A Comprehensive Analysis of PID Control Applications in Automation Systems: Current Trends and Future Directions

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Abstract. Proportional-integral-derivative (PID) control is a reliable control system that is often utilized in engineering practice because to its simplicity, stability, and ease of tuning. The proportional, integral, and derivative terms that make up PID control are crucial for managing a variety of systems across many sectors. These controllers have shown to be particularly successful in scenarios when complete system information is lacking. This essay explores the foundations of PID control and highlights its adaptability to a variety of scenarios, including manufacturing, chemical reactions, and power systems. PID control is continuously changing to satisfy the dynamic demands of modern industry in addition to conventional applications. The investigation covers the most recent research results and sheds light on the difficulties that the PID control area faces. New complications are coming up as the sector develops, necessitating constant improvement of PID control techniques. Ultimately, the story offers suggestions for PID control's future, acknowledging that improvements are required to keep up with the demands of developing technology. The study highlights PID control's ongoing importance as a foundational engineering technique and provides evidence of its flexibility and ongoing significance in influencing the direction of technological advancements across a range of industries.

Keywords: PID Control, Automation Systems, manufacturing, chemical reactions, power systems

1. Introduction

PID (proportional-integral-derivative) control was first introduced around 70 years ago and has since become a mainstay in engineering applications. The proportional, integral, and derivative (PID) control approach is a frequently used feedback control mechanism that is based on these three essential components. This control technique is essential for resolving complicated dynamics issues in a range of engineering systems because of its simplicity, flexibility, and efficacy. PID control is a commonly used industrial automation technique in manufacturing, production processes, and other industrial applications. PID control is now used in industrial automation, although there are still issues with it, including the need for complicated systems, performance optimization, and disturbance immunity [1]. Thus, a thorough examination of the theory and practice of PID control today is particularly important for its advancement.

This paper explores the concept and uses of PID control, a regulatory approach that has been extensively used in engineering for almost seven decades. The definition and mathematical illustration of PID control are first presented in the work, with a focus on the functions of derivative, integral, and proportional tuning parameters. Each component—integral, derivative, and proportional control—is broken down further, offering a thorough explanation of their significance and effects on system behavior. The essay then delves further into the uses of PID control in power systems, chemical processes, and industrial industries. It illustrates how PID control improves system stability, guarantees product quality, and maximizes production efficiency in different sectors using real-world examples. In the final section, the article discusses recent developments in PID control, including its integration with neural networks, model predictive control, virtual sensor technology, and artificial intelligence. The article concludes by proposing future research directions, such as domain specific PID parameter optimization, multi-model PID control, PID integration in networked control systems, and the development of novel adaptive PID control theories. These research directions collectively aim to enhance the adaptability and performance of PID control systems in the continually evolving technological landscape.

2. Principle of PID controller

2.1. Definition and function of PID control

In engineering practice, PID control is one of the most significant control systems and consists of proportional, integral, and differential control. Introduced almost 70 years ago, a major technology in industrial control has been established by this control, owing to its excellent steadiness, simple structure, convenient tuning, and dependable manipulate.

The utilization of PID control comes in handy when the developer does not fully understand the structure and parameters of the system of study, or when there is no precise mathematical model and other control theories may be difficult to apply, a time when the structure and parameters of the system's controllers must be determined by experience and field debugging. The PID control technique is most appropriate when there is a lack of comprehensive knowledge of the system and the object to be charged, or when accurate parameterization cannot be obtained in a systematic manner. In practice, variants of PID control are also used, the classical ones being PI and PD control [2].

A PID controller is a type of linear controller that generates a control output on the basic of deflection between the value set and the practical result. The linear combination of the proportional, integral and derivative components of the deviation forms the PID control system. This controller is named PID due to these three components. The principal schematic is shown in Figure 1 below.

According to the process of PID control, mathematical representation of PID controller is given by:

$$u_{(t)} = K_p \cdot e_{(t)} + K_i \cdot \int_0^t e_{(t)}\, dt + K_d \cdot \frac{de_{(t)}}{dt} \tag{1}$$

where u(t) is the controller's output, e(t) is the current error. and K_p, K_i, K_d are the proportional, integral, and derivative tuning parameters, respectively.

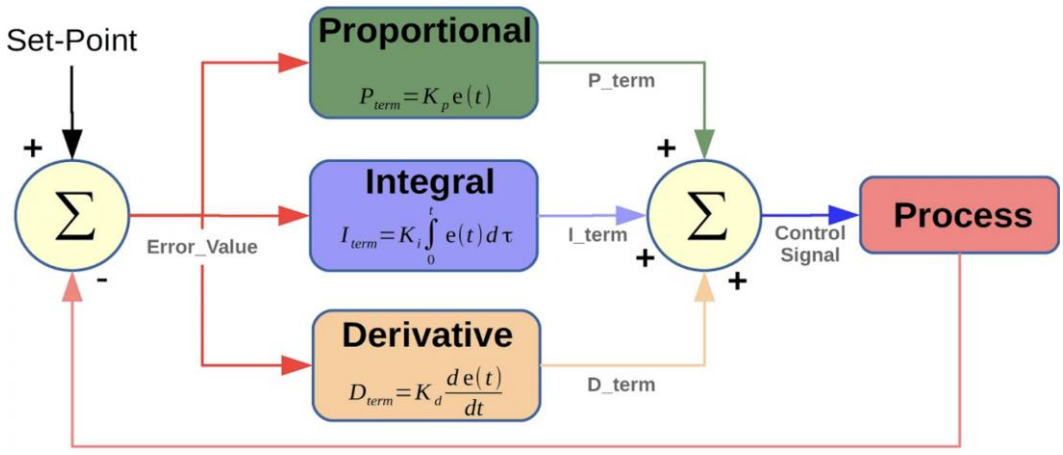


Figure 1. PID control process [2]

2.2. Proportional control

According to the expression, the proportional control is proportional to the current control error

$$u_{(t)} = K_p \cdot e_{(t)} \tag{2}$$

If the proportional value is high, it results in a larger output for the same error. However, an excessively high proportional gain can lead to system instability. Conversely, a low proportional gain yields a smaller output for the same error, making the controller not too sensitive. Yet, if the value of proportional is too small, the support signal is likely to be insufficiently large to correct for interference effects.

2.3. Integral control

Integral control is positively dependent on the integral of the set of control uncertainties. The expression is shown below:

$$u_{(t)} = K_i \cdot \int_0^t e_{(t)}\, dt \tag{3}$$

Integral control reduces the time to converge to setpoint and eliminates some of the steady state error. The higher the integrated charge gain, the shorter the time to converge to setpoint, but since the integral control cumulates whole previous errors, it may result in an overshoot of the return value.

2.4. Derivative control

The role of derivative control is to forecast future values on the basis of the control error. The expression is as follows:

$$u_{(t)} = K_d \cdot \frac{de_{(t)}}{dt} \tag{4}$$

Differential control improves tuning time and system stability [3].

3. Application of PID control in different fields

3.1. Manufacturing industries

In the manufacturing industry, PID control plays a crucial role with its key applications in temperature, flow, pressure, speed, liquid level, quality, gas mixing, and mechanical positioning. By precisely adjusting production line speeds, maintaining constant temperature, pressure, and liquid levels, as well as achieving quality control, PID control contributes to improving production efficiency, product consistency, and system stability. In cases involving gas mixing and mechanical positioning control, PID control ensures accurate mixing ratios and precise positioning of mechanical equipment, further enhancing the competitiveness of the manufacturing industry and the reliability of production processes. There are many examples.

In the manufacturing industry, the quantitative determination of inventory, i.e., the quantity of products a factory needs to produce, has always been a challenging issue. Accumulating too many products can increase maintenance costs and waste storage space. On the other hand, having too few products in stock may lead to a decrease in sales revenue. Therefore, maintaining inventory at an appropriate and constant level is not an easy task. This requires considering the constantly changing business environment and market demands while ensuring product quality and maintaining high levels of customer satisfaction. Additionally, there is a need to minimize costs and maximize profits. Santiago Tosetti proposes an Automatic Pipeline Inventory Production Control System (APIOBPCS) that changes production in response to changes in orders. The cyclicality of the market and the randomness of customer demand are taken into account. The architecture of control system consists of a PID controller and a model for demand prediction on the basis of Kalman filtering. This is a combined approach referred to as PID-APIOBPCS. This dynamic controller works on the principle of using changes in supply and demand in the market to moderate and to stability inventory levels. The results indicate that this method is practically feasible and performs well in production inventory systems, showing positive effects in terms of cost savings and increased customer satisfaction [4].

In addition, hydraulic presses are extensively applied in the areas of mechanical engineering such as hydraulic presses, bending machines, molding technology, etc. as a result of their high power-to-mass ratio, fast response, high stiffness, and high load carrying capacity. However, the complicated construction, high energy consumption, high heat production, high noise, severe vibration, high demand for oil filtering accuracy, and high throttling loss of control valve are the drawbacks of the classic hydraulic press with valve-controlled hydraulic system. Consequently, Jian-ming Zheng

suggested a brand-new kind of servo-hydraulic press that is volume-controlled and powered by a switching reluctance motor (SRM). By addressing the saturation and dead band nonlinearity, time-variation, and time-lag of the SRM direct-drive volumetric control system, a fuzzy PID control approach is developed to enhance the overall performance of the electrohydraulic position servo system. He evaluated the connection between the electrohydraulic position servo system's response characteristics and the PID parameters. Fuzzy inference rules that may adaptively modify the PID parameters are constructed based on the error and error variation. On an SRM direct-drive hydraulic press, step response and cosine tracking simulations and tests were conducted. The outcomes demonstrate that the fuzzy self-tuning PID technique can successfully enhance the volume control electro-hydraulic servo system's position tracking capabilities while also having a strong capacity to suppress external disturbances [5].

Besides the conveyor system has found widespread applications in manufacturing workshops and production lines. Improving production efficiency and cost reductions are directly correlated with the conveyor system's efficacy. While striving for optimal responses, the performance of conveyor systems is susceptible to the influence of both the controller and the DC motor itself. In light of this, Nur Naajihah Ab Rahman delved into the impact of a PID controller, fine-tuned using the Ziegler-Nichols method, on the conveyor system's functionality. To substantiate the efficacy of the proposed controller and tuning method in enhancing conveyor system performance, a comparative analysis was conducted against a DC motor operating without any controller. This assessment was carried out on a prototype of a linear conveyor system. The outcomes underscore that the implementation of a PID controller significantly elevates the performance of the DC motor in the conveyor system, outperforming its non-controlled counterpart [6].

3.2. Chemical industry

In chemical processes, PID control (Proportional-Integral-Derivative control) plays a crucial role by precisely regulating temperature, pressure, and flow. This optimization enhances reaction efficiency, improves product quality, and ensures the system's steady and secure functioning. This control method not only contributes to increased production efficiency but also reduces energy consumption, providing a reliable automation solution for chemical production.

Chemical facilities utilize heat exchanger systems extensively because of their ability to tolerate a broad range of pressures and temperatures. Temperature management of the exit fluid is vital since the primary function of the heat exchanger system is to transfer heat from the hot fluid to the cooler fluid. Due to inherent deficiencies in traditional control techniques, in order to regulate the temperature of the heat exchanger system's output fluid, Yuvraj Bhushan Khare designed an internal model-based PID controller using model-based control technology. The developed controller is impervious to load and process disruptions, equipment saturation, and nonlinear impacts, and can quickly bring the output fluid's temperature down to the predetermined setpoint. The proposed internal model-based PID controller exhibits an 84% improvement in overshoot and a 44.6% increase in settling time when compared to classical controllers. [7].

In addition to this, the industrial application of Coupled Tank Systems (CTS) has gained extensive use, particularly in the chemical process industry. The entire process involves pumping liquid, storing it in tanks, and subsequently pumping it to another tank to achieve the desired level. A specific height or level needs to be maintained for the liquid. Businesses or industries may suffer losses if the water level is not kept at the specified height. The management of chemical mixing and storage tank liquid levels is a frequent control problem in process industries. It is necessary to adjust the liquid flow into and out of the tanks to achieve the desired constant liquid level. Jaafar used a PID controller as a result to regulate the appropriate liquid level in CTS. He evaluated the system's performance using metrics including overshoot, steady-state error, rising time, and settling time. Finally, his achievement indicates that employing an appropriate PID tuning method can enhance the performance of CTS [8].

Biogas is an essential renewable energy source for reducing greenhouse gas emissions; nevertheless, the inclusion of contaminants like sulfides, ammonia, or siloxanes makes it difficult to

utilize effectively. Among these contaminants, hydrogen sulfide (H2S) is the most important one, with concentrations varying from 0.01% to 2% by volume. The first step towards realizing the energy potential of biogas is to remove H2S since it is toxic and caustic, and burning it releases sulfur dioxide. Anaerobic bio trickling filters (BTFs) are a crucial technique for desulfurizing biogas. Although anaerobic bio trickling filters have demonstrated a significant capacity for removing hydrogen sulfide (H2S), accurate nitrate dosage monitoring is still required. Biogas is an essential renewable energy source for reducing greenhouse gas emissions; nevertheless, the inclusion of contaminants like sulfides, ammonia, or siloxanes makes it difficult to utilize effectively. Among these contaminants, hydrogen sulfide (H2S) is the most important one, with concentrations varying from 0.01% to 2% by volume. The first step towards realizing the energy potential of biogas is to remove H2S since it is toxic and caustic, and burning it releases sulfur dioxide. Anaerobic bio trickling filters (BTFs) are a crucial technique for desulfurizing biogas. Although anaerobic bio trickling filters have demonstrated a significant capacity for removing hydrogen sulfide (H2S), accurate nitrate dosage monitoring is still required. The results show that the bio trickling filter operating on a PID control scheme has good stability and resistance to the evaluated perturbations and disturbances. Changing the output H2S concentration from 25 to 200 ppmv may not affect the control system's functionality. The desulfurized biogas can be immediately fed into an internal combustion engine, or a solid oxide fuel cell equipped with a zeolite purification unit. [9].

3.3. Power system

PID control has various key applications and significant effects in power systems. Its primary applications include voltage regulation to ensure stable voltage output, frequency regulation to maintain the system frequency within an appropriate range, reactive power compensation to enhance power system efficiency, and maintaining system stability in the face of load variations. Furthermore, PID control effectively suppresses potential oscillations in power systems, enhancing the stability and dependability of the system. When taken as a whole, these applications guarantee the power systems' effective operation and give the electrical grid a steady and dependable power production.

One of the most valuable renewable energy sources is wind power. However, there are more links between new transmission lines, power plants, and other power systems due to human activity and the ongoing growth of electrical demands, particularly in industrial facilities. Due to this, linked power systems are experiencing problems with frequency and power oscillation as well as power variations in connecting lines. These can lead to many outcomes, including equipment damage, disconnections, loss of multiple lines, regional islands, and overloading transmission lines. Additionally, the penetration of wind energy can also impact system stability. As a result, Gaber Magdy has suggested a unique, PID-based moth swarm algorithm (MSA) for the system. In the Egyptian power system (EPS), this method is used to coordinate the use of superconducting magnetic energy storage (SMES) technology, also known as auxiliary LFC, and load frequency control (LFC), taking into account high wind power penetration (HWPP) as part of the system's future planning. The tactic is employed to mitigate power fluctuations from wind power plants, correct for variations in EPS frequency, and keep conventional generators from producing more power than intended during load disruptions. Final results indicate that this algorithm exhibits strong robustness in all scenarios with different load distributions, contributing significantly to improving the stability of the power system [10].

Frequency variations in each region and power fluctuations on the linked power system contact lines can result from tiny, abrupt changes in any one section of an interconnected power plant. Since frequency variations can directly impact power system operation, stability, reliability, and efficiency, frequency should be maintained almost constant to guarantee good power system operation. Excessive frequency variations have the potential to harm machinery, impair load capacity, overload transmission lines, and compromise the effectiveness of system protective mechanisms. The term "load frequency control" (LFC) may refer to any control system that can be applied to an interconnected power system and is capable of restoring the frequency and contact line power in each

region to either the original set point value or a very near substitute. All control systems applicable to an interconnected power system that can successfully restore the frequency and contact line power in each region to the initial set point value or very near to it following an abrupt load shift are collectively referred to as load frequency control (LFC) schemes. Dharmendra Jain therefore used the PID controller to adjust the two zonal power systems' LFC. The findings demonstrate that during a sudden load change, the zonal frequency can be quickly restored to its predefined value or very close to it by appropriately adjusting the PID controller's parameters, all the while maintaining the contact line power within an acceptable tolerance range [11].

For nuclear power plants, traditional control strategies perform poorly under load-following conditions due to the complex nonlinear nature and time-varying parameters of nuclear reactors. In addressing this challenge, Cheng Liu proposed combining a fuzzy logic controller (FLC) with a PID controller to form a fuzzy-PID system. This innovative approach, further enhanced through secondary optimization of FLC's membership functions (MF) using a genetic algorithm, successfully achieves effective control of nuclear reactor power. Not only does this novel control strategy improve performance and precision, but it also demonstrates practical simplicity for complex, nonlinear nuclear reactor power control systems [12].

4. Conclusion

An understanding of the function and applicability of PID control is given in this article. It is extensively employed in engineering and is crucial to manufacturing, chemical reactions, power systems, and overall system productivity, quality, and stability. This article attempts to offer a thorough introduction of PID control through a thorough and in-depth discussion, highlighting its significance in practical engineering and how to combine new technologies to further improve the performance and flexibility of PID control systems. It is extremely important for the development of PIDs in the future.

In conclusion, recent developments in PID control have witnessed innovative approaches to enhance its efficacy. The integration of PID with neural networks, specifically Convolutional Neural Networks (CNN) and Recurrent Neural Networks (RNN), proves beneficial in adapting to complex, nonlinear systems. Additionally, the combination of PID with Model Predictive Control (MPC) enhances accuracy in multivariable systems. The introduction of virtual sensor technology addresses the challenge of unmeasurable variables, improving control accuracy. Incorporating artificial intelligence for online PID parameter tuning further enhances adaptability.

Future trends in research will focus on improving PID control systems. Domain-specific parameter optimization, multi-model PID control for a range of operating points, PID investigation in networked control systems, and the creation of novel adaptive PID control theories to take nonlinear aspects into account are some examples of this. In order to ensure that PID systems can adapt to the dynamic needs of automation systems in a constantly changing environment, these initiatives are essential to their evolution.

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