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Controlling the Position of the DC Motor using PID, and the Sliding Mode Algorithm

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ABSTRACT

With the development of information technology and smart technology to meet the Industrial Revolution 4.0, and to meet life requirements. Automatic control devices require high-precision control quality. Therefore, in this paper, we focus on researching the Sliding mode controller to improve the control quality compared to PID controller. First, the sliding mode control is designed using the Lyapunov algorithm. Next, the process of simulating the position signal of a DC motor with a PID controller is compared with a sliding mode control to prove the effectiveness of the proposed controller.

Keywords: DC motor, PID controller, Fuzzy PID controller, Sliding Mode controller

1. Introduction

Small DC motors are used in tools, toys, and household appliances. In retail, the applications of DC motors include conveyors and turntables, while in an industrial setting, large DC motor uses also include braking and reversing applications. DC motors are accurately applied to control mechatronic systems such as precise control of angular position is very crucial for robotic applications shown in (Paul et al., 2007; Wang et al., 2022). Authors (Paul et al., 2007), propose a new technique of combining the existing low-cost geared DC motor with the IR sensor to form a closed-loop system to control a precise angular position with high torque and to reduce current. The authors (Wang et al., 2022), applied traditional control algorithms to cancel automatic noise often with many adjustable parameters and complex adjustment problems to achieve fast, accurate control

of angles. With (Jiang & Zhou, 2019), the author applies a fast and accurate control scheme with high durability. The author proposes an integrated control method for the permanent magnet synchronous motor system by combining the extended state observation (ESO) technique with fast terminal sliding mode (FTSM) control. FTSM ensures fast convergence speed and ESO can estimate interference accurately. The proposed method has a robust response and good noise rejection properties compared to other sliding mode methods. In addition to precise motor position control, many authors researched precise speed control using many different algorithms such as researchers focus on studying control systems using PID controllers were shown in (Al-Mustansiriyah University, Baghdad, Iraq & Mezher, 2019; Maung et al., 2018; Moulahcene et al., 2022; Saad, 2021). The author (Al-Mustansiriyah University, Baghdad, Iraq & Mezher, 2019) used a PID (proportional, integral and derivative) controller to control the feedback angle position of the DC motor to achieve the set angle position quickly through the Arduino microcontroller board to control the 12V brushed Namiki DC motor. L298N dual H-bridge motor driver is applied to execute the pulse width modulation (PWM) signal and to drive the direction control. The implementation code is considered to generate the PWM output using PID tuning algorithms. The authors (Maung et al., 2018) also used a PID controller to control the angular position of the DC-gear motor for the robot through the Arduino UNO microcontroller board. Pulse width modulation (PWM) signals were used to operate the DC Gear 12V ASLONG JGY-371 motor. L298N dual H-bridge module can drive two DC motors in both directions. The performance of the DC motor achieves high stability and extremely low error oscillation for the output angular position, by adjusting the gain parameters k_p , k_i and k_d of the PID controller. With the author (Moulahcene et al., 2022) applied LabVIEW to control the position of the DC motor utilizing the 298 encoders aim to provide a feedback position signal to the PID controller. The PID controller performed in LabVIEW software sends control signals to the DC motor in real time through the Arduino board. The author (Saad, 2021) used the algorithms to optimize the parameters of the PID controller in simulating the DC motor by Matlab, which is applied to many research cases. In addition, many authors have studied the control Linear-quadratic regulator algorithms (LQR) to control DC motors as shown in (Dani et al., 2017; Xiang & Wei, 2021). Optimal control LQR and controller design process are introduced, the output angle position of the DC motor is taken as the control object, and some standard control methods are compared with the suggested control algorithm. Experimental results show that the response signal was the achieved desired signal. In particular, the control system also has the characteristics of short adjustment time, slight overshoot, and high tracking accuracy as shown from the authors (Xiang & Wei, 2021). However, the authors (Dani et al., 2017) apply a Model Predictive Control (MPC) control algorithm whose control signal response outperforms the control signal of PID and LQR controllers. A fuzzy logic controller (FLC) is also implemented to control the DC motor speed as shown in (Ismail et al., 2018), (Almatheel

& Abdelrahman, 2017). Here, the popular PID controller is also considered to compare with the FLC controller. The characteristics of the PID controller require a mathematical model of the system while the fuzzy logic controller is based on experience through rule-based knowledge. A combination of a PID controller and a Fuzzy controller is performed by the authors in (Messaadi & Amroun, 2021; Somwanshi et al., 2019; Sra & Sra, 2016). The fuzzy-based PID controller is proposed by the authors (Somwanshi et al., 2019). The authors also have compared the control signal when using fuzzy PID controller with PID controller in terms of performance to show that fuzzy-based PID controller exhibits better performance than PID controller.

2. Modeling and Controller Design of DC Motor

2.1. Modeling of DC Motor

The Dynamics Equation of the DC motor is expressed

$$J\ddot{\theta} = T - \xi \tag{1}$$

Here DC motor parameters are shown in Figure 1:

J : Inertia

θ : Angle rotation

T : Torque

ξ : Disturbance

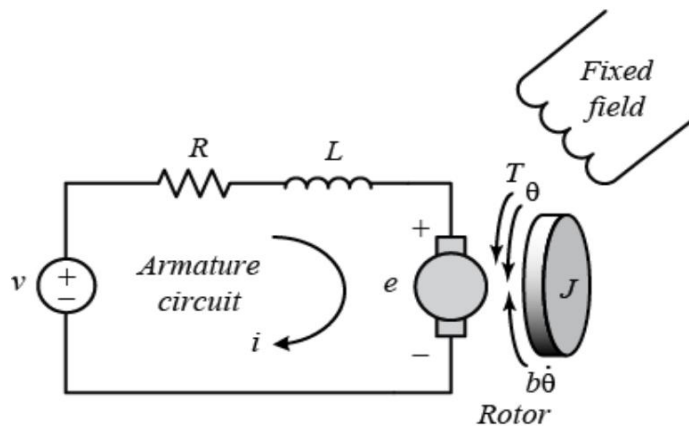


Figure 1. Scheme of the DC motor.

The motor torque is proportional to the armature current i and a constant factor k_t , as described in the equation below

$$T = k_t i \tag{2}$$

The back emf in the DC motor is proportional to the angular velocity of the shaft ω and a constant factor k_e

$$e_m = k_e \omega \quad (3)$$

Applying Kirchoff's law to the armature circuit in Figure 1 we have

$$J\varepsilon + k_b \omega = k_t i - \xi \quad (4)$$

Where ε is the angular acceleration

ξ is disturbance

Similarly, for the fixed field circuit, we have

$$L \frac{di}{dt} + Ri = u - e_m \quad (5)$$

From Eq (3) and (5), we can express as

$$L \frac{di}{dt} + Ri + k_e \dot{\theta} = u \quad (6)$$

2.2. Designing Controllers

2.2.1. Sliding Mode Controller Design

In state-space form, the governing equations above can be expressed by choosing the rotational speed and electric current as the state variables. Again the armature voltage is treated as the input and the rotational speed is chosen as the output. We transfer Equations from (1) to (6) in state space with the state-space variables, control input variables, and the output variable as follows:

$$\begin{aligned} \dot{x} &= Ax + Bu + D\xi \\ y &= Cx \end{aligned} \quad (7)$$

where $x = [x_1 \ x_2 \ x_3]^T$ is a state vector, u is the control input vector, y is the system output, and A , B , C , and D are the system matrices with appropriate sizes.

$$x_1 = \theta \quad (8)$$

$$x_2 = \dot{\theta} \quad (9)$$

$$x_3 = i \quad (10)$$

derivative on both sides of the equations from (8) to (10), we obtain

$$\dot{x}_1 = x_2 \quad (11)$$

$$\dot{x}_2 = \frac{k_t}{J} x_3 - \frac{b}{J} x_2 - \frac{1}{J} \xi \quad (12)$$

$$\dot{x}_3 = \frac{di}{dt} = \frac{u}{L} - \frac{R}{L} x_3 - \frac{k_e}{L} x_2 \quad (13)$$

These equations can be written in a state-space form:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{b}{J} & \frac{k_t}{J} \\ 0 & -\frac{k_e}{L} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} u + \begin{bmatrix} 0 \\ -\frac{1}{J} \\ 0 \end{bmatrix} \xi \quad (14)$$

Considering nonlinear Eq. (14), we can be rewritten this equation in form:

$$y^{(n)} = a(x) + b(x)u \quad (15)$$

where

$$a(x) = L_f^n h(x),$$

and

$$b(x) = L_g L_f^{n-1} h(x) \neq 0$$

with

$$h(x) = Cx$$

$$\dot{y} = \dot{x}_1 = x_2 \quad (16)$$

$$\begin{aligned} \ddot{y} &= \dot{x}_2 \\ &= \frac{k_t}{J} x_3 - \frac{b}{J} x_2 - \frac{1}{J} \xi \end{aligned} \quad (17)$$

$$\begin{aligned} \ddot{\ddot{y}} &= \dot{x}_3 \\ &= \frac{u}{L} - \frac{R}{L} x_3 - \frac{k_e}{L} x_2 \end{aligned} \quad (18)$$

We obtain:

$$a(x) = -\frac{R}{L} x_3 - \frac{k_e}{L} x_2, \text{ and } b(x) = \frac{1}{L}$$

3. Sliding Mode Controller Design

To control the position of the DC motor system, the tracking error is computed as

$$e = y_d - y, \quad (19)$$

$$\dot{e} = \dot{y}_d - \dot{y}, \quad (20)$$

and

$$\ddot{e} = \ddot{y}_d - \ddot{y}, \quad (21)$$

The sliding variable is designed as

$$s = c_1 e + c_2 \dot{e} + \ddot{e} \quad (22)$$

where $c_1 > 0$, $c_2 > 0$

or

$$\begin{aligned} s &= c_1 (y_d - y) + c_2 (\dot{y}_d - \dot{y}) + \ddot{y}_d - \ddot{y} \\ &= c_1 e + c_2 \dot{e} + \ddot{y}_d - \ddot{y} \end{aligned} \quad (23)$$

Therefore,

$$\begin{aligned} \dot{s} &= c_1 (\dot{y}_d - \dot{y}) + c_2 (\ddot{y}_d - \ddot{y}) + (\ddot{y}_d - \ddot{y}) \\ &= c_1 \dot{e} + c_2 \ddot{e} + \ddot{y}_d - a(x) - b(x)u \end{aligned} \quad (24)$$

According to the exponential reaching law, we have

$$\dot{s} = -\varepsilon \operatorname{sgn} s - \mu s \quad \varepsilon > 0, \mu > 0 \quad (25)$$

From (22) and (23), we may be got

$$c_1 \dot{e} + c_2 \ddot{e} + \ddot{y}_d - a(x) + \varepsilon \operatorname{sgn} s + \mu s = b(x)u \quad (26)$$

The auxiliary controller is designed as:

Then we can get the sliding mode controller as

$$u = \frac{1}{b(x)} [c_1 \dot{e} + c_2 \ddot{e} + \ddot{y}_d - a(x) + \varepsilon \operatorname{sgn} s + \mu s] \quad (27)$$

Consider a Lyapunov function is written as

$$V = \frac{1}{2} s^2 \quad (28)$$

Therefore, we have

$$\begin{aligned} \dot{V} &= s \dot{s} \\ &= s [c_1 \dot{e} + c_2 \ddot{e} + \ddot{y}_d - a(x) - b(x)u] \\ &= s [c_1 \dot{e} + c_2 \ddot{e} + \ddot{y}_d - a(x) - (c_1 \dot{e} + c_2 \ddot{e} + \ddot{y}_d - a(x) + \varepsilon \operatorname{sgn} s + \mu s)] \\ &= s(-\mu s - \varepsilon \operatorname{sgn} s) \\ &= -\mu s^2 - \varepsilon |s| \leq 0 \end{aligned} \quad (29)$$

4. Simulation and Results

4.1 Modeling DC Motor in Simulink

4.1.1 DC Motor parameters

The parameters of the DC motor used in the test are in table 1 follows

TABLE 1. DC Motor parameters

Parameters	Unit	Symbol	Value
Moment of inertia of the rotor	kg.m ²	J	0.01
Motor viscous friction constant	N.m.s	b	0.1
Electromotive force constant	V/rad/sec	K _e	0.01
Motor torque constant	N.m/Amp	K _t	0.01
Electric resistance	Ohm	R	1
Electric inductance	H	L	0.5

4.1.2 DC Motor Simulink

The plant of the DC motor is built by the S_function algorithm in Matlab Simulink as below.

```
function [sys,x0,str,ts] = s_function(t,x,u,flag)
switch flag,
case 0,
[sys,x0,str,ts] = mdlInitializeSizes;
case 1,
sys = mdlDerivatives(t,x,u);
case 3,
sys = mdlOutputs(t,x,u);
case {2, 4, 9 }
sys = [];
otherwise
error(['Unhandled flag = ',num2str(flag)]);
end
function [sys,x0,str,ts] = mdlInitializeSizes
sizes = simsizes;
sizes.NumContStates = 3;
sizes.NumDiscStates = 0;
sizes.NumOutputs = 3;
sizes.NumInputs = 1;
sizes.DirFeedthrough = 0;
sizes.NumSampleTimes = 1;
sys = simsizes(sizes);
x0 = [0.5,0,0];
str = [];
ts = [-1 0];
function sys = mdlDerivatives(t,x,u)
```

```

% T = 18.5;
% K = 0.20;
J = 0.01; % moment of inertia of the rotor kg.m^2
B = 0.1; % motor viscous friction constant N.m.s
Ke= 0.01; % electromotive force constant V/rad/sec
Kt= 0.01; % motor torque constant N.m/Amp
R = 1; % electric resistance Ohm
L = 0.5; % electric inductance H
R = 1.5;
L = 8.5e-3;
J = 0.008;
Ke = 0.43;
Kt=Ke;
B = 0.01;
Ksi=0.0025;
sys(1) = x(2);
sys(2) = (Kt/J)*x(3)-(B/J)*x(2)-(1/J)*Ksi;
sys(3) = -(R/(L))*x(3) - (Ke/(L))*x(2) + (1/L)*u(1);
function sys = mdlOutputs(t,x,u)
sys(1) = x(1);
sys(2) = x(2);
sys(3) = x(3);
    
```

PID control and sliding mode scheme of the DC motor are designed as shown in Figure 2.

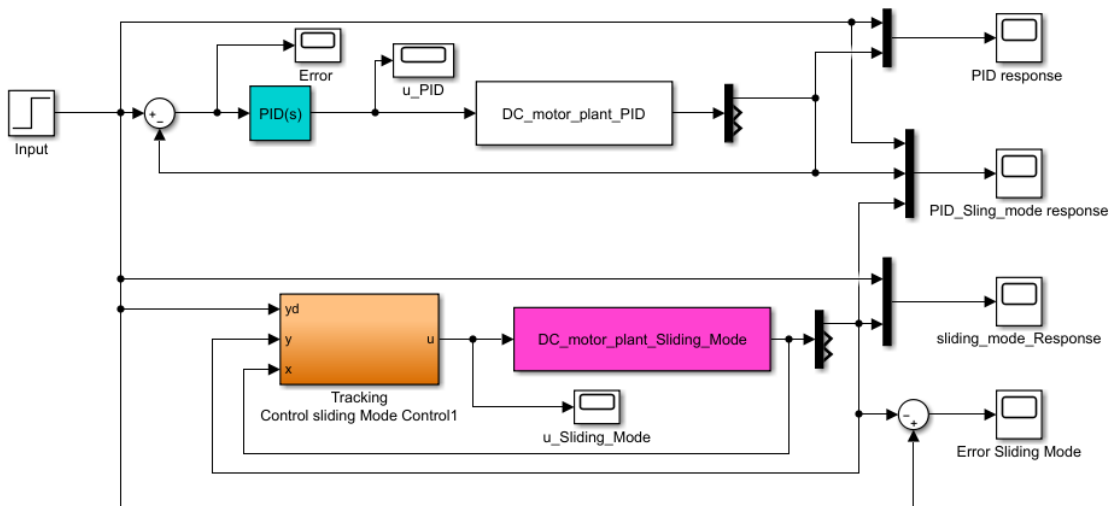


Figure 2. PID control and sliding mode scheme of the DC motor in Simulink.

4.1.2.1 PID Simulation Result

Parameters of PID controller are determined by tune in Matlab as $K_p= 29.607$; $K_i= 94.837$; $K_d= 1.316$

Response position simulation result of DC motor with PID controller is shown Figure 3

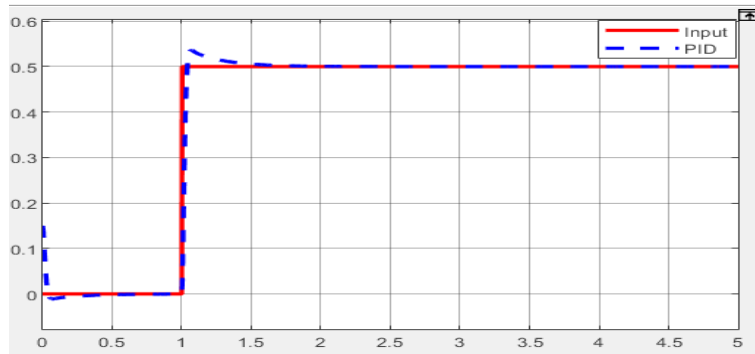


Figure 3. Response position signal of the DC motor with PID controller.

4.1.2.2 Sliding Mode Simulation Result

Parameters of sliding mode controller are choose as $c_1= 20$; $c_2= 10$; $\varepsilon= 0.15$; $\mu=12$

Response position simulation result of DC motor with sliding mode controller is shown Figure 4

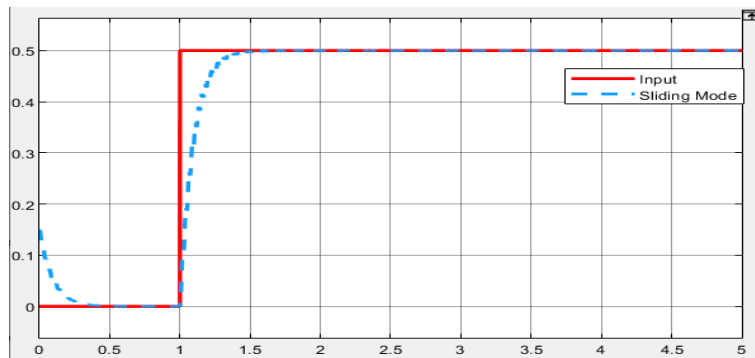


Figure 4. Response position signal of the DC motor with sliding mode controller.

Control signal u of sliding mode controller is shown in Figure 5

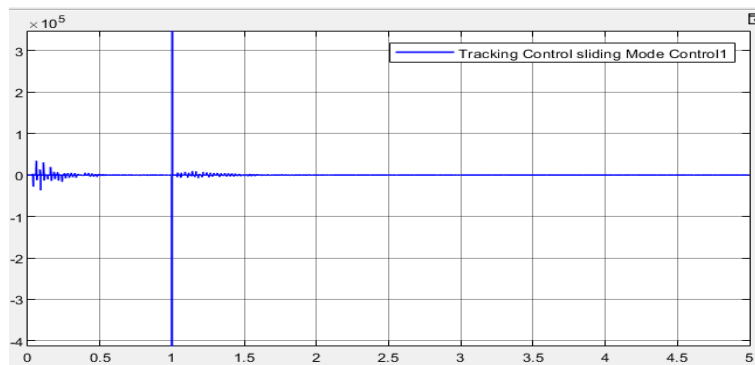


Figure 5. Control signal of sliding mode controller.

4.1.2.3 Comparison Control Signal Between Sliding Mode and PID

Response position signal of DC motor with sliding mode and PID controller is shown Fig.6

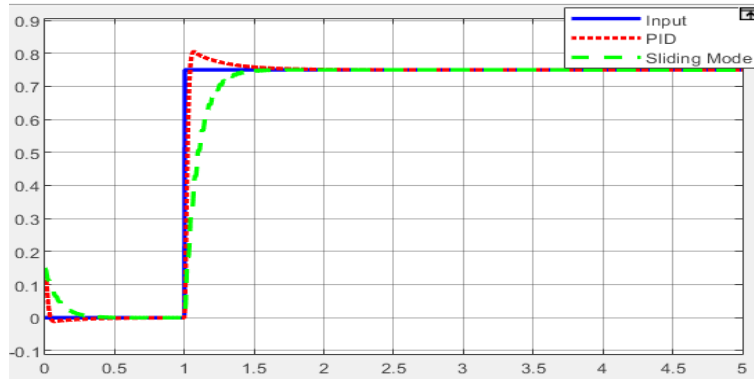


Figure 6. Control signal of sliding mode and PID controller.

Response position error of DC motor with sliding mode and PID controller is shown Fig. 7

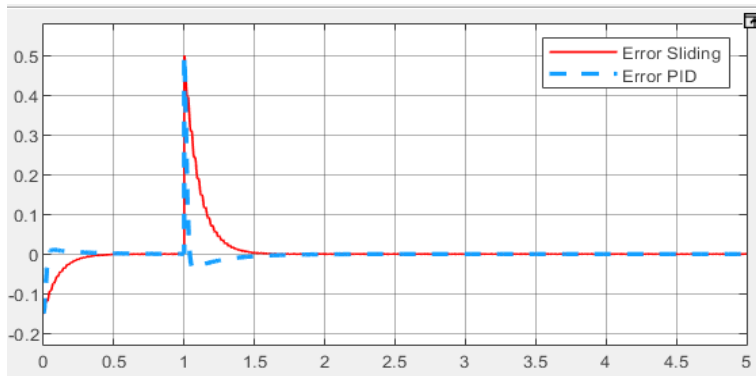


Figure 7. Control signal of sliding mode and PID controller.

5. Conclusion

The sliding mode control algorithm has been used previously and is applied to many different applications because the control quality is quite good compared to PID and LQR controllers. However, the design of sliding mode control controllers has many different forms. In this article, we have designed a sliding mode control controller for a DC motor in the form of feedback. The simulation results of the feedback signal are very good as shown in Figure 4. In particular, the feedback signal when applying sliding mode control is compared with the feedback signal when applying the PID controller as shown in Figure 6. The response signal in the PID controller is relatively high compared to the sliding mode control.

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