, indicating well-damped dynamics. Under a 500 N step load disturbance, the maximum position deviation is contained within 0.72 mm, and the system recovers to the ± 0.3 mm tolerance band within 0.45 s, demonstrating strong robustness against external perturbations. These findings validate that the integration of a well-tuned digital PID algorithm within a PLC-based closed-loop architecture not only addresses the inherent limitations of traditional hydraulic control methods but also provides a practical, reliable solution suitable for high-precision industrial applications.

VII. CONCLUSION

This paper addresses the issues of insufficient control accuracy and stability in machinery hydraulic systems by designing and implementing a PLC-based closed-loop control strategy. Research shows that the combination of the constructed PLC hardware platform and the digital PID control algorithm effectively improves the dynamic response speed and anti-interference capability of the hydraulic system, achieving high-precision position control. This strategy is simple in structure, highly reliable, and possesses good engineering applicability and promotional value. However, this research primarily focuses on parameter tuning under fixed operating conditions. When facing a wider range of load variations and strong nonlinear coupling, the adaptability of the control parameters still has room for improvement. Future work will explore the integration of adaptive and fuzzy PID algorithms on the PLC platform to enhance the system's autonomous adjustment capability under high-speed production conditions, while validating this control strategy across a broader range of hydraulic machinery.

AUTHOR CONTRIBUTIONS

Conceptualization – Hongbing Zeng and Fangyu Pan; methodology – Hongbing Zeng and Fangyu Pan; investigation – Hongbing Zeng and Fangyu Pan; writing-original draft preparation – Hongbing Zeng and Fangyu Pan. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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