

RESEARCH ARTICLE

Investigate The Performance of The ABSA-PD Controller on a DC Motor Based Pendulum System

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ABSTRACT - The position of the pendulum system must be precisely controlled and maintained by a direct current (DC) motor. This project demonstrates using an ABSA-PD controller to keep the DC motor in its desired position. The prototype of a pendulum system powered by a DC motor must have a mathematical model developed to reproduce that. Matlab/Simulink is used to create and test the mathematical model. The mathematical model is tested in two scenarios: one without a controller and one with a PD controller. The first method of the Ziegler-Nichols approach is used to obtain the gain value of the controller. The created model will undergo further positional verifications. The Simulink toolbox in Matlab is used for the simulation. The controller's effectiveness in regulating the pendulum system was taken into account. The transient response parameters of rise time (T_r), settling time (T_s), percentage overshoot (%OS), and steady-state error of the system response will be used for comparison. The findings will demonstrate that the best projection to mimic the functionality of the pendulum system comes from a sound mathematical model.

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1. INTRODUCTION

Pendulum systems, mechanical structures comprising a mass suspended from a fixed point, find widespread applications in physics, engineering, and mathematics [1]. This study delves into basic pendulum systems and explores their dynamics influenced by factors like pendulum length and bob mass. Notably, traditional mechanical pendulum clocks utilize pendulum systems for timekeeping, employing a DC motor to regulate oscillations and ensure accurate timekeeping [2].

DC motors, electric devices converting electrical energy into mechanical motion, are crucial components in mechatronic systems [3]. Categorized into brushed and brushless types based on architecture, DC motors play a pivotal role in various applications, including motion, position, and velocity control. Integrating DC motors into pendulum systems allows for precise control of motion and the achievement of specific objectives like stabilization or trajectory creation [4]. To facilitate effective control of DC motors within pendulum systems, the implementation of a Proportional-Derivative (PD) controller is proposed in this project. The PD controller, combining proportional and derivative control components, enhances system stability and performance. Proportional control generates output proportionate to the error, while derivative control anticipates error changes over time, minimizing overshoot and oscillations [5].

Additionally, this study explores the Adaptive Bat Sonar Algorithm (ABSA), a bio-inspired optimization method inspired by bat echolocation behavior. ABSA, belonging to swarm intelligence algorithms, mimics the adaptive sonar signals of bats, allowing for efficient navigation, prey detection, and obstacle avoidance [6]. DC motors, with exceptional torque characteristics and precise control capabilities, are ideal for applications demanding rapid acceleration and accurate control, such as robots and electric cars. This research sets the stage for investigating the integration of DC motors and pendulum systems, highlighting their potential in diverse applications and the role of advanced control strategies for optimized performance. The remainder of this paper is organized as follows: Section 2 briefly presents an overview of brushed DC motor modelling. Section 3 explains the Adaptive Bat Sonar Algorithm. Section 4 provides the experimental setup and experiment results. Section 5 concludes the paper.

2. RELATED WORK

The investigation into the precise positioning of a pendulum system reveals critical insights into theoretical models, influencing factors, measurement techniques, and control methods. Theoretical models, including the simple, compound, and double pendulum, utilize characteristics such as length, mass distribution, and damping effects to predict the pendulum's location [7]. Factors like pendulum length, damping forces, external impacts, and vibrations have been studied, with strategies proposed to mitigate these effects for enhanced accuracy. In the realm of precise control for pendulum systems, feedback control methods play a pivotal role. Continuous adjustments based on position data stabilize pendulum positions, finding applications in precision clocks and scientific instruments [8]. Furthermore, the integration of control strategies such as the Proportional-Derivative (PD) controller enhances stability, reduces steady-state error, and improves the response to sudden changes, making it an invaluable tool in precise pendulum system control.

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Shifting focus to brushed DC motors, their role in applications demanding precise motor position control, such as robotics and automation systems, is underscored [9]. Brushed DC motors, with their stator and rotor configuration, offer excellent torque control at low speeds but require regular maintenance due to brush wear. Understanding the fundamental principles, construction, and mathematical models of DC motors lays the groundwork for devising control strategies that precisely regulate the motor's position [10]. The application of the Proportional-Derivative (PD) controller to brushed DC motors emerges as a significant development in position control research. The PD controller, combining proportional control and derivative control, enhances system stability by generating an output proportional to the current error and adjusting the response based on the rate of change of the error over time. This integration proves crucial in achieving accurate position control for brushed DC motors, contributing to improved overall system performance and efficiency [11].

In the realm of optimization algorithms, the Adaptive Bats Sonar Algorithm (ABSA) stands out as a bio-inspired method designed to address complex optimization problems efficiently. Inspired by bat echolocation, ABSA combines bat search abilities with an adaptive system to improve exploration and exploitation during optimization. The algorithm has been compared with other optimization techniques, demonstrating strengths in solution quality, convergence speed, robustness, and scalability [6]. In this report unveils a comprehensive understanding of the precise positioning of pendulum systems, the role of brushed DC motors in demanding applications, the application of the PD controller to enhance motor position control, and the innovative use of the ABSA algorithm for optimization. These insights collectively contribute to advancements in fields such as timekeeping, automation, and optimization.

3. METHODS AND MATERIAL

3.1 Brushed DC Motor Modelling System

In general, the mathematical model of a brushed DC motor circuit can be used to determine the transfer function for a PD controller. The electrical component and the mechanical component are the two main parts of the mathematical model. The rotor represents the mechanical component, while the input voltage, resistor, and inductor make up the electrical component. The Kirchhoff's voltage law states that the DC motor's electrical equation can be written as follows:

$$E_a = R_a I_a + \frac{d i_a}{dt} + E_b \quad (1)$$

$$E_b = K_b \frac{d\theta}{dt} \quad (2)$$

Furthermore, the equation for the mechanical part can be derived as:

$$J_m \frac{d^2\theta}{dt^2} + B_m \frac{d\theta}{dt} = K_t \cdot I_a \quad (3)$$

$$E_a(s) - K_b s \theta(s) = (R_a + sL_a) I_a(s) \quad (4)$$

$$J_m s^2 \theta + B_m s \theta(s) = K_t \cdot I_a(s) \quad (5)$$

To obtain a transfer function, mathematical manipulations, such as rearranging and substituting, are applied to equations (4) and (5). The resulting transfer function is expressed as:

$$\frac{\theta(s)}{E_a(s)} = \frac{K_t}{J_m L_a s^3 + (J_m R_a + B_m L_a) s^2 + R_a B_m s + K_t K_b s} \quad (6)$$

So, brushed DC motor transfer function model is developed in this project as shown in equation (6). The transfer function is used in the Simulink brushed DC motor model. The parameters values of this project are determined by using brushed type of DC motor. Table 1 below shown the parameter values of brushed DC motor of this project.

Table 1. Parameter value of brushed DC motor

Parameter	Value
Armature resistance, R_a	0.5 Ω
Armature inductance, L_a	0.009 H
Moment of inertia, J_m	0.0093 kg. m ²
Friction coefficient, B_m	0.2389 Nms
Torque constant, K_t	0.556 Nm/A
Back emf constant, K_b	0.497 V/rad. sec ⁻¹

Equation (7) will be employed to assess the brushed DC motor's performance, generating an output response through simulation in MATLAB/Simulink software.

$$\frac{\theta(s)}{E_a(s)} = \frac{0.556}{0.00008s^3 + 0.0068s^2 + 0.396s} \quad (7)$$

3.2 System Identification without Controller

The first step in system identification is to measure the output signals when the system is loaded with an input signal. This can be done by using the transfer function of the DC motor that was determined in equations (7) was implemented to construct the block diagram without controller in the MATLAB/Simulink software. Figure 1 below is the input-output signals that will be exported to the workspace of MATLAB.

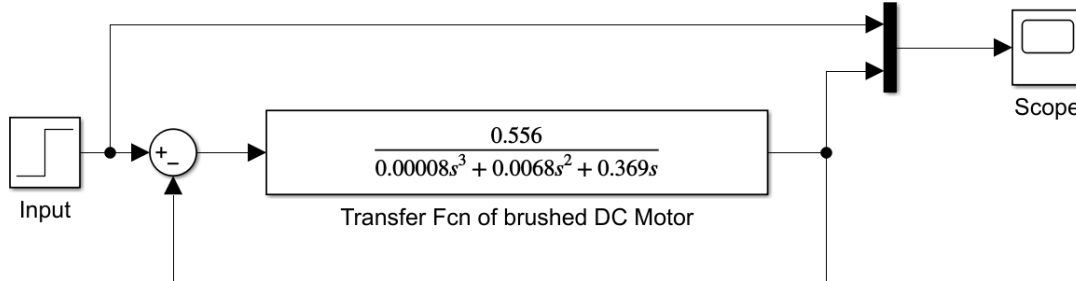


Figure 1. Block diagram of DC motor without controller

3.3 Proportional-Derivative (PD) Controller

In the tuning of PD controllers, the Ziegler-Nichols approach, introduced by Ziegler and Nichols, provides a widely accepted and straightforward mathematical method for adjusting PID controllers in control systems. Ziegler-Nichols equations dictate that the proportional, integral, and derivative gains (K_p , K_i , K_d) of the controller are determined by the plant's step reactions. Key aspects of the closed-loop step response, including rise time (T_r), overshoot percentage (%Os), and settling time (T_s), influence the dynamics structure during this tuning process. This method is particularly effective for plants with step responses, common in first-order systems with transportation delays. The PD controller, vital for systems like DC motors, utilizes both proportional (K_p) and derivative (K_d) gains, where K_p defines the corrective forces for error and K_d ensures system stabilization.

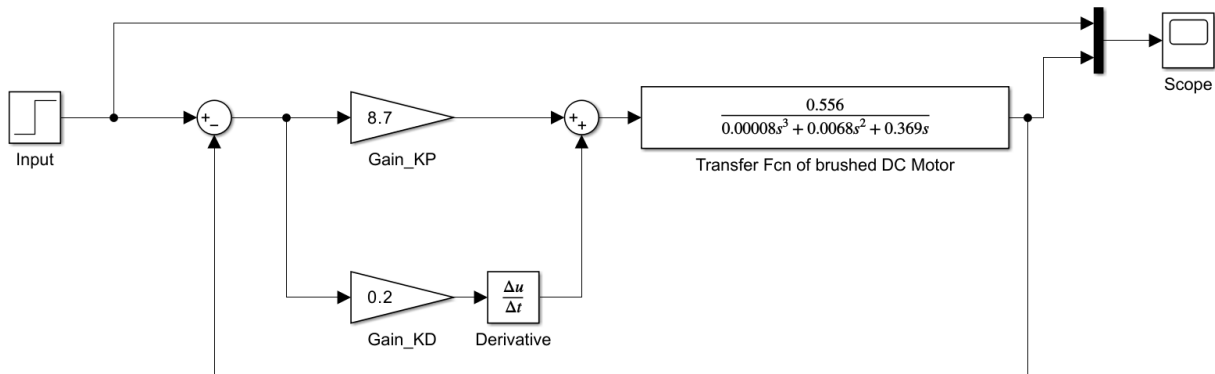


Figure 2. Block diagram of PD controller

3.4 Development of Adaptive Bats Sonar Algorithm

In the development of the Adaptive Bats Sonar Algorithm (ABSA) methodology, the solution range (SS_Size) is crucially defined by the upper search space (SS_Max) and lower search space (SS_Min) limits through Equation 7:

$$SSSize = SSMax - SSMin \quad (7)$$

Subsequently, ABSA establishes the beam length (L) in relation to SS_Size using Equation 8:

$$L \leq Rand \times \left(\frac{SS_{size}}{10\% \times Bats} \right) \quad (8)$$

$$pos_i = pos_{SP} + L \cos [\theta_m + (i - 1)\theta]$$

Each emitted NBeam with length L originates at a specific angle from the starting point (pos_{SP}), constrained by Equation 6, limiting the first beam to a maximum of 45° from the horizontal axis. By dynamically setting the angle between beams (i) with θ_m as $rand \leq 0.7854$, ABSA ensures smooth rotation without aggressive or sluggish movements. Equation 9 calculates the end point position (pos_i) for each transmitted beam in ABSA, employing $i = 1, \dots, N$. The repositioning factor (τ), derived from Equation 3.8.1, facilitates bats in relocating beam transmissions to new endpoints within the search space boundaries, enhancing adaptability and collision avoidance in the algorithm's iterations.

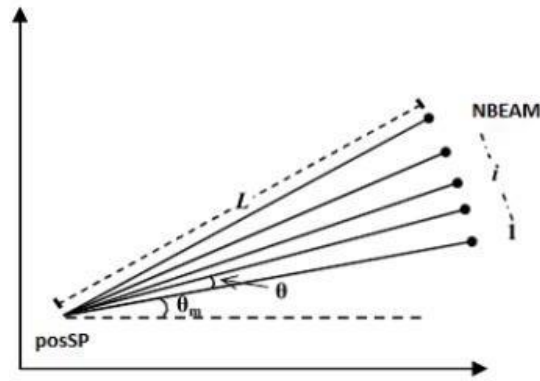


Figure 3. Single batch of beams transmitted by a bat

Algorithm 1 Adaptive bats sonar algorithm

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1: Objective function  $F(x)$ ,  $x = (x_1, \dots, x_d)^T$ 
2: Initialise:  $Bats$ ,  $MaxIter$ ,  $Dim$ ,  $SSSize$ ,  $NBeam_{MAX}$  and  $NBeam_{MIN}$ 
3: for  $n \leftarrow 1$  to  $Bats$  do
4:   for  $d \leftarrow 1$  to  $Dim$  do
5:     Generate random  $pos_{SP}$ 
6:     Evaluate  $F_{SP}$  value for  $F(pos_{SP})$ 
7:   end for
8: end for
9: Assign the most optimum value as  $F_{GB}$  and its position as  $pos_{GB}$ 
10: while  $t \leq MaxIter$  do
11:   Define  $NBeam$  to transmit by using BNI (Equation 5 and Equation 6)
12:   Set  $L$  and limit  $\mu$  (Equation 3 and Equation 4)
13:   Generate random  $\theta_m$  and  $\theta_i$  (Equation 7)
14:   for  $n \leftarrow 1$  to  $Bats$  do
15:     Transmit  $NBeam$  starting from  $pos_{SP}$ 
16:     for  $N \leftarrow 1$  to  $NBeam$  do
17:       for  $d \leftarrow 1$  to  $Dim$  do
18:         Determine  $pos_i$  for each transmitted beam (Equation 8)
19:       end for
20:       Evaluate  $F_i$  value for  $F(pos_i)$ 
21:     end for
22:     Assign the optimum value of  $F_i$  as  $F_{LB}$  and its position as  $pos_{LB}$ 
23:     if  $F_{LB} \leq F_{SP}$  then
24:       Assign  $F_{LB}$  as  $F_{RB}$  and  $pos_{LB}$  as  $pos_{RB}$ 
25:     else
26:       Assign  $F_{SP}$  as  $F_{RB}$  and  $pos_{SP}$  as  $pos_{RB}$ 
27:     end if
28:   end for
29:   Select the optimum value among  $F_{RB}$  as current  $F_{GB}$  and its  $pos_{RB}$  as current  $pos_{GB}$ 
30:   if current  $F_{GB} \leq$  previous  $F_{GB}$  then
31:     Update current  $F_{GB}$  as new  $F_{GB}$  and current  $pos_{GB}$  as new  $pos_{GB}$ 
32:   else
33:     Retain previous  $F_{GB}$  and  $pos_{GB}$ 
34:   end if
35:   for  $n \leftarrow 1$  to  $Bats$  do
36:     Determine new  $pos_{SP}$  using (Equation 9)
37:     Evaluate new  $F_{SP}$  value for  $F(x)$ 
38:   end for
39: end while
40: Declare  $F_{GB}$  as optimum fitness evaluated and  $pos_{GB}$  as its optimum value(s)

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Figure 4. The pseudo code of ABSA

3.5 Experimental Setup

Based on the Figure 4 below, the prototype of pendulum system is constructed. In the development of the pendulum system based on brushed DC motor control circuit, the implemented a PD control system using an Arduino microcontroller and a motor driver module. The DC motor was connected to the motor driver, and the encoder channels

(ENCA and ENCB) were linked to digital input pins on the Arduino. A suitable power supply was provided for both the motor driver and the DC motor, ensuring it met the motor's specifications.

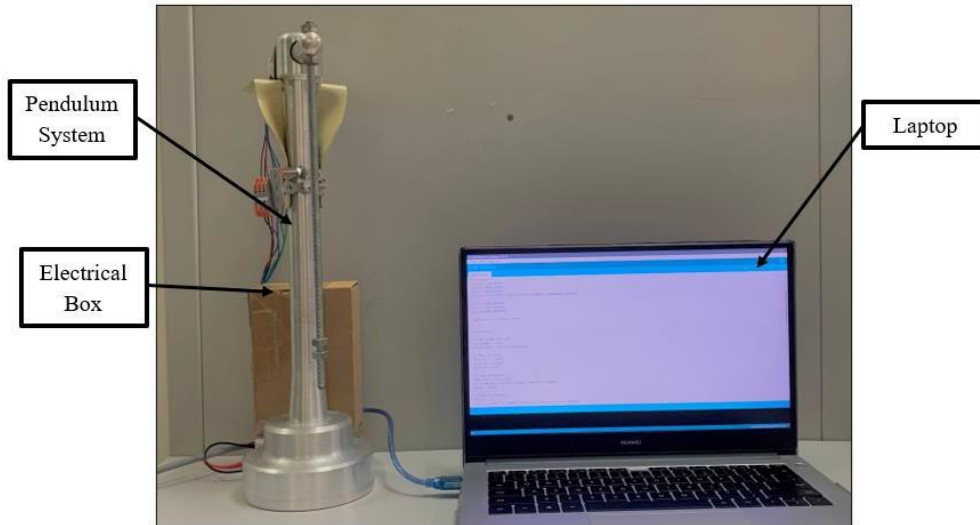


Figure 5. Prototype of pendulum system

The PD constants (k_p and k_d) in the code were tuned to optimize the control system for the specific motor and system characteristics. The Arduino code was uploaded using the Arduino IDE, the serial monitor, and the serial plotter was employed to monitor the system's behaviour. The system was tested iteratively, and adjustments were made to the PD constants and other parameters to achieve the desired performance, ultimately enabling the DC motor to move to a target position of 10 radians and come to a stop. This process involved careful consideration of the motor driver, encoder, and power supply connections, as well as systematic tuning of the PD control parameters to ensure effective motor control.

4. RESULTS AND DISCUSSION

In this part, the analysis of the mathematical model is discussed. A mathematical model is used to simulate in MATLAB and Simulink software. The PD controller and ABSA-PD controller that has been created is used to analyse the performance of brushed DC motor on the Simulink and on the pendulum system prototype. The result of performance, Settling Time (T_s), Rise Time (T_r), Percent Overshoot (%OS) and Steady State Error (E_{ss}) are discussed in this chapter. The results shown involved the position control performances of brushed DC motor without using controller and by using PD Controller and ABSA-PD controller. All simulations and experiments are shown in Figure 5 and 6. The characteristic of DC motor's performance are tabulated in Table 1.

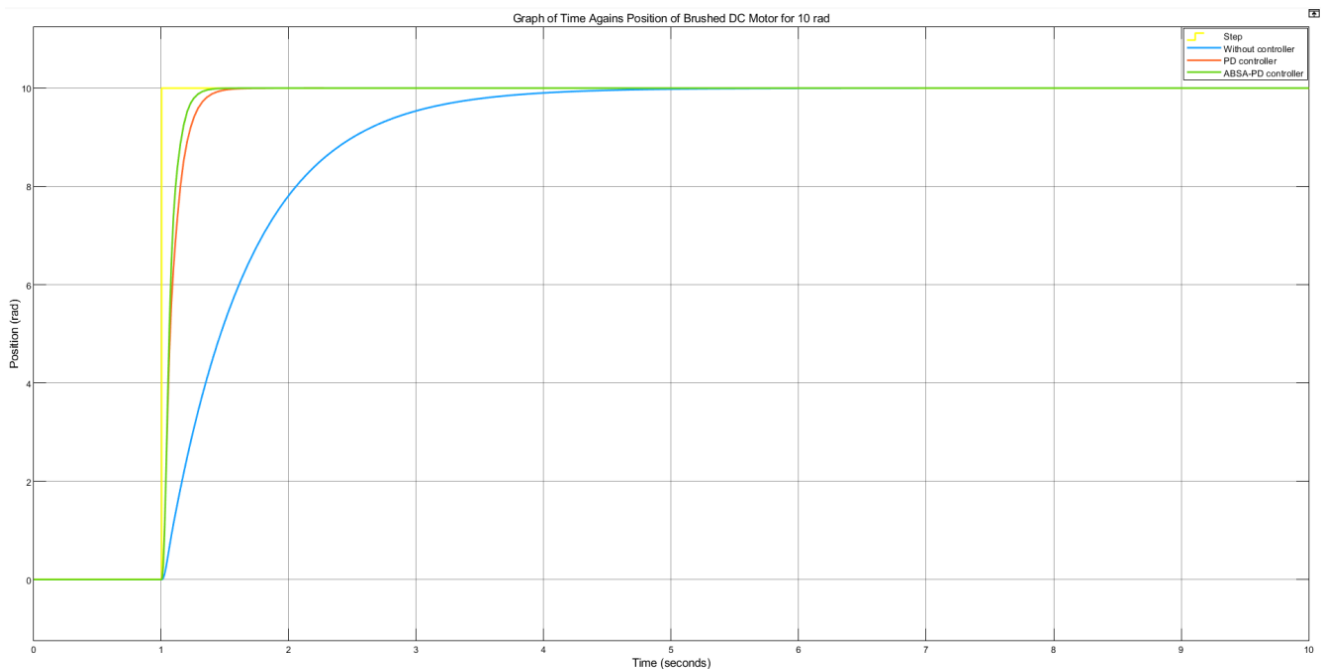


Figure 6. Combination graph of different controllers in Simulink

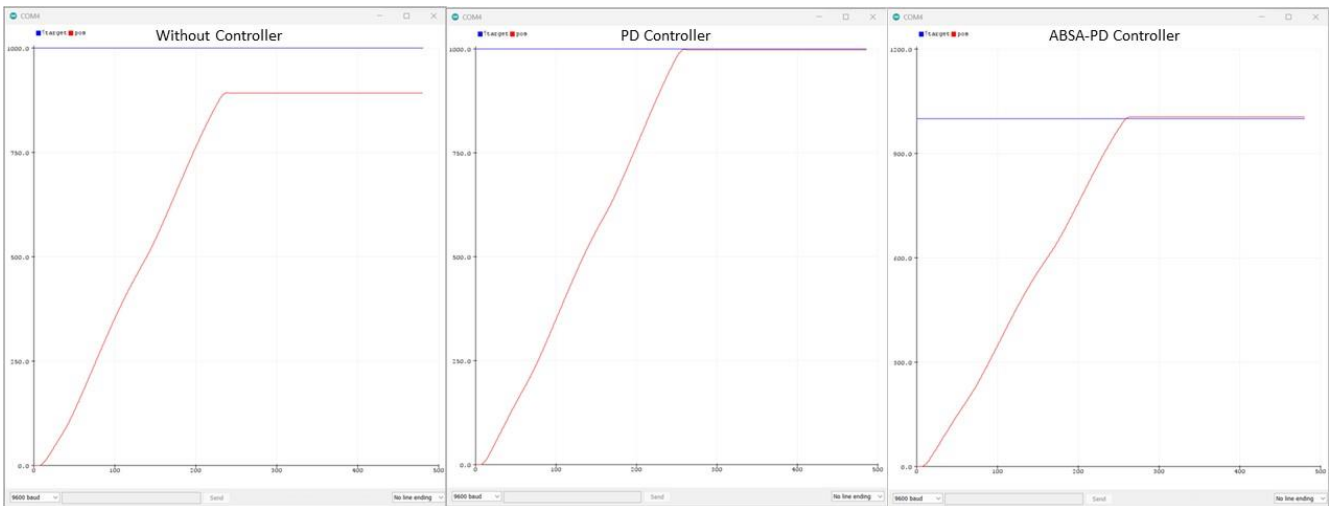


Figure 7. Combination graph of different controllers in pendulum system

Table 2. Comparison of Brushed DC Motor for 10 rad

Types of Controllers	Parameter	Simulation	Experiment
Without controller	Tr (s)	1.389	2.387
	Ts (s)	2.612	2.522
	OS (%)	0.500	1.500
	Ess	0.053	1.250
With PD controller	Tr (s)	0.183	2.423
	Ts (s)	1.334	2.601
	OS (%)	0.449	1.220
	Ess	0.015	0.450
With ABSA-PD controller	Tr (s)	0.130	2.314
	Ts (s)	1.241	2.510
	OS (%)	0.468	0.600
	Ess	0.010	0.010

Performance at 10 rad without controller, the simulation results without a controller differ significantly from the experimental results, emphasizing the importance of real-world testing. The overshoot in the experiment is higher (1.500%) compared to the simulation (0.500%), and the steady-state error is also greater in the experiment. The ABSA-PD controller consistently exhibits superior performance compared to the PD controller. In both simulation and experimentation, the ABSA-PD controller achieves faster rise times, lower settling times, reduced overshoot, and minimal steady-state error.

In summary, the results highlight the need for careful consideration of practical aspects when designing control systems. The ABSA-PD controller consistently proves its superiority over the PD controller, showcasing its robust performance across different rotation angles and emphasizing its potential for real-world applications. The discrepancies between simulation and experimental results without a controller underscore the importance of incorporating practical considerations into control system design and validation.

5. CONCLUSION

This research report culminates in a thorough investigation into the control dynamics of a brushed DC motor-based pendulum system. With a threefold objective encompassing mathematical modeling, simulation-based performance assessment using the Adaptive Bat Sonar Algorithm (ABSA)-PD controller, and real-world validation, the findings provide valuable insights into system behavior. The consistent and notable enhancements achieved in the dynamic response of the brushed DC motor through the ABSA-PD controller are evident in reduced rise time, settling time, overshoot, and steady-state error across diverse rotation angles. These improvements were observed both in simulated environments and practical experiments, affirming the controller's robustness and applicability in real-world scenarios. Discrepancies between simulation and experimental outcomes without a controller highlight the necessity of considering practical factors in control system design. In summary, the ABSA-PD controller emerges as a superior choice for optimizing the brushed DC motor's performance in the pendulum system, emphasizing its potential for applications requiring precise and adaptive control.

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