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An Adaptive PID Controller for Precisely Angular DC Motor Control

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ABSTRACT

In industrial production as well as academic research, developing a precise automatic control system is one of the most concerned topics. Moreover, applicability of optimizing controllers with low-cost hardware is now still on going. However, time-varying uncertainties and external disturbances in the system dynamics are barriers in development of outstanding controllers. In this paper, we propose a simple-yet-efficient adaptive control method for accurate tracking-control problems of DC motors. Structure of the controller is designed based on a Proportional-Integral-Derivative (PID) control framework. For significantly improving quality of the control system, a nonlinear-spatial adaptation law is proposed to reasonably adjust the control parameters based on information of the control error acquired. The effectiveness of this method has been verified using proper theoretical analyses based on the Lyapunov approach. The possibility of the proposed controller was first carefully investigated on simulation environment. Comparative experiments were then performed on a real-time test rig and were analyzed to confirm the feasibility of the intelligent control method for practical applications.

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1. Introduction

Accurate position control of DC motors is a critical topic for industrial automation systems such as robotic arms that require high accuracy and robustness. There are many servo-motor manufactures nowadays that serve the need of precise motion control, but price of the drivers and motors are not friendly, especially for learning and researching purposes. Instead, we usually use small DC motors with incremental encoders, although they have some disadvantages such as weight, responsiveness, and nonlinear characteristics.

In recent decades, a number of research have been studied to improve the performance of the PID controllers [1-3], [11-12] using intelligent approaches such as Ant system algorithms and fuzzy logic methods [4-5]. By using online and offline tuning methods, excellent control results were achieved. In the offline tuning phase, one could indeed calculate nominal control coefficients based on Zeigler – Nichols measurement, they were then optimized with an Ant-colony algorithm. In the online running phase, the system was re-optimized using the operating control error recorded to adjust the control coefficients throughout a fuzzy inference engine. In fact, since the fuzzy-logic inference mechanism is mostly based on experience of the operators, this approach is limited as universal ability. Another research direction of the intelligent controllers is biologically inspired with Genetic Algorithm and Bacterial Foraging Optimization Algorithm (BFOA) [6-7] that mimic natural processes such as hybridization, reproduction, mutation, natural selection, etc. Simulation of these natural processes has advantages of giving optimal solutions to the problems, but it requires more time and a large number of samples for high-precision results. Intelligent PID controllers using neural networks applied to artificial muscles [8], or inverted Pendulum systems [9], are interesting approaches. In these controllers, the PID control parameters are somehow automatically increased to reduce control errors, which explicitly improve the control performance. However, lack of intensive consideration of learning rules in steady-state time could make the system instable in a long time used.

In this paper, we introduce a new intelligent PID controller for effectively minimizing the system error using non-linear adaptation laws. The proposed controller is structured mainly based on a conventional PID control framework. For well treat unpredictable impacts from working environment, the control gains are yet integrated into an adaptation mechanism under highly nonlinear guarantee rules. The most suitable control gains are found to meet the best allowed error domain through designed laws. Stability of the closed loop system is proved using proper automatic control theories, and feasibility of the proposed controller has been verified by simulations and comparative real-time experiments.

The rest of the paper is organized as follows: A mathematical model of the control plant is briefly derived and identified in **Section 2**; The methodology to obtain the sub-optimal PID control gains and how to design the adaptive control rules are discussed in **Section 3**. Validation results on simulation and real-time experiments are presented in **Section 4**. The paper is concluded in **Section 5**.

2. Problem Statement

A general model of the DC motor could be expressed in the following state-space form [**13**], [**10**]:

$$\ddot{x} = -a\dot{x} + bu + d \tag{1}$$

where x is the motor angle, a and b are systematic parameters, u is the control input, d in a nonlinear function denoting feedforward disturbances.

Remark 1: Note that a and b are positive yet exactly unknown. Control objective is to find out a proper control signal (u) to force the system output (x) track to a desired trajectory (x_d). However, the system parameters a, b, and the disturbance d are unknown and might vary during the working process. Besides, other requirements for the control design is model-free, simple, and easy to implementation. Thus, designing such a controller satisfying the predefined conditions is not trivial work.

3. Adaptive Controller

In this section, design of the proposed adaptive PID controller is presented for high control performance of the DC motor model (1) by dealing with shortcoming of conventional ones. Obviously, effect of the conventional PID controller on the plant is analyzed. New advanced features are then proposed along with proper theoretical proofs.

3.1. Conventional PID Controller

From the model (1), it can be observed that the velocity and acceleration of the DC motor are bounded [13-14]. Thanks to the special natures, the following conventional PID controller could be employed to ensure the stability of the closed-loop system:

$$u = K_p e + K_i \int edt + K_d \frac{de}{dt} \tag{2}$$

where $e \equiv x_d - x$ is the control error, K_p, K_i, K_d are the positive bounded control gains.

Practical control effect of the closed-loop system was confirmed throughout a vast of industrial applications [3], [5-6], [9]. Its stability was also verified by previous state-of-the-art works [14-15], or using the linear control theories [10], [16-18]. Please note that the given proofs [14-15] require constraints of the control gains depending on the system parameters. Meanwhile, such the linear theories cannot directly apply to the nonlinear model (1). Here, we employ a more general method for proving the closed-loop control effectiveness. Consider the following Lyapunov function:

$$L = 0.5\left(\dot{e} + \frac{K_p^2}{4K_i}e + \frac{K_p}{2}\int edt\right)^2 \tag{3}$$

Its time derivative along with the dynamics (1) and the linear controller (2) is

$$\dot{L} = -\frac{2K_i}{K_p}\left(2L - \delta\sqrt{2L}\right) \tag{4}$$

where $\delta \equiv \frac{K_p}{2K_i}\left(\ddot{x}_d + a\dot{x} + \left(\frac{K_p^2}{4K_i} - K_d + \frac{2K_i}{K_p}\right)\dot{e}\right)$ is a bounded term.

Remark 2: The result (4) confirms the stability of the closed-loop system for all positive control gains. However, its transient performance and steady-state error depend on the specific gains chosen. Thus, one needs an intelligent selection method for the given demand.

3.2. Design of Adaptive PID Controller

From the aforementioned analyses, we propose an intelligent controller based on the ordinary PID controller. The main idea is that the controller will collect the current control errors to make proper changes on the control gains. After the error gets into a predefined region, the gains will be decreased to release the control system.

We propose the following gain learning mechanism:

$$\begin{cases} \dot{K}_p = \beta_p\left(e^2 \operatorname{sgn}(e^2 - e_0)\right) \\ \dot{K}_i = \beta_i\left(e^{1/3}\left(\int edt\right)\operatorname{sgn}(e^2 - e_0)\right) \\ \dot{K}_d = \beta_d\left(e^{5/3}\dot{e}\operatorname{sgn}(e^2 - e_0)\right) \end{cases} \tag{5}$$

where β_p, β_i and β_d are positive learning gains, and e_0 is a predefined steady-state error.

Remark 3: As seen in the adaptation rule (5), the proportional gain *Kp* will be increased when the control error is outside of the expected region. Whenever the accumulated error has the same sign with the current error, it means that the system needs more energy to remove the offset control error, the integral control gain *Ki* is creased and vice versa. Meanwhile, the derivative control gain *Kd* will be decreased when the error and its time derivative have opposite sign that reveals convergence of the closed-loop system. A further interested point can be observed is that the learning speeds of the gains are different depending on the current distance from the region. Hence, the law could effectively reduce the overshoot of the control performance. The designing idea of the adaptive PID controller is summarized in **Figure 1**.

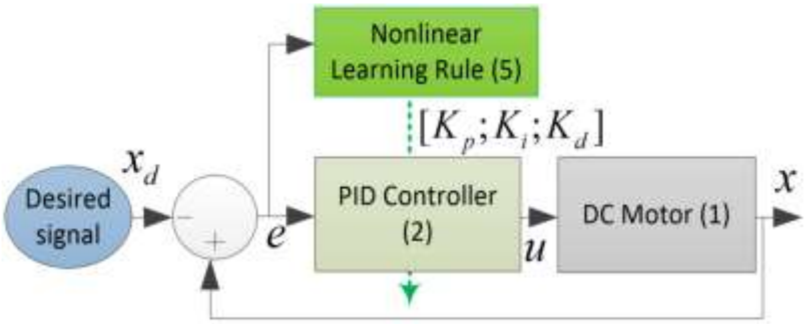

Figure 1. *Control diagram of the adaptive-PID controller.*

4. Validation Results

The controller was carefully verified on simulation and real-time experiments. Its advantages and disadvantages were clearly evaluated by comparing with a conventional PID controller on the same testing conditions. A test rig including a DC motor, driver, incremental encoder, and electronic controller, was built as presented in **Figure 2** for the verification. The obtained data are then intensively discussed thereafter.

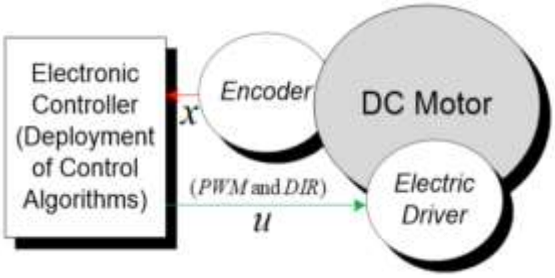

Figure 2. *Schematic of the real-time control system.*

4.1. Simulation Results

To conduct simulation tests, the mathematical model (1) of the control plant was identified based on real-time data. Step response of the testing system was performed, and its data are presented in **Figure 3**. Employing an identification toolbox in Matlab [19], the mathematical model could be approximately determined as follows:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{7.5}{0.0069s^2 + 2.026s} \tag{6}$$

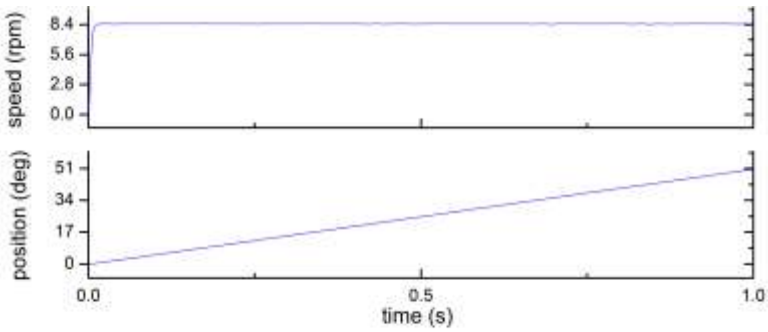

Figure 3. *Step Response of the open-loop real-time system.*

The proposed controller was applied on the detailed model (6). The simulation results accomplished are shown in **Figures 4-5**. Excellent control error could be observed in **Figure 4** with very short transient time of 0.05s and without overshoot. To this end, the control gains were varied in nonlinear manners to force the control error go into a desired region regardless of unknown environments. The learning of the K_p and K_i gains was respectively designed for fast transient time and the best steady-state phase, while that of the K_d acted as a trade-off between the two phases.

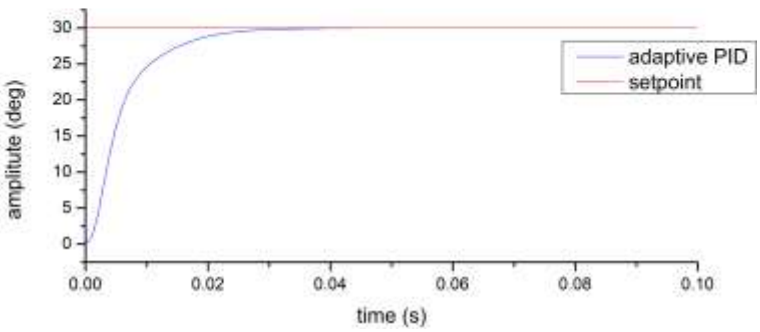

Figure 4. *System response of the adaptive PID controller with step signal.*

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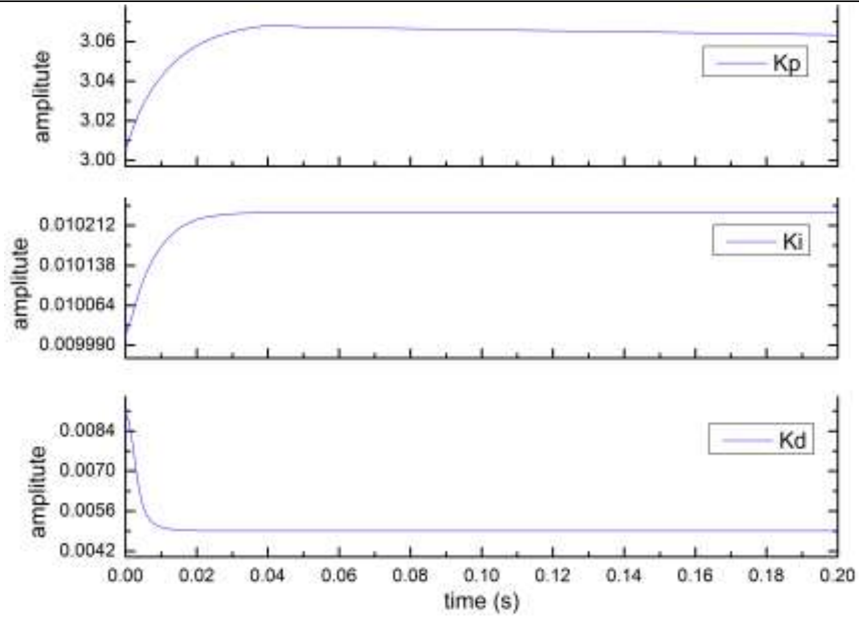


Figure 5. *Behaviors of the adaptive gains in the step response.*

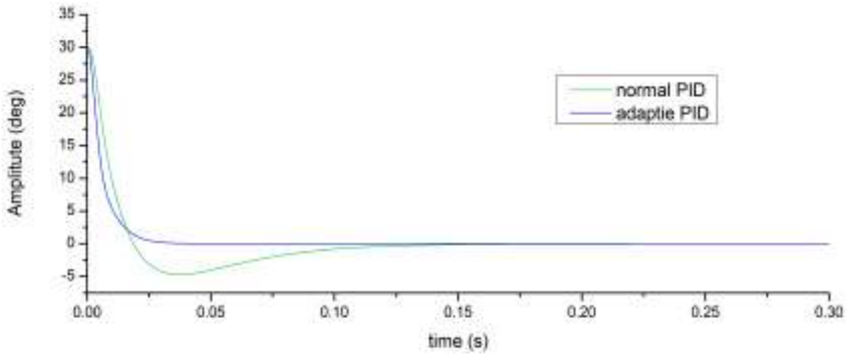
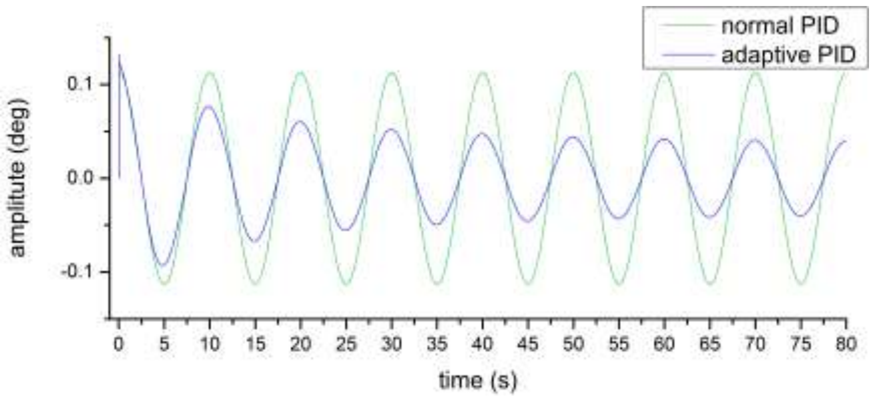


Figure 6. *Control errors of the controllers for step control in simulation.*

For a fair comparison of the proposed control method, gains of the conventional PID controller were next automatically tuned by an optimal toolbox supported by the Matlab software. The suboptimal ones were applied to the model (6). Comparative control errors are plotted in **Figure 6**. Outstanding steady-state errors were achieved by the two controllers, but the transient performances were different at which small overshoot and longer settling time were resulted in by the conventional one even though in the suboptimal working condition.



(a)

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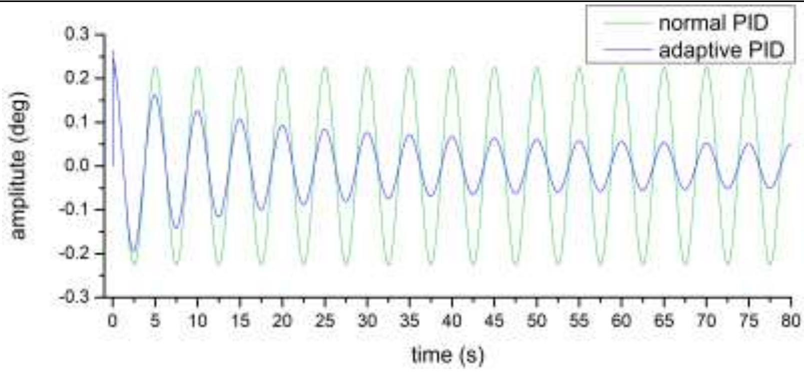
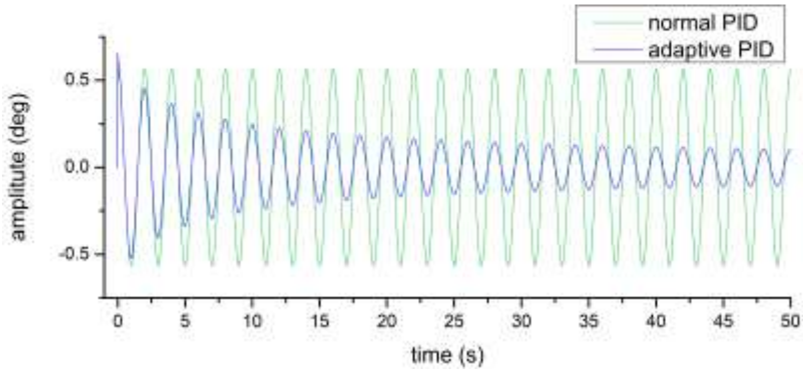


(b)



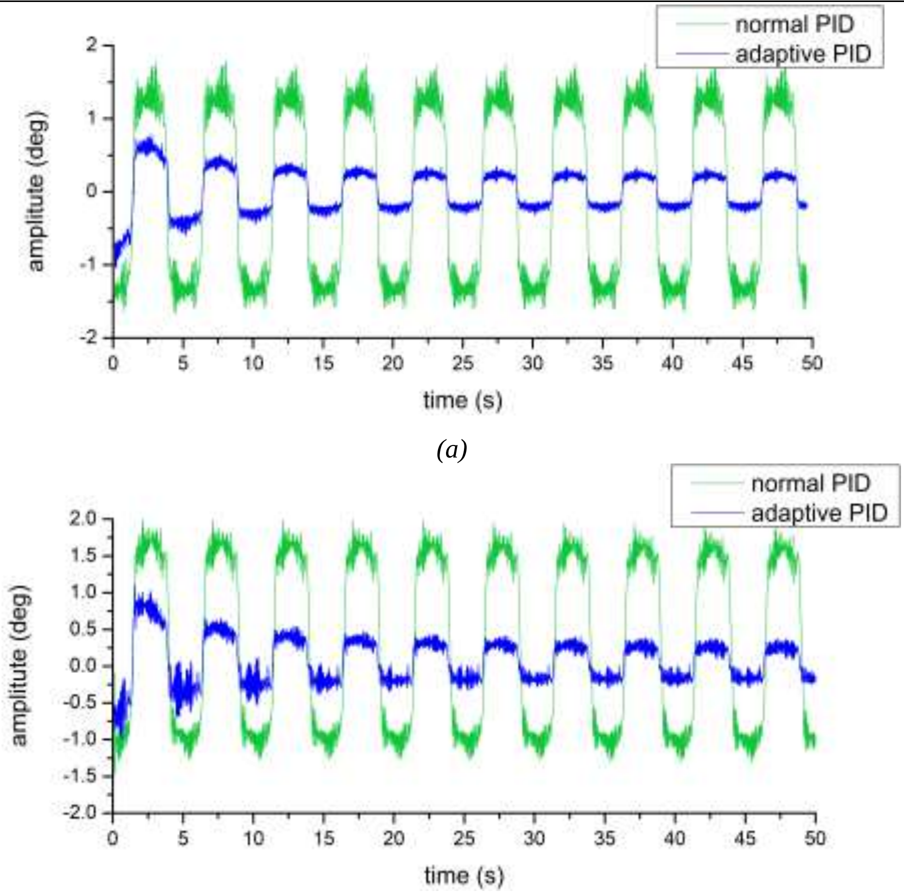
(c)

Figure 7. *Control errors of the controllers with various sinusoidal reference inputs: a) 0.1 Hz; b) 0.2 Hz; and c) 0.5 Hz.*

To further investigate the control performance of the proposed controller on time-varying signals, simulations with sinusoidal signals of 0.1, 0.2, and 0.5 Hz with an amplitude of 30 degrees were conducted. The testing results are depicted in **Figure 7**. The control performance of the sub-optimal PID controller was degraded with higher reference frequencies due to the fixed gains used. As observed in the figure, the control error of the proposed controller was improved over time and approached to the desired zone. Hence, its control performance was significantly enhanced as comparing to the hard control method.

4.2. Real-time Experimental Results

In fact, the model (6) just presented for one certain case of the real-time system. Its parameters might change in different working conditions. To validate feasibility of the proposed approach, real-time experiments were performed in two cases: with/without a static load. The reference input was the sinusoidal with the frequency of 0.2Hz and the amplitude of 30 degrees. The real-time data obtained are shown in **Figure 8**. By applying the conventional PID controller, the error was significantly changed in two working modes: with no load and with load, the PID error was ±1.5 (deg) and in a range of [-1.1; 1.9] (deg), respectively. The error drifting problem could be attenuated by the intelligent controller: with no load and with load, the APID error was ±0.3 (deg) and in a range of [-0.27; 0.33] (deg), respectively. Furthermore, the learning ability could be easily observed by the history of the APID control errors, which tended to converge to a small possible value. Here, outperformance of the flexible PID controller over the conventional one has been strongly confirmed.



(b)

Figure 8. *Comparative control errors obtained by the controllers in the real-time experiments of the sinusoidal reference signals in different testing conditions: a) without a load and b) with a load*

5. Conclusions

This paper proposes an intelligent PID controller for position control of DC motor systems. The adaptive algorithm is designed based on a conventional PID framework. Their parameters are activated by proper learning rules to minimize the control error in various working conditions. Effectiveness of the proposed controller were carefully discussed by theoretical proofs and simulation as well as real-time experimental results. The key advantages of the control algorithm are model-free, easy to apply, and high control performance. However, the control accuracy could be further improved for high-frequency profiles by employing dynamical-based compensation terms. Integrating the new features to the APID controller could open new research in the future.

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