Evaluation of the dynamic performance and practical limitations of a two-wheeled self-balancing robot

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ABSTRACT

Two-wheeled self-balancing robots (TWSBR) are statically unstable. However, using closed-loop controllers can stabilize. In this work, the proportional-integral-derivative (PID) controller was designed to maintain the TWSBR stability by adding two zeros and a pole at the origin to the loop gain and by determining the parameter K via root-locus analysis. Then using the K value K_p, K_i, and K_d parameters were calculated. By applying an impulse response to the system, it was found that the system is able to reach a dynamic balance in less than 1.2 seconds with minimum steady-state error. The dynamic performance and limitations of the developed system were investigated. The highest disturbance angle that can be applied to the system while keeping the motor input voltage below 12 V, in order to create counterbalancing torque and achieve dynamic balance, is determined to be $\theta = 0.0524$ rad. Additionally, it was found that the TWSBR system managed to retain stability in a significantly large range of sudden payload changes with the same PID controller.

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1. INTRODUCTION

Two-wheeled self-balancing robots (TWSBR) have garnered significant attention from robotics experts [1]–[4]. “Segway” is the best application where TWSBR is in action in the field of transportation [5], [6]. The basic physics of the TWSBR is the principle of an inverted pendulum [7]. The inverted pendulum is a widely used model in robotics and control theory [8], [9], where it consists of a mass held above a pivoted point and the system is inherently unstable. But it can be held without falling by applying suitable torques with the aid of a properly tuned control system [10], [11].

The vertical orientation of an inverted pendulum is an unstable equilibrium state. Any slight disturbance can topple the pendulum. However, providing counterbalancing torques at appropriate time intervals through motors connected to its wheels makes it possible to keep the pendulum vertically, without falling. In order to generate torques with the correct magnitude at the correct time, the orientation of the pendulum must be monitored using suitable sensors. Using this feedback from sensors, a suitable algorithm can be used for calculating the counterbalancing torque.

In some previous research works discuss the application of classical proportional-integral-derivative (PID) controller for maintaining the balance of TWSBR [12]–[15]. The design and simulation of a TWSBR with a PID controller to maintain balance by adjusting the angular velocity of direct current (DC) motors through pulse width modulation (PWM) is presented in [13]. In [12] implementation of a two-wheel self-balancing robot using MATLAB Simscape multibody to simulate, hardware design, and calculate the torque and speed requirements to maintain the stability of TWSBR using the PID algorithm was discussed. Nevertheless, it is important to note that none of the studies presented in [12]–[15] specifically address payload adaptability or practical voltage limitations.

The application of linear-quadratic regulator (LQR) control for TWSBR balancing is discussed in [16]–[20]. In [16], the LQR control has been developed by using the particle swarm optimization (PSO) algorithm, leading to enhanced controller performance with less overshoot and keeping the steady-state error zero. The mathematical model of the TWSBR system was initially analyzed using Newtonian mechanics in the research work presented by [17]. Subsequently, the authors effectively implemented an LQR controller for this system and conducted simulations in a MATLAB/Simulink environment to evaluate the controller under various conditions. An and Li [21] presented the comparison of the performance of TWSBR with the PID control algorithm and linear-quadratic regulator (LQR) control algorithm, the result shows that LQR has a better performance than PID for TWSBR control.

Some researchers employed nonlinear controllers, specifically fuzzy logic controller and fuzzy PID controllers, in their study to ensure the stability of TWSBR [22], [23]. The results demonstrated that both fuzzy logic control and fuzzy PID controller effectively prevented the robot from falling, achieving the desired control objectives and improving dynamic performance. Hassan *et al.* [24] presents a detailed overview of the mathematical model development using Lagrange kinematics, the design of a stabilizing PID controller, and the evaluation of real-time optimal parameter estimation techniques. Haddout [6] discussed the utilization of nonholonomic mechanics for the purpose of modeling and simulating the TWSBR system. The paper demonstrates the application of reinforcement learning (RF) to achieve equilibrium in the TWSBR system and optimize the training process by incorporating PID control.

Zad *et al.* [25] proposed an optimal controller design for a self-balancing two-wheeled robot system using a robust model predictive control (MPC) scheme. Additionally, the MPC controller was simulated using MATLAB/Simulink and compared with a PID controller. The simulation results show better stability and improved reference position tracking for the MPC controller, with good robustness against perturbations in the system model. Study [1] presented a new configuration of TWSBR designed to enhance flexibility and increase degrees of freedom using a movable linear actuator on the second pendulum link.

While various control techniques have been explored for TWSBRs, many existing studies tend to overlook key practical challenges, such as the limitations imposed by motor voltage and the robot's ability to handle sudden changes in payload without adjusting the controller settings. These factors are highly relevant in real-world scenarios, where a TWSBR may experience unexpected loads or operate within strict power limits. This study addresses these gaps by investigating the dynamic performance and practical limitations of a TWSBR controlled using a PID algorithm. Specifically, we evaluate how the system behaves under varying payload conditions and disturbance angles, while adhering to the real-world constraint of a 12 V motor input limit. Our simulations show that the robot can recover from disturbances up to 0.0524 radians without exceeding this voltage threshold. Furthermore, the robot demonstrates robust stability across a wide range of payloads, up to five times the nominal mass, without requiring any retuning of the PID controller. These findings contribute to the growing body of TWSBR research by demonstrating that simple PID control, when properly designed, can meet practical performance requirements even under varying real-world constraints.

2. METHOD

The first dynamic model for the TWSBR, shown in (1), was established in order to design a PID controller for stabilization. Based on Newtonian mechanics and the system shown in Figure 1, the following linearized state-space representation of the TWSBR was derived, following methods similar to found in the literature [26], [27].

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dot{\theta}\\ \ddot{\theta}\end{bmatrix}=\begin{bmatrix}0 & 1 & 0 & 0\\ 0 & \frac{2k_m k_e(M_p l r-I_p-M_p l^2)}{Rr^2\alpha} & \frac{M_p^2 g l^2}{\alpha} & 0\\ 0 & 0 & 0 & 1\\ 0 & \frac{2k_m k_e(r\beta-M_p l)}{Rr^2\alpha} & \frac{M_p g l\beta}{\alpha} & 0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \theta\\ \dot{\theta}\end{bmatrix}+\begin{bmatrix}0\\ \frac{2k_m(I_p-M_p l^2-M_p l r)}{Rr\alpha}\\ 0\\ \frac{2k_m(M_p l-r\beta)}{Rr\alpha}\end{bmatrix}V_a \tag{1}$$

Here, x and $\dot{x}$ represent the horizontal displacement and velocity, respectively, of the TWSBR and θ is the inclination angle, $\dot{\theta}=\omega$ is the angular rate, and V_a is the motor input voltage. The model parameters are defined as:

$$\beta = \left(2M_w + \frac{2I_w}{r^2} + M_p\right)$$
$$\alpha = \left[I_p\beta + 2M_pl^2\left(M_w + \frac{I_w}{r^2}\right)\right]$$

M_p = mass of the robot's chassis, I_p = moment of inertia of the robot's chassis, l = distance between the center of the wheel and the robot's center of gravity, M_w = mass of the robot's wheel, k_m = motor's torque constant, k_e = back electromotive force (back EMF) constant.

Figure 2 presents the physical prototype of the TWSBR used in this study. All physical parameters were determined experimentally to ensure the accuracy of the simulation and modeling processes. The chassis mass M_p and wheel mass M_w was measured using a precision digital scale, while the wheel radius r was determined using a digital caliper. The center of mass location l was identified through a static balancing method. The moment of inertia of the chassis I_p was calculated mathematical method. Motor constants, including the torque constant k_m and the back electromotive force constant k_e, were verified using both datasheets and experimental open-loop tests. Additionally, the motor resistance R was measured using a high-accuracy multimeter. The physical parameters determined experimentally are listed below. By taking the tilt angle θ as the system output and V_a (motor input voltage) as the input, the transfer function *G(s)* can be derived from the dynamic model of TWSBR as (2):

$$\frac{\theta(s)}{V_a} = G(s) = \frac{7.697s}{s^3+28.12s^2-139.7s-2479} \quad (2)$$

The transfer function of a PID controller can be expressed as (3):

$$G_c(s) = K_p + K_ds + \frac{K_i}{s} = K\frac{(s+z_1)(s+z_2)}{s} \quad (3)$$

where $K = K_d$, $z_1 + z_2 = K_p/K_d$ and $z_1z_2 = K_i/K_d$. Then PID controller can be implemented by inserting the PID controller transfer function into the TWSBR system open-loop transfer function $G(s)$ as (4):

$$L(s) = G(s)G_c(s) = \frac{K(s+z_1)(s+z_2)7.697s}{s(s^3+28.12s^2-139.7s-2479)} \quad (4)$$

The PID controller design can be performed by adding two zeros and a pole at the origin to the loop gain $L(s) = G(s)G_c(s)$, and by determining the control gain K via root-locus analysis. In this design, the following zeros are chosen to meet the transient response specifications AS (5):

$$z_{1,2} = 4.7 \pm j0.15 \quad (5)$$

Then, using the control gain K, the K_p, K_i and K_d values were calculated, and the entire dynamic model and PID controller were implemented in MATLAB/Simulink as shown in Figure 3. Here, the dynamic model shown in (1) was created inside the two-wheeled robot block, and initially, the set angle was kept at zero.

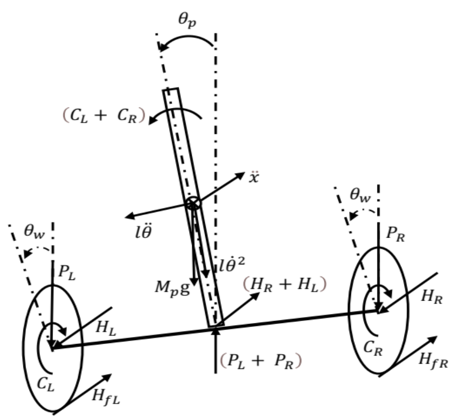

Figure 1. Diagram of forces and moments acting on the TWSBR

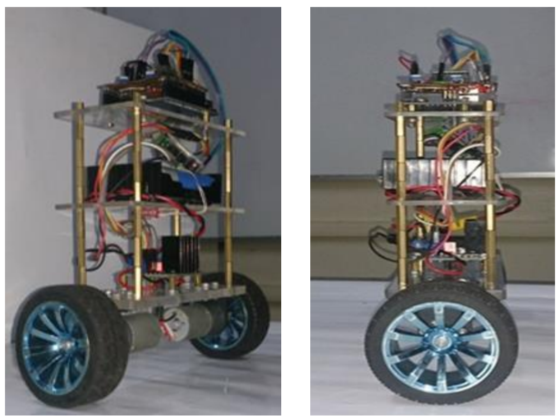

Figure 2. Physical prototype of the TWSBR system

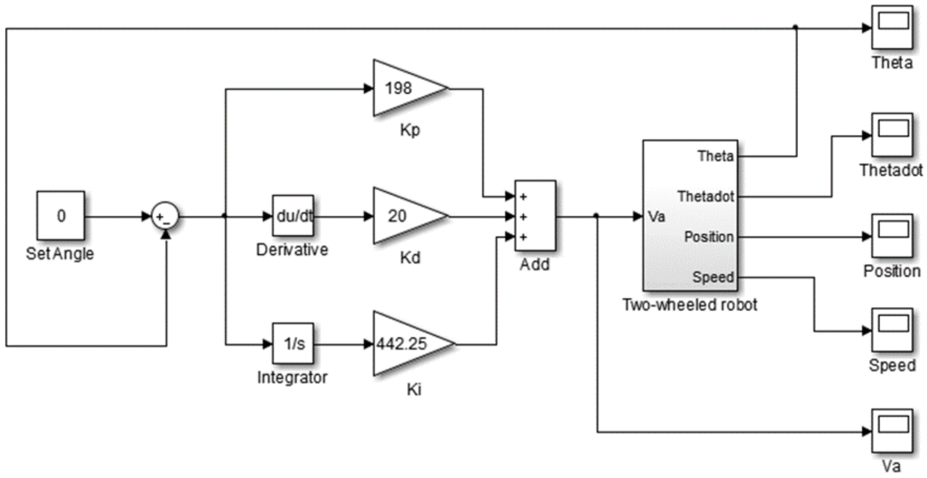

Figure 3. The TWSBR system is designed in MATLAB/Simulink environment with a PID controller

3. RESULTS AND DISCUSSION

The resulting root locus of the transfer function $L(s) = G(s)G_c(s)$ is shown in Figure 4. It can be seen that the closed-loop poles enter the open left-half-plane for a large enough gain. At a damping ratio equal to 1, we obtained the gain K = 20. The values of K_p, K_i and K_d were calculated accordingly.

Figure 5 shows the response of the two-wheeled robot under the PID controller design. The disturbance applied here is equivalent to releasing the pendulum after moving it to an inclination angle of 0.05 radian (2.86 degrees). From this figure, it is clear that the system can come to a vertical position within about 1.2 seconds.

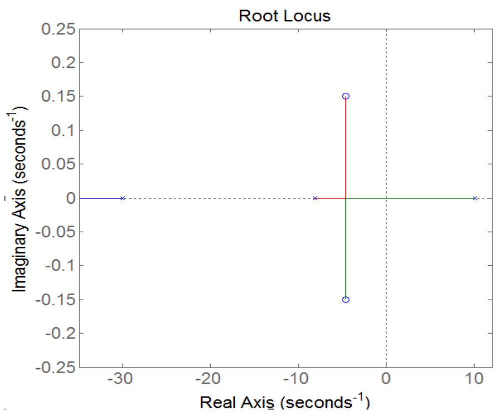

Figure 4. Root locus of the loop gain $L(s) = C(s)G(s)$

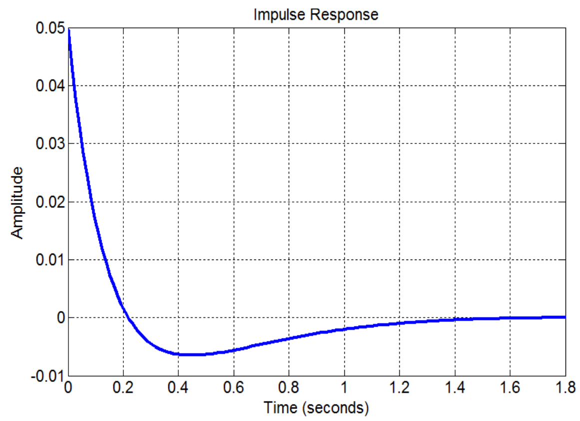

Figure 5. Response of the two-wheeled robot to an impulse disturbance under PID controller

Figure 6 presents the system's response to a large disturbance angle of $\theta = \pi/2$ rad. As shown in Figure 6(a), when the disturbance of the angle is given as $\theta = \pi/2$ rad, the system is capable of coming to a dynamic balance within about 3 seconds. However, as shown in Figure 6(b), the motor input voltage within the first few seconds needs to be unrealistically high. Because the constructed vehicle is operated with 12 V DC motors, such voltages cannot be used. Also, as shown in Figure 6(c), when the $\theta = \pi/2$ rad disturbance angle is given, the vehicle must move a very large linear distance (about 9 m, within 10 seconds) before returning to stability. Figure 6(d) shows that the initial linear velocity needs to be as high as about 4 m/s. These results show that it is practically not possible for the vehicle to return to the vertical position after such a large disturbance.

After conducting a series of simulations with varying disturbance angles, it was found that $\theta = 0.0524$ rad is the maximum disturbance angle, that can be applied to the system while the motor input voltage does not exceed the 12 V limit to generate counterbalancing torque to come to dynamic balance. This threshold is important because it defines the system's upper limit for disturbance rejection without requiring hardware-level changes, such as higher voltage motors or additional energy sources. This result was consistent with the observed behavior of the experimental system.

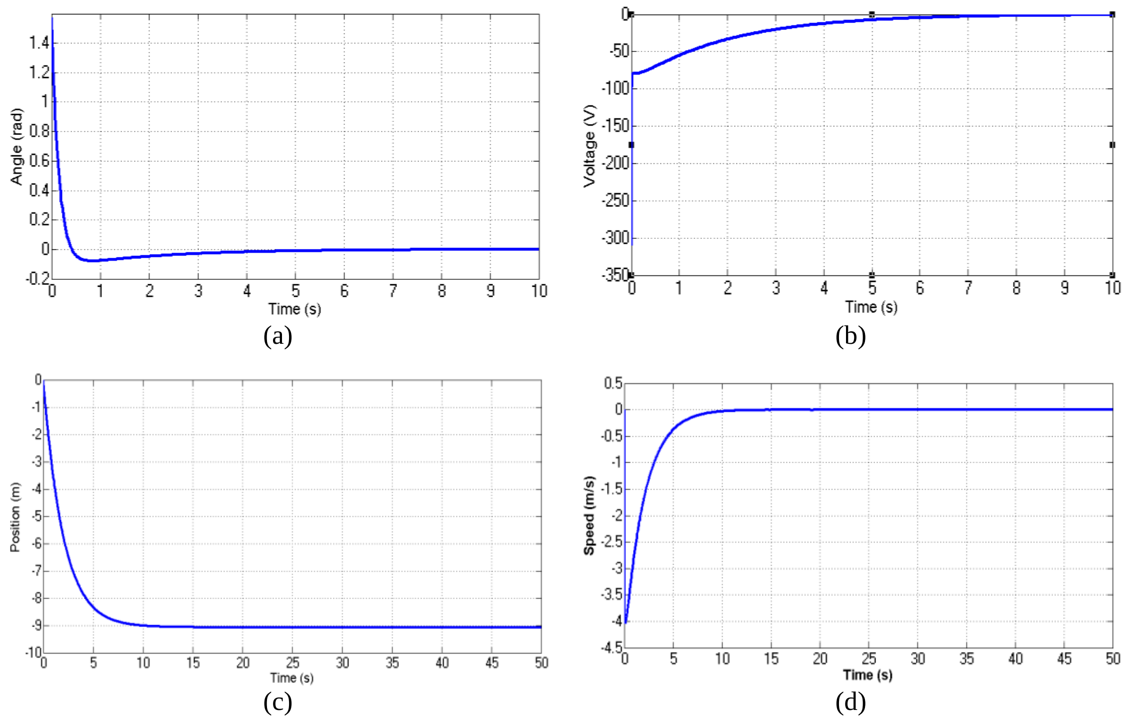

Figure 6. Response of the robot to a large disturbance angle of $\theta = \pi/2$ rad: (a) inclination angle θ vs. time (b) motor input voltage V_a vs. time (c) position of the robot vs. time and (d) speed of the robot vs. time

Figure 7 presents the system's response to a disturbance angle of θ = 0.0524 rad (approximately 3 degrees). As shown in Figure 7(a), the inclination angle returns to the vertical position (θ = 0) within about 3 seconds, indicating successful stabilization and optimal dynamic performance. As shown in Figure 7(b), when the disturbance of the angle is given as θ = 0.0524, the initial motor input voltage is about 10.5 V, and 5 seconds later it reduces to 0. As shown in Figure 7(c), when the disturbance of the angle is given as θ = 0.0524 rad, the initial angular velocity of the system is about -0.35 rad/s, and 0.5 seconds later it returns to zero. In addition, Figure 7(d), shows that when the θ = 0.0524 rad disturbance angle is given to the robot moves a linear distance of 0.3 m within 10 seconds, and Figure 7(e) shows that it achieves an initial speed of about 0.14 m/s. These values are practically possible and consistent with the behavior of the actual system.

Figure 8 shows how the system responds to sudden changes in payload while maintaining the same set of PID controller parameters. This analysis is crucial for evaluating the robustness of the control system in real-world conditions, where payloads can fluctuate due to added components, sensors, or carried objects. In Figure 8(a), the robot is simulated with a nominal payload mass of 0.702 kg. The inclination angle stabilizes quickly, confirming the controller's ability to maintain balance under standard operating conditions. In Figure 8(b), the payload is increased to 2.106 kg, which is three times the nominal mass. Although the initial deviation from the vertical position is larger and the recovery time slightly longer compared to the baseline case, the system still manages to return to equilibrium. This demonstrates that the PID controller provides sufficient corrective torque even with a significantly increased load. Figure 8(c) shows the response with a payload mass of 3.510 kg, five times the nominal mass. In this scenario, the stabilization process is slower and exhibits larger oscillations. However, the robot can still regain balance without any changes to the controller parameters. This result strongly supports the claim that the system is robust to a wide range of payload variations. These findings are particularly important because many existing TWSBR studies assume constant system parameters and do not test the impact of payload variability. The ability to maintain stability under such conditions without re-tuning the controller enhances the practicality and versatility of the system for real-world deployment.

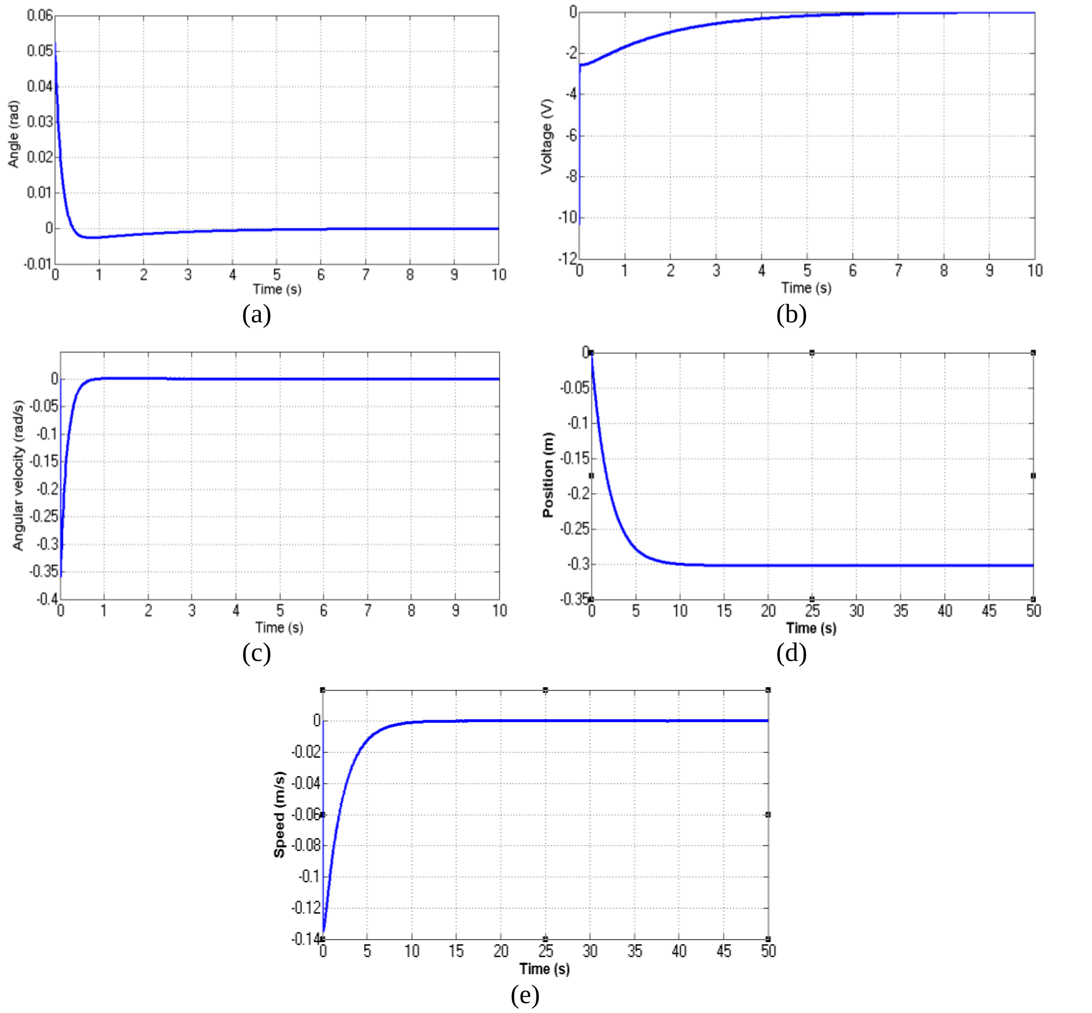

Figure 7. Response of the robot to a disturbance angle of $\theta = 0.0524$ rad: (a) inclination angle θ vs. time, (b) motor input voltage V_a vs. time, (c) angular velocity $\dot{\theta}$ vs. time, (d) position of the robot vs. time, and (e) speed of the robot vs. time

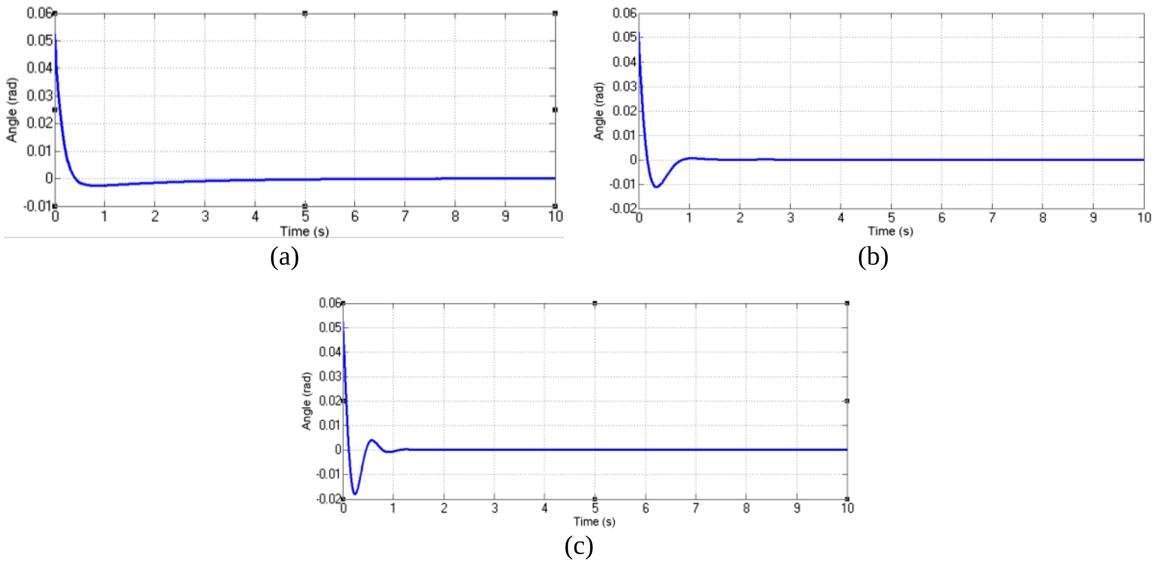

Figure 8. Inclination angle θ vs. time for (a) m = 0.702 kg, (b) m = 2.106 kg, and (c) m = 3.510 kg

4. CONCLUSION

This study examines the assessment of the dynamic performance and practical constraints of the TWSBR system. The dynamic model for the TWSBR was established in order to design a PID controller to maintain stability. The PID controller was designed and implemented and the system response against the implemented control algorithms was tested and simulated using computational tools. From the PID controller implemented TWSBR system successfully stabilized with good dynamic performance. It was found that the TWSBR system when equipped with a PID controller, is capable of maintaining stability up to a maximum disturbance angle of $\theta = 0.0524$ radians (equivalent to 3 degrees) and it can return to the vertical position in approximately 3 seconds. In addition, it was discovered that the TWSBR system was capable of maintaining stability even when the mass of the system varied across a wide range, using the same set of PID settings.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Rupasinghe Arachchige Don Dhanushka Dharmasiri	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	
Malagalage Kithsiri Jayananda	✓	✓				✓	✓			✓		✓		✓

CONFLICT OF INTEREST STATEMENT

The authors state there is no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this paper as no new data were created or analyzed in this study.

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