International Journal for Housing Science and Its Applications
Publish August 4, 2025. Volume 46, Issue 3 Pages 3507-3518

https://doi.org/10.70517/ijhsa463296

Combining PID control with microcontroller programming for intelligent control of inverted pendulum in linear level

Yalei Shang[1,*]
[1] School of Artificial Intelligence, Hebi Polytechnic, Hebi, Henan, 458030, China
Corresponding authors: (e-mail: 20020420@hbzy.edu.cn).

Abstract The linear one-level inverted pendulum system is a typical nonlinear unstable system, but it has an important role in the application of microcontroller programming. Aiming at the nonlinear and natural instability of linear one-level inverted pendulum, this paper proposes an adaptive fuzzy PID control algorithm after completing the mathematical modeling of linear one-level inverted pendulum, and designs a fuzzy adaptive controller by synthesizing the stability theory of Li Yapunov to satisfy the stability and control effect. The adaptive fuzzy PID control algorithm in this paper is the core algorithm, and the intelligent control system programmed by microcontroller is constructed. In the system simulation experiment, the overshoot of the displacement, lower pendulum angle and upper pendulum angle of the adaptive fuzzy PID control system of this paper is about 0.02m, 0.012rad, 0.005rad, and the adjustment time is about 3s, 2.5s, 2.5s, and the results of the experimental simulation are better than that of the conventional PID control system as a comparison, which shows an excellent performance of the system.

Index Terms linear primary inverted pendulum, PID control, fuzzy adaptive controller, microcontroller programming control

I. Introduction

The inverted pendulum system is a typical nonlinear, strongly coupled, multivariable and naturally unstable system, and is also one of the typical experimental equipments in universities [1]. In the whole process of control, the inverted pendulum system can effectively reflect certain key issues, such as the key issues of system calmness, robustness, followability and tracking [2], [3]. Many experts and scholars utilize the linear one-level inverted pendulum system to test the correctness of various control theories and algorithms [4]. Therefore, the linear one-level inverted pendulum system is widely used in control theory scientific research [5], [6]. The control strategy of the inverted pendulum is extremely similar to the tricks performed by acrobats balancing on the top bar, which is extremely interesting. Therefore, many abstract control theories such as stability, controllability of the system and the system's immunity to interference, etc., can be visually simulated by the inverted pendulum device in the laboratory [7]-[9]. Therefore, the system has been very popular with automatic control scholars.

PID controller has the advantages of simple principle, easy to use, adaptability, robustness and reliability, which precisely solves a series of characteristics of inverted pendulum at linear level [10], [11]. Many scholars have studied the combination of PID control and linear primary inverted pendulum system. For example, literature [12] stabilizes the inverted pendulum in vertical position by four different control algorithms such as PID through the established dynamic mathematical model of the inverted pendulum system. Literature [13] investigated the magnetic bearing using a linear model, analyzed the stability of various linear controllers, and examined the performance of the proposed PID controller based on laboratory data. Literature [14] designed four different PID neural network (PIDNN) controller structures for the intelligent control of an inverted pendulum (IP) system and optimized the parameters and weights using an ant colony optimization algorithm. Literature [15] constructed a self-balancing inverted pendulum system and utilized a PID controller to control the stability of the inverted pendulum and it was found that the PID was adjusted by adjusting the proportional gain for oscillations, and then adjusting the integral and derivative gains for a smoother and faster response. Literature [16] in his study introduces a nonlinear PID controller that employs a “flash search” evolutionary tuning method to control an x-z inverted pendulum system. Literature [17] designed a multi-PID controller control system to track the spatial inverted pendulum trajectory (SIP) and used the Big Bang-Big Crunch optimization algorithm to tune the PID parameters, and the simulation results confirmed the effectiveness of the proposed method. Literature [18] proposed an adaptive fuzzy proportional-integral-derivative (AF-PID) controller for an inverted pendulum system and demonstrated that the controller can reduce the oscillation of the inverted pendulum system and improve the system performance. Literature [19] proposed a stabilizing PID controller for inverted pendulum system based on genetic algorithm, which effectively suppresses the perturbations and additive disturbances caused by parameter vibrations of the linear level inverted pendulum control system, and outperforms the conventional PID controller in stabilization time and peak overshoot.

The linear level inverted pendulum has poor control accuracy when using traditional PID control, which cannot meet the accuracy requirements of intelligent control programmed by microcontroller. In order to solve this problem, this paper establishes the mathematical modeling of the linear inverted pendulum, adopts the control method combining fuzzy control and adaptive control, and proposes the adaptive fuzzy PID control algorithm. Based on the fuzzy controller, the adaptive law is solved according to the feedback control and adjusted parameter vectors to eliminate the deviation of the output from the set value. The fuzzy quantities are defuzzified by the maximum affiliation method, and the control quantities which are transformed from fuzzy quantities to exact quantities are obtained, and the fuzzy control table is obtained. The fuzzy control table is obtained by synthesizing the Liapunov stability theory and further adding adaptive control on the basis of the fuzzy controller. Based on the Gaussian-type affiliation function and the definition of adaptive law, the fuzzy logic system of the adaptive fuzzy controller is designed and the boundary control is added, which makes the fuzzy controller in a globally stable condition even under the closed-loop state. The effectiveness of the adaptive fuzzy PID control algorithm proposed in this paper is examined through linear level inverted pendulum simulation experiments. At the same time, the simulation experiment of microcontroller programming intelligent control system is carried out to explore the performance of the microcontroller programming intelligent control system constructed in this paper.

II. Mathematical modeling of inverted pendulums at the linear level

A linear primary inverted pendulum consists of a trolley, a pendulum and other components, which are freely connected to each other [20]. The conditions for a linear first-order inverted pendulum to swing are that the pendulum rod of the lead hammer is able to swing freely in a plane; the cart needs to move freely on a guide rail (without considering friction, etc.). It is assumed that the angle of rotation and moment are positive in the counterclockwise direction. In addition, we specify the following symbols: M is the mass of the pendulum, O is the coordinate of the rotation point, m is the mass of the trolley, D is the center of mass coordinates of the pendulum, L is the length of the pendulum, l is the distance from the point O to the point D, f_1 is the friction factor between the trolley and the guide rail, J is the moment of inertia of the pendulum, f_2 is the frictional resistance moment coefficient of the pendulum around the axis of rotation, F is the external force, and φ is the angle between the pendulum and the vertical upward direction, and x is the displacement of the trolley from the origin.

II. A.Pendulum kinematics analysis and mathematical modeling

Establish a right-angle coordinate system, and let the coordinates of the rotation point O and the center of mass D be $(O_x, O_y) = (x, 0)$ and $(D_x, D_y) = (x - l\sin\varphi, l\cos\varphi)$, respectively.

So the force in the horizontal direction of the pendulum is:

$$F_x = Mx'' - Ml\varphi''\cos\varphi + Ml\varphi'^2\sin\varphi \tag{1}$$

Then the moment balance equation of the pendulum around the point O is:

$$(J + Ml^2)\varphi'' = Mgl\sin\varphi - f_2\varphi' + Mx''l\cos\varphi \tag{2}$$

II. B.Kinematic analysis and mathematical modeling of a cart

The force on the cart in the horizontal direction is:

$$F - f_1 x' - F_x = mx'' \tag{3}$$

Let $T = m + M$, $V = J + Ml^2$, and $U = Ml$, then the set of differential equations for the motion of a first-order inverted pendulum is:

$$\begin{pmatrix} T & -U\cos\varphi \\ -U\cos\varphi & V \end{pmatrix}\begin{pmatrix} x'' \\ \varphi'' \end{pmatrix} = \begin{pmatrix} -f_1 & -U\varphi'\sin\varphi \\ 0 & -f_2 \end{pmatrix}\begin{pmatrix} x' \\ \varphi' \end{pmatrix} + \begin{pmatrix} 0 \\ Ug\sin\varphi \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \end{pmatrix}F \tag{4}$$

The differential equation for a first order inverted pendulum is obtained by linearizing the matrix equation (4) near the stability point:

$$\begin{pmatrix} T & -U \\ -U & V \end{pmatrix}\begin{pmatrix} x'' \\ \varphi'' \end{pmatrix} = \begin{pmatrix} -f_1 & 0 \\ 0 & -f_2 \end{pmatrix}\begin{pmatrix} x' \\ \varphi' \end{pmatrix} + \begin{pmatrix} 0 \\ Ug \end{pmatrix}\begin{pmatrix} x \\ \varphi \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \end{pmatrix}F \tag{5}$$

Taking the pendulum angle as the output, the transfer function is:

$$\frac{\Phi(s)}{U(s)}=\frac{Ug}{(-U-TV)s^4-(Tf_2-Vf_1)s^3+(-TU-f_1f_2)s^2-Uf_1gs} \tag{6}$$

The state equation of the system is obtained from equation (5) as:

$$\begin{pmatrix} x' \\ x'' \\ \varphi' \\ \varphi'' \end{pmatrix}=\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{f_1V}{Q} & \frac{Ug}{Q} & -\frac{Uf_2}{Q} \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{Uf_1}{Q} & -\frac{TUg}{Q} & -\frac{Tf_1}{Q} \end{pmatrix}\begin{pmatrix} x \\ x' \\ \varphi \\ \varphi' \end{pmatrix}+\begin{pmatrix} 0 \\ \frac{V}{Q} \\ 0 \\ -\frac{U}{Q} \end{pmatrix}F \tag{7}$$

where $Q=TV-U^2$.

For practical control, we use the acceleration of the motor, not the force, and have $J=\frac{1}{3}Ml^2$ for a pendulum with a uniform mass distribution, so that a first-order inverted pendulum can be physically modeled.

III. Adaptive fuzzy PID control algorithm

Linear primary inverted pendulum has been a popular research object in the field of control because of its nonlinearity, high order, and instability. PID control still occupies a relatively large proportion in the practical field applications due to its simple design principle, easy to realize, better reliability and robustness. However, PID control relies on linear system and cannot effectively deal with nonlinear control requirements, and traditional PID control is difficult to achieve the desired control effect. For this reason, this chapter will combine fuzzy control with PID control to form an adaptive fuzzy PID and propose an adaptive fuzzy PID control algorithm [21].

III. A. PID control theory

The research object of classical control theory is mainly single-input single-output system, PID controller is widely used in practical control because of its simple structure, easy to adjust, and does not need to establish an accurate model of the system.

III. A. 1) PID control principle analysis

The physical model of the actual system is known from the previous analysis: $G(s)=\frac{\Phi(s)}{A(s)}=\frac{6.122}{s^2-60}$ ($\Phi(s)$ is the output of the system, $A(s)$ is the input to the system), and for the inverted pendulum system the output is the angle of the pendulum whose equilibrium position is vertically upward case. The block diagram of the system control structure is shown in Fig. 1, where $K_C(s)$ is the controller transfer function and $G(s)$ is the transfer function of the controlled object. $K_C(s)=K_Ds+K_P+\frac{K_I}{s}$ (K_P is the proportional gain, K_I is the integral gain, K_D is the differential gain), and by adjusting the parameters of the PID controller, in order to get a satisfactory control effect.

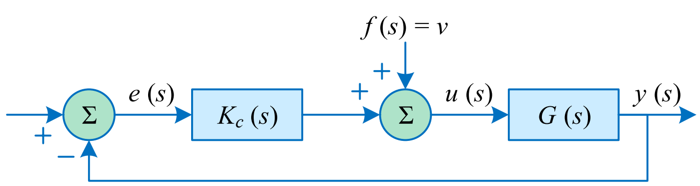


Figure 1: System control structure diagram

In this way the control quantity is only the angle of the pendulum, the displacement of the cart is not controlled, if it is a single closed loop, after standing up the pendulum, the cart moves in one direction until it hits the limit signal.

III. A. 2) Stabilization conditions for the fixed position of an inverted pendulum

To stabilize the inverted pendulum at a fixed position, it is necessary to add closed-loop control of the motor position, thus forming a double closed-loop control of the pendulum angle and motor position. After the upright pendulum is manifested as the motor moves left and right in a fixed position to control the pendulum from falling.

III. B. Fuzzy controller design

n -order nonlinear systems:

$$\begin{cases} x^{(n)} = f(x, \dot{x}, \cdots, x^{(n-1)}) + g(x, \dot{x}, \cdots, x^{(n-1)})u \\ y = x \end{cases} \tag{8}$$

In Eq. (8), u is the input to the system; y is the output of the system with $u, y \in R$, and both $f(\cdot)$ and $g(\cdot)$ are unknown continuous functions. $(x_1, x_2, \cdots, x_n)^T$ belongs to R^n, which is an n-dimensional state vector of the system and is assumed to be measurable.

III. B. 1) Input and output variables and fuzzy language description

According to the nonlinear system in Eq. (1), the input variables of the controller are the error e and the rate of change of the error e_c, and the output variable is the control variable u. Where e represents the tracking error and is the difference between y_d and y. e_c is the first-order derivative of e, representing the rate of change of the error, and u is the amount of change of the system output. Since the error e, the rate of change of the error e_c and the control variable u are constantly changing during the actual system control process, it is necessary to establish a conversion relationship between the fuzzy and exact quantities. In order to improve the steady state accuracy of the system, e is classified into 8 levels and its fuzzy set is $\{NB, NM, NS, NO, PO, PS, PM, PB\}$, and the fuzzy sets of e_c and u are $\{NB, NM, NS, 0, PS, PM, PB\}$, in which these 8 fuzzy linguistic variables are, PB (positive large), PM (positive medium), PS (positive small), PO (positive zero), NO (negative zero), NS (negative small), NM (negative medium), and NB (negative large).

III. B. 2) Fuzzy rule design of the controller

The purpose of fuzzy control is to eliminate the deviation of the output for the set value [22]. When selecting the control quantity, the principle is that when the error e is relatively small, the stability of the system should be the main focus, and the control quantity is selected to prevent the system from overshooting; when the error e is relatively large, the main focus of selecting the control quantity is to eliminate the error as soon as possible.

The fuzzy rules of this controller can also be described using fuzzy conditional statements as follows:

(1) if $e = NB$ or NM and $e_c = NB$ or NM then $u = NB$;
(2) if $e = NB$ or NM and $e_c = NS$ or 0 then $u = NB$;
(3) if $e = NB$ or NM and $e_c = PS$ then $u = NM$;
……
(21) if $e = PN$ or PB and $e_c = PM$ or PB then $u = PB$.

III. B. 3) Assignment of fuzzy variables

According to the fuzzy conditional statement of the above fuzzy controller and the conversion relationship between exact and fuzzy quantities, assuming that the change interval of error e is $[-6, 6]$, then the domain of error e is $\{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\}$. The error variation e_c is the same as the domain of the error e, and the interval of variation of the control variable u is $[-7, 7]$. Determining the thesis domains of the fuzzy variable error e, the rate of change of error e_c and the control variable u is equivalent to determining the corresponding degrees of affiliation of the fuzzy linguistic variables.

III. B. 4) Determination of fuzzy control table

According to the fuzzy conditional statement the corresponding fuzzy relationship can be determined, if the fuzzy relationship of the first statement is:

$$r = [NB_e + NM_e] \times NB_u \cdot [NB_{e_c} + NM_{e_c}] \times NB_u \tag{9}$$

From the affiliation of the fuzzy variables, the control quantity is obtained as:

$$u_1 = \min\left\{\max\left[\mu_{NB_e}(i)\right]\max\left[\mu_{NB_{e_c}}(j) \cdot \mu_{NB_u}(x)\right]\right\} \tag{10}$$

where $\mu_{NB_e}(i)$, $\mu_{NM_e}(i)$ and $\mu_{NB_{ec}}(i)$, $\mu_{NM_{ec}}(i)$ are the affiliation degrees of the corresponding elements of μ_{NB_e}, μ_{NM_e} and $\mu_{NB_{ec}}$, $\mu_{NM_{ec}}$ corresponding to the affiliation of i and j elements. From this, the fuzzy relationship of the remaining statements can be obtained, then the set of fuzzy control quantities is:

$$u = u_1 + u_2 + u_3 + \cdots + u_{21} \tag{11}$$

The fuzzy quantities are defuzzified by the maximum affiliation method, i.e., the control quantities are selected as the elements in the fuzzy subset with the largest affiliation. In this way the control quantities which are converted from fuzzy quantities to exact quantities can be obtained and thus the fuzzy control table can be obtained.

A simple fuzzy controller can be designed by the above 4 steps.

III. C. Adaptive fuzzy controller design

The fuzzy adaptive controller, which is based on fuzzy controllers with the addition of adaptive control, has the main objective of obtaining an adaptive law and a feedback control that makes the system globally stable. The fuzzy logic system that defines the adaptive fuzzy controller is:

$$\hat{f}_{\theta f}(x) = \frac{\prod_{i=1}^{N} \mu_{F_i^k}(x_i)}{\sum_{k_i=1}^{M_i} \prod_{i=1}^{N} \mu_{F_i^k}(x_i)} \theta_f^T \tag{12}$$

$$\hat{g}_{\theta g}(x) = \frac{\sum_{i=1}^{N} \mu_{F_i^k}(x_i)}{\sum_{k_i=1}^{M_i} \sum_{i=1}^{N} \mu_{F_i^k}(x_i)} \theta_g^T \tag{13}$$

where $\mu_{F_i^k}(x_i)$ is a Gaussian-type affiliation function and:

$$\mu_{F_i^k}(x_i) = a_i^k \exp\left(-\frac{1}{2}\left(\frac{x_i - \overline{x}_i^k}{\sigma_i^k}\right)^2\right) \tag{14}$$

where $k_i = 1, 2, 3, \cdots, M_i$, $\theta_f \in R$ and $\theta_g \in R$ are adaptive laws and are constants used to regulate the parameters.

Based on Eq. (12) and Eq. (13) the control law u of the fuzzy logic system, which cannot meet the requirements of Liapunov's stability theory, so a boundary control u_d is added and is:

$$u_d = I^* \operatorname{sgn}(e^T Pb) \frac{1}{gk(x)} \left[\left| \hat{f}_{\theta f}(x) \right| + f^U(x) + \left| \hat{g}_{\theta g}(x) u_c \right| + g^U(x) u_c \right] \tag{15}$$

where we have $I^* = 1$ when $\frac{1}{2} e^T Pe$ is greater than the specified constant, and zero otherwise.

So that the system state is within a bounded range and satisfies Lyapunov's theoretical stability. Then the control law is:

$$u = u_c + u_d \tag{16}$$

where u_c is the equivalent control, which is the output of the fuzzy logic system. The error equation obtained by substituting Eq. (12) into Eq. (8) is:

$$e = Ee + b\left[\hat{f}(x \mid \theta_f) - f(x) + (\hat{g}(x \mid \theta_g) - g(x)) u_c - g(x) u_d \right] \tag{17}$$

Among them:

$$E = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & 1 \\ -t_n & -t_{n-1} & -t_{n-1} & \cdots & -t_2 & -t_1 \end{bmatrix}, b = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \tag{18}$$

In the equation of E, $T = (t_n, t_{n-1}, \cdots, t_1)^T \in R^n$ is polynomial:

$$h(s) = S^n + t_1 S^{n-1} + \cdots + t_n \tag{19}$$

Coefficient terms of their solutions.

The adaptive law used in this paper is:

$$\dot{\theta}_f = -\beta_1 e^T Pb \frac{\prod_{i=1}^{N} \mu_{F_i^k}(x_i)}{\sum_{k_i=1}^{M_i}\sum_{i=1}^{N} \mu_{F_i^k}(x_i)} \tag{20}$$

$$\dot{\theta}_g = -\beta_2 e^T Pb \frac{\prod_{i=1}^{N} \mu_{F_i^k}(x_i)}{\sum_{k_i=1}^{M_i}\sum_{i=1}^{N} \mu_{F_i^k}(x_i)} u_c \tag{21}$$

For simplicity, define a $\xi(x)$ as:

$$\xi(x) = \frac{\prod_{i=1}^{N} \mu_{F_i^k}(x_i)}{\sum_{k_i=1}^{M_i}\sum_{i=1}^{N} \mu_{F_i^k}(x_i)} u_c \tag{22}$$

Verify the stability of this controller with respect to this system according to the Liapunov stability theory. The proof considers the following Lyapunov function:

$$V = \frac{1}{2} e^T \mathbf{P} e + \frac{1}{2\beta_1}(\theta_f - \theta_f^*)^T(\theta_f - \theta_f^*) + \frac{1}{2\beta_2}(\theta_g - \theta_g^*)^T(\theta_g - \theta_g^*) \tag{23}$$

Let there be $\theta_f - \theta_f^* = \phi_f$ and $\theta_g - \theta_g^* = \phi_g$, which can be obtained from Eq. (23), Eqs. (20)~(22):

$$\begin{aligned}
\dot{V} &= \frac{1}{2} e^T P \dot{e} - g(x) e^T Pbu_d + \frac{1}{\beta_1}\phi_f^T\left[\dot{\theta}_f + \beta_1 e^T Pb\xi(x)\right] \\
&+ \frac{1}{\beta_2}\phi_g^T\left[\dot{\theta}_g + \beta_2 e^T Pb\xi(x)u_c\right] \\
&= -\frac{1}{2} e^T Pe - g(x) e^T Pbu_d = -\frac{1}{2} e^T Pe - \left|e^T Pb\right| \\
&\left[\left|\hat{f}_{\theta_f}(x)\right| + f(x) + \left|\hat{g}_{\theta_g}(x)u_c\right| + g(x)u_c\right] \\
&- \frac{g}{gk(x)}\left[\left|\hat{f}_{\theta_f}(x)\right| + f^U(x) + \left|\hat{g}_{\theta_g}(x)u_c\right| + g^U(x)u_c\right] \\
&\le -\frac{1}{2} e^T Pe \le 0
\end{aligned} \tag{24}$$

From the proof process, it can be concluded that the designed adaptive law satisfies the Liapunov stability theory. So the fuzzy adaptive controller designed by the above steps can make the system globally stable in the closed loop state.

IV. Linear level inverted pendulum simulation experiment

In this chapter, the simulation experiment of linear level inverted pendulum will be carried out to verify the effectiveness of the adaptive fuzzy PID control algorithm proposed in this paper. The experimental environment is a digital computer, using Matlab software, the adaptive fuzzy PID control algorithm in this paper is compared with the fuzzy control algorithm, traditional PID and other algorithms to carry out simulation experiments.

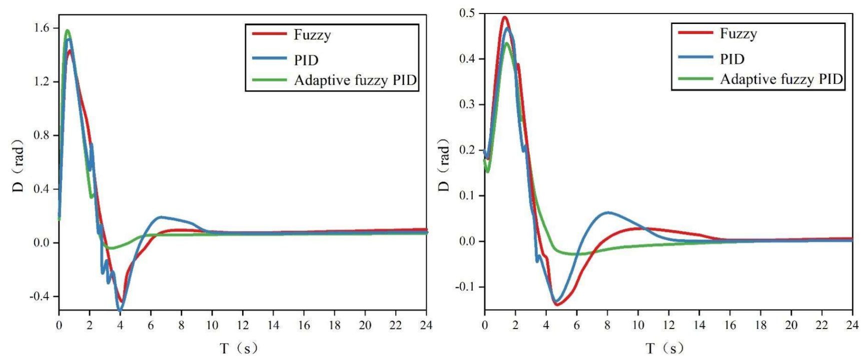
IV. A. Experimental setup

In Matlab environment, the motion of the cart on the belt is modeled and the relevant parameters of the cart are defined and entered. The controller is built in Similink module and the corresponding S-functions are written in Matlab. The simulation is carried out again for 30s and the up and down swing angles and displacements of the trolley are recorded and plotted.

The actual parameters of the cart are defined as: cart mass $m_0 = 1.096kg$, pendulum 1 mass $m_1 = 0.2kg$, pendulum 2 amount $m_2 = 0.1kg$, pendulum 1,2 moment of inertia around the origin $J_1 = 0.015kg\square m^2$, distance from the center of rotation of pendulum 1 to the center of mass of the rod $l_1 = 0.06m$, distance from the center of rotation of pendulum 2 to the center of mass of the rod $l_2 = 0.13m$, coefficient of friction between the cart and the guideway $f_0 = 17.19$, acceleration of gravity $g = 9.801m/s^2$. The initial position of the cart is {r,z1,z2}={0.2,0.1,0.2}.

IV. B. Randomized Perturbation Simulation Experiments

In order to investigate the fuzzy, PID, adaptive fuzzy PID three kinds of control methods of anti-disturbance ability, the design of the controller, in a random position to impose a perturbation signal, compared with the addition of the perturbation signal, the cart performance indicators change amplitude. In the system running to the second s, applying the disturbance signal, considering the maximum change of the trolley's pendulum angle, selecting the upper and lower pendulum angles of the trolley for simulation experiments, and obtaining the curves of the trolley's pendulum angle as shown in Fig. 2, and Figs. (a) and (b) correspond to the upper and lower pendulum angles, respectively. As can be seen from the figure, after applying the disturbance signal at 2 s of system operation, the upper and lower pendulum angles of the adaptive fuzzy PID control system return to the stable state at 3 s. The upper and lower pendulum angles of the fuzzy control and PID control require 3.5 s and 4.0 s, respectively, to return the system to the stable operation state. After the system is gradually stabilized in a wide range, the upward and downward swing angles of the fuzzy PID-controlled cart are still significantly better than those of the fuzzy control and PID control. This verifies that the adaptive fuzzy PID algorithm in this paper has better suppression of external perturbations and has better algorithm performance.



(a)Upper swing angle (b)Lower pendulum angle

Figure 2: Upper and lower swing angle contrast simulation curve

V. Microcontroller Programming Intelligent Control System

The microcontroller programmed intelligent control system consists of STM32F103 microcontroller, MG513 encoder gearmotor, first-order inverted pendulum mechanism, and WDD35D4 angle sensor of several major parts of the closed-loop system. The overall block diagram of the first-order inverted pendulum is shown in Figure 3.

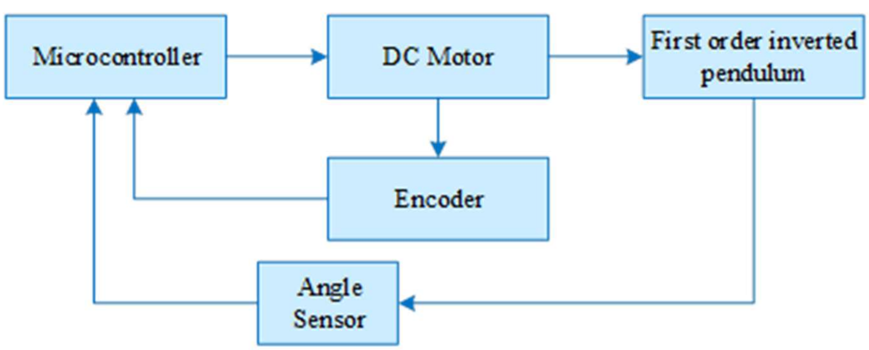


Figure 3: Overall framework of the system

V. A. How the system works

In the previous chapter, this paper verifies the effectiveness of the adaptive fuzzy PID control algorithm proposed in this paper through the linear one-level inversion simulation experiment. The designed microcontroller programmed intelligent control system will be the control system with this paper's adaptive fuzzy PID control algorithm as the core algorithm, and the basic function of human-computer interaction will be realized by OLED display.

The first-order inverted pendulum adopts the WDD35D4 angle sensor as the sensor of the angle loop PID controller, which detects the inclination of the pendulum and transmits the detected real-time angle analog to the STM32F103C8T6 microcontroller, which carries out the A/D conversion and real-time processing, and calculates the deviation from the given value, and then applies the positional PID control algorithm to derive the inclination control output signal. The positional PID control algorithm is applied to derive the tilt control output signal. At the same time, the MG513 encoder is used as the sensor of the position loop PID controller, which detects the position of the base and transmits the detected real-time position information to the microcontroller. The microcontroller uses the positional PID control algorithm to obtain the positional control output signal, and the two control signals are combined to obtain the final control signal, which controls the actuator MG513 encoder geared motor to make the base move horizontally on the belt. Thus, the pendulum of the inverted pendulum and the base are in a relatively stationary, i.e. vertically upward state.

V. B. Processing module

This paper uses STM32F103C8T6 microcontroller from STMicroelectronics, which is a 32-bit microcontroller based on ARM Cortex-M kernel STM32 series, featuring fast response speed, multi-functionality and low power consumption.

V. C. Detection module

The detection module is divided into the tilt detection part of the pendulum and the position detection part of the base. The tilt detection is done by WDD35D4 angle sensor, and the position detection is done by MG513 encoder geared motor.

The WDD35D4 angle sensor is mainly used for tilt detection. Its hard shell is used to protect the sensor from damage. At the same time using resin and conductive substances mixed with conductive plastic as a resistive material. Through the selection of the housing and resistive materials, the WDD35D4 angle sensor is characterized by high resolution and long mechanical life.

VI. Microcontroller Programming Intelligent Control System Simulation Experiment

In the previous chapter, the proposed adaptive fuzzy PID control algorithm was used as the core algorithm to construct the microcontroller programming intelligent control system. In this chapter, the proposed adaptive fuzzy PID control, conventional PID control and LQR quadratic optimal control will be used to simulate the microcontroller programming intelligent control system at the same time to check the performance of the microcontroller programming intelligent control system based on adaptive fuzzy PID control.

VI. A. Experiments comparing adaptive fuzzy PID control with PID control

In this section, the conventional PID control is compared with the adaptive fuzzy PID control method in this paper to do comparison experiments, and the performance of inverted pendulum control at the linear level of the microcontroller programmed intelligent control system based on conventional PID control and microcontroller programmed intelligent control system based on adaptive fuzzy PID control is analyzed in terms of the angle of pendulum, displacement, lower pendulum angle and upper pendulum angle through random perturbation experiments.

VI. A. 1) Comparative analysis of pendulum angles

The pendulum angle curves of the conventional PID control system and the adaptive fuzzy PID control system of this paper are specifically shown in Fig. 4. From the figure, it can be seen that with PID control, the output of the system will produce a large overshoot, and the output fluctuates greatly after being perturbed, but finally it can be restored to the steady state without static difference. After the use of fuzzy PID control, the output curve of the system becomes smooth, the overshoot is obviously reduced, and the output fluctuation after perturbation does not change much, and the system performance is improved.

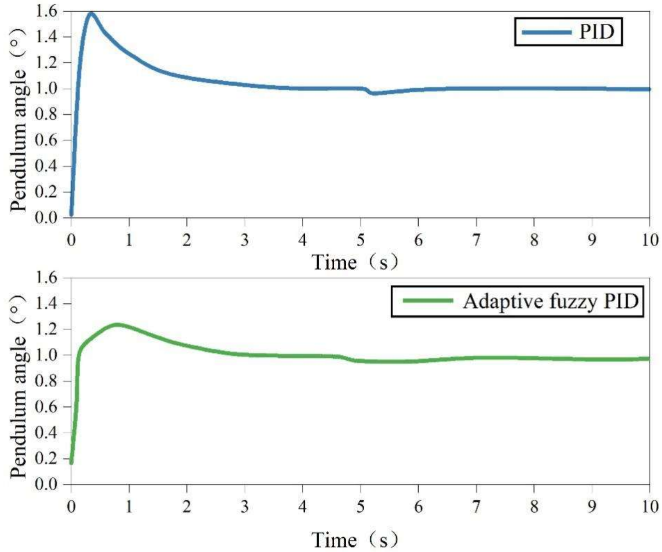
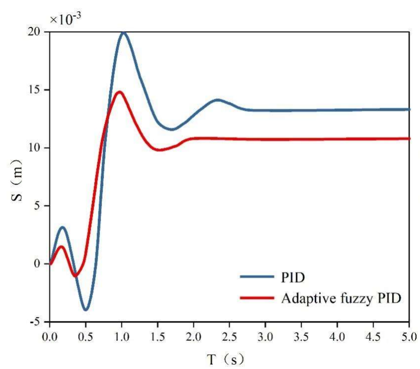


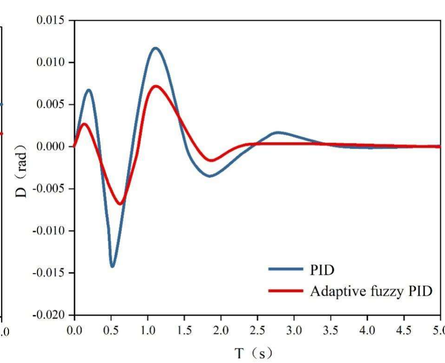
Figure 4: Pendulum angle curve

VI. A. 2) Comparative Analysis of Displacement, Pendulum Angle, and Upper Pendulum Angle

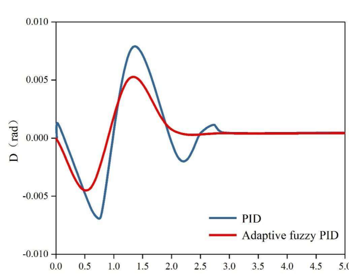
The simulation curves of the cart control of the adaptive fuzzy PID control system and the conventional PID control system in this paper are specifically shown in Fig. 5, and Figs. (a) to (c) are the displacement, lower pendulum angle, and upper pendulum angle, respectively. From the figure, it can be seen that the overshoots of the displacement, lower pendulum angle and upper pendulum angle of the system based on conventional PID control are about 0.06 m, 0.016 rad, 0.008 rad, and the regulation time is about 3.5 s, 3.5 s, 3 s. The overshoots of the displacement, lower pendulum angle, and upper pendulum angle of the system using the adaptive fuzzy PID control system are about 0.02 m, 0.012 rad, 0.005 rad, and 0.012 rad, respectively. rad, 0.005 rad, and the adjustment time is about 3 s, 2.5 s, 2.5 s. Obviously, the system in this paper further realizes the intelligent stabilization control of the inverted pendulum by using the adaptive fuzzy PID control algorithm.



(a)Displacement



(b)Lower pendulum angle

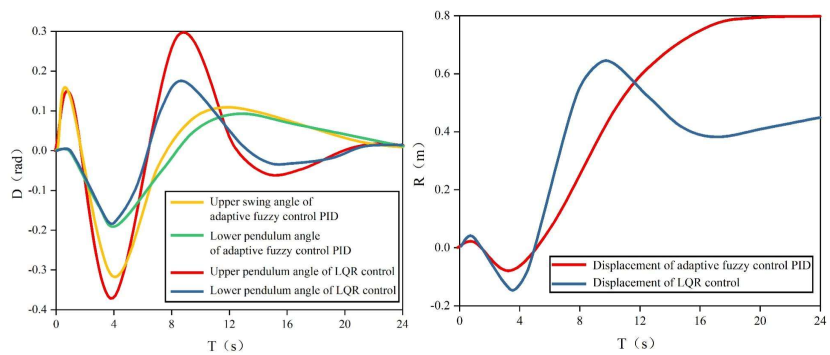


(c)Upper swing angle

Figure 5: Simulation curve

VI. B. Comparison experiment of adaptive fuzzy PID control and LQR

In order to examine the good or bad performance of the adaptive fuzzy PID control system, LQR quadratic optimal control system in this paper, as well as whether there is a local optimization problem, the control performances of the two are compared, and the simulation curves are obtained as shown in Fig. 6. Figure (a) shows the upper and lower swing angles, and figure (b) shows the displacement. From the figure, it can be seen that the control system of the LQR method has a smaller variation of the upper and lower pendulum angles and displacement compared with the adaptive fuzzy PID, and the control performance is better than that of the adaptive fuzzy PID method. After the system runs for a period of time under the action of the controller, the dynamic performance of the system is not as ideal as that in the first 3 s. The change amplitude of the upward and downward pendulum angles increases compared with that in the first 3 s, and the rise time of the displacement curve of the trolley becomes longer. It shows that the control system performance of LQR method is characterized by local optimization. The adaptive fuzzy PID control system has smaller overshooting and regulation time compared with the LQR method. After running for 3s, the swing angle and displacement of the trolley change significantly less than the LQR method, and the control effect is better than that of the LQR controller.



(a)Upper swing angle and lower swing angle (b)Displacement

Figure 6: Comparative experiment of LQR and adaptive fuzzy PID

After adding a continuous 2 s perturbation to the system during operation, the system's pendulum angle response curve is shown in Fig. 7. The LQR control system has basically failed after receiving the continuous perturbation. However, the adaptive fuzzy PID control system in this paper can still maintain the stability of the system in a small range, which indicates that the adaptive fuzzy PID in this paper possesses better anti-disturbance ability than LQR, and is more suitable for the occasions where the environmental parameters are easy to change.

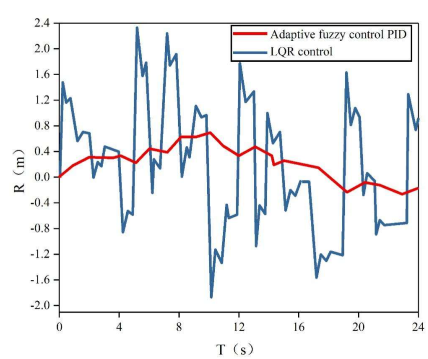


Figure 7: Comparative simulation of fuzzy PID and LQR after being disturbed

The above experimental results, with the adaptive fuzzy PID control algorithm proposed in this paper as the core algorithm of the microcontroller programming intelligent control system, can better realize the stability control of the level inverted pendulum, with better system performance.

VII. Conclusion

This paper establishes the mathematical modeling of linear one-level inverted pendulum and proposes the adaptive fuzzy PID control algorithm to effectively deal with the nonlinear control demand of linear one-level inverted pendulum, and constructs the intelligent control system programmed by MCU with the proposed adaptive fuzzy PID control algorithm as the core algorithm. The effectiveness of this paper's adaptive fuzzy PID control algorithm is examined through the simulation experiment of linear one-level inverted pendulum. When the system runs for 2s, the upper and lower pendulum angles of the linear inverted pendulum with adaptive fuzzy control in this paper return to the stable state at 3s, while the fuzzy control and PID control as a comparison need 3.5s and 4s respectively. Obviously, the adaptive fuzzy PID control algorithm proposed in this paper has a better control effect in the linear inverted pendulum.

Simulation experiments are carried out on the microcontroller programmed intelligent control system established in this paper with the adaptive fuzzy PID control algorithm as the core to explore the performance of the system. Compared with the conventional PID control system, the output of the adaptive fuzzy PID control system in this paper has a smoother pendulum angle curve, and the overshooting amount is obviously reduced compared with the conventional PID control system, and the output fluctuation does not change much after being perturbed. In addition, the overshooting amount of displacement, lower pendulum angle and upper pendulum angle is about 0.02m, 0.012rad, 0.005rad, and the adjustment time is about 3s, 2.5s, 2.5s, and the performance of displacement, lower pendulum angle and upper pendulum angle control is still significantly better than that of conventional PID control system. Compared with the LQR quadratic optimal control system, the adaptive fuzzy PID control system in this paper has smaller overshooting amount and regulation time compared with the LQR method, and the swing angle and displacement of the cart after running for 3s are significantly smaller than that of the LQR method, which has better control performance. The LQR control system basically fails after adding continuous 2s perturbation, but the adaptive fuzzy PID control in this paper can still maintain a small range of stability of the system. In conclusion, the microcontroller programmed intelligent control system constructed in this paper based on the proposed adaptive fuzzy PID control algorithm has better system performance and can better realize the stable control of the inverted pendulum.

References

[1] Boubaker, O. (2013). The inverted pendulum benchmark in nonlinear control theory: a survey. International Journal of Advanced Robotic Systems, 10(5), 233.

[2] Kafetzis, I., & Moysis, L. (2017). Inverted Pendulum: A system with innumerable applications. School of Mathematical Sciences.

[3] Waszak, M., & Łangowski, R. (2020). An automatic self-tuning control system design for an inverted pendulum. IEEE Access, 8, 26726-26738.

[4] Özalp, R., Varol, N. K., Taşci, B., & Uçar, A. (2020). A review of deep reinforcement learning algorithms and comparative results on inverted pendulum system. Machine Learning Paradigms: Advances in Deep Learning-based Technological Applications, 237-256.

[5] Leng, X. (2024). Second-order sliding mode optimization control of an inverted pendulum system based on fuzzy adaptive technology. Frontiers in Mechanical Engineering, 10, 1458852.

[6] Liu, C., Wang, Y. F., & An, Y. H. (2024, July). Stability Analysis and Controller Design of First-Order Inverted Pendulum with Time-Varying Delay. In 2024 14th Asian Control Conference (ASCC) (pp. 786-791). IEEE.

[7] Li, Y., Feng, J., Wang, R. Y., Chen, H. S., & Gong, Y. (2023). Study on Control of Inverted Pendulum System Based on Simulink Simulation. International Journal of Advanced Engineering Research and Science, 10, 12.

[8] Gao, H., Li, X., Gao, C., & Wu, J. (2021). Neural network supervision control strategy for inverted pendulum tracking control. Discrete Dynamics in Nature and Society, 2021(1), 5536573.

[9] Irfan, S., Mehmood, A., Razzaq, M. T., & Iqbal, J. (2018). Advanced sliding mode control techniques for inverted pendulum: Modelling and simulation. Engineering science and technology, an international journal, 21(4), 753-759.

[10] Yoshikawa, N., Suzuki, Y., Kiyono, K., & Nomura, T. (2016). Intermittent feedback-control strategy for stabilizing inverted pendulum on manually controlled cart as analogy to human stick balancing. Frontiers in computational neuroscience, 10, 34.

[11] Kharola, A. (2016). A PID based ANFIS & fuzzy control of inverted pendulum on inclined plane (IPIP). International Journal on Smart Sensing and Intelligent Systems, 9(2), 616.

[12] Okubanjo, A., & Oyetola, O. (2019). Dynamic mathematical modeling and control algorithms design of an inverted pendulum system. Turkish Journal of Engineering, 3(1), 14-24.

[13] Psonis, T. K., Nikolakopoulos, P. G., & Mitronikas, E. (2015). Design of a PID controller for a linearized magnetic bearing. International Journal of Rotating Machinery, 2015(1), 656749.

[14] Mohsen, Z. S., & Mohamed, M. J. (2023). PID neural controller design for nonlinear inverted pendulum system. International Journal of Intelligent Engineering and Systems (INASS), 16(6), 783-798.

[15] Lim, Y. Y., Hoo, C. L., & Wong, Y. M. F. (2018, February). Stabilising an inverted pendulum with PID controller. In MATEC Web of Conferences (Vol. 152, p. 02009). EDP Sciences.

[16] Özmen, N. G., & Marul, M. (2022). Stabilization and tracking control of an xz type inverted pendulum system using Lightning Search Algorithm tuned nonlinear PID controller. Robotica, 40(7), 2428-2448.

[17] Wang, J. J., & Kumbasar, T. (2018). Optimal PID control of spatial inverted pendulum with big bang–big crunch optimization. IEEE/CAA Journal of Automatica Sinica, 7(3), 822-832.

[18] Abut, T., & Soyguder, S. (2022). Two-loop controller design and implementations for an inverted pendulum system with optimal self-adaptive fuzzy-proportional–integral–derivative control. Transactions of the Institute of Measurement and Control, 44(2), 468-483.

[19] Pratheep, V. G., Priyanka, E. B., Thangavel, S., & Gomathi, K. (2021). Genetic algorithm–based robust controller for an inverted pendulum using model order reduction. Journal of Testing and Evaluation, 49(4), 2441-2455.

[20] Bingyou Liu,Jinwen Hong & Lichao Wang. (2019). Linear inverted pendulum control based on improved ADRC. Systems Science & Control Engineering,7(3),1-12.
[21] Yukang Jin,Zhenhao Gao,Zhiqin Cai & Haijun Peng. (2025). Attitude control method for tilt-trirotor UAV based on adaptive fuzzy PID. Journal of Physics: Conference Series,2977(1),012082-012082.
[22] Abdulbasid Ismail Isa,Mukhtar Fatihu Hamza & Mustapha Muhammad. (2019). Hybrid Fuzzy Control of Nonlinear Inverted Pendulum System. CoRR,abs/1910.07995.