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Robust Control Design for Two-Wheel Self-Balanced Mobile Robot

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Abstract
As a key type of mobile robot, the two-wheel mobile robot has been developed rapidly for varied domestic, health, and industrial applications due to human-like movement and balancing characteristics based on the inverted pendulum theory. This paper presents a developed Two-Wheel Self-Balanced Robot (TWSBR) model under road disturbance effects and simulated using MATLAB Simscape Multibody. The considered physical-mechanical structure of the proposed TWSBS is connected with a Simulink controller scheme by employing physical signal converters to describe the system dynamics efficiently. Through the Simscape environment, the TWSBR motion is visualized and effectively analyzed without the need for complicated analysis of the associated mathematical model. Besides, 3D visualization of real-time behavior for the implemented TWSBR plant model is displayed by Simulink Mechanics Explorer. Robot balancing and stability are achieved by utilizing Proportional Integral Derivative (PID) and Linear Quadratic Regulator (LQR) controllers' approaches considering specific control targets. A comparative study and evaluation of both controllers are conducted to verify the robustness and road disturbance rejection. The realized performance and robustness of developed controllers are observed by varying object-carrying loaded up on mechanical structure layers during robot motion. In particular, the objective weight is loaded on the robot layers (top, middle, and bottom) during disturbance situations. The achieved findings may have the potential to extend the deployment of using TWSBRs in the varied important application.

KEYWORDS: Two-Wheel Self-Balancing Robot, Simscape Multibody, PID, LQR, Robust controller.

I. INTRODUCTION

Robotics has been developed and employed widely with advanced technology to handle complex designs and activities similar to humans[1]. The use of two instead of four wheels on robots provides a wide-range of advantages. This includes low cost, small size, and the ability to rotate quickly (to change the direction and pass through small gaps) due to the need of only two points of contact with the floor [2]. Therefore, two-wheel robots are utilized in different life-sectors and applications such as automobiles, rockets, military transportation, public health, industry, and human transportation (Segway) [3]. In particular, the hardware is used to develop an object-carrying vehicle that can reduce human efforts in the workplace significantly [4]. The Two-Wheel Self-Balancing Robot (TWSBR) can stand in the upright position with the help of an inverted pendulum controller. Inverted pendulum stability is well known as a key issue for dynamically unstable TWSBR [5], [6]. However, these works have addressed stability problem for TWSBR motion on the simple scenario of straight surfaces. The existing utilized methods to control the equilibrium position of the robot body (i.e. keeping the robot stable on the horizontal ground) include proportional integral derivative (PID) [7], Linear Quadratic Regulator (LQR), Linear Quadratic Gaussian control (LQG) [8], Neural Network control (NN) [9], and fuzzy logic controlling [10], [11]. Furthermore, three mathematical methods were used to analyze the dynamical model of TWSBRs including, Newtonian method [12], Euler-Lagrange method [13], and Kane's method [14]. Nevertheless, an accurate model is required for the design of efficient controllers. It was observed that using the mathematical equations to model a TWSBR plant had some drawbacks such as the neglecting of some term for approximate solutions. This has direct impact on reducing the modeling accuracy as well as the dynamical equations must be manually derived and prepared for usage in the block diagram. Basically, it is so hard to understand how the physical components of this system communicate in practice. Besides, the process of deriving the essential mathematical equations is rather complex [15], [16]. To mitigate this issue, the Simscape toolbox in Matlab can be used as an alternative method to model the TWSBR's structural

features. This environment has been used effectively in other applications such as Quadruped Robot [17], inverted pendulum system [18], Stewart Platform in [19], Rotary Inverted Pendulum [20], and 3RPS Robotic Platform Motion [21].
The main contribution of this work is to design a dynamical model for TWSBR by using the MATLAB Simscape Multibody package to simulate and visualize the system without the need for mathematical equations. This new environment provides a 3D visualization motion of the real-time behavior of constructed system model. Moreover, it allows studying the effect of road inclination on the performance and stability regions, and recommendations for identifying the stability region for TWSBR design. In particular, this paper includes controlling mechanical stability issues. The TWSBR motion controller system is designed using PID and LQR methods. The auto-tuning method is used to find the best values for the controller parameters. Also, changing the object-carrying weights on robot layers under road disturbance effects is utilized to demonstrate the controller's performance and robustness.
The rest of this paper is organized as follows. In Section II, the system model is detailed. Section III explains how the control design is carried out. Simulation results and discussion are shown in Section IV. Finally, Section V presents the paper's conclusion.

II. System Design and Modeling

A. System Design

The idea behind building this type of robot comes from the inverted pendulum concept as referenced theory. The pendulum rod is replaced with a 3-layers structure while the cart base is replaced with two wheels. A TWSBR structure is simulated. It consists of an assemblage of layers that are mounted on wheels and moving along a solid body. The system goal is to keep the layered structure (robot chassis) in upright with a zero inclination angle. To achieve this target, an external horizontal control force is used to drive the robot along the x-axis as the system input. The outputs of the system are the robot position (x) and inclination angle (θ).

B. Simscape Multibody Model

Simscape Multibody (SimMechanics) is a modeling tool that is used to simulate 3D robotics, vehicle suspensions, and construction equipment. Simscape blocks can be used to represent bodies, joints, constraints, force components, and sensors for proposed system plant [22]. Therefore, simscape Multibody can solve mathematical motion equations and test the control system performance. Simulink can be used to design a control system that is connected to the Simscape modelling environment [23].
Simscape Multibody library configures a 3D model of TWSBR based on the design parameters and constraints. The upper body of the robot is built as a pendulum compared with an inverted pendulum structure. It consists of three rectangular layers of a solid brick block (top, middle, and bottom) with assumed dimensions of (18cm length * 8cm width * 0.3cm thickness). This block provides a solid element to the related frame which is connected to the model using reference frame (R). All of the above layers are attached together using four rods of the solid cylinder block with assumed dimensions of (25 cm length * 0.5 radius). However, a rigid transform block is used to connect one solid block to another because it remains fixed as one solid rigid during motion simulation. Through using this block, the next port (F) element is translated relative to the base port (B). Figure 1 illustrates the connections between the different mechanical parts of the robot chassis subsystem. The wheels on the self-balancing platform are constructed of cylinder blocks with assumed dimensions of (3.25cm radius * 1.25cm length). A shaft is linked to the two wheels as shown in Fig.2. Each wheel is translated to one end of the shaft by the rigid transform before being collected in the robot cart subsystem. Also, a rigid transform is used to connect the robot cart to the world frame while the rotation transform is used to connect the chassis and the cart. To accurately position the shaft under the body, it configured a rotation transform of 90 degrees around the x-axis and 180 degrees around the y-axis. Considering the rotation is set to the x y z sequence. Also, the rotation joint is configured to turn the robot to face the positive z-direction.
A revolute joint is used to connect the chassis and cart which gives the robot rotational motion and allows the robot chassis to swing like a pendulum while a prismatic joint is used to connect the whole construction to the world frame which it gives translational motion to the robot and allows it to move back and forth. Figure 3 visualizes a 3D proposed structure of TWSBR in Simulink Mechanics Explorer.

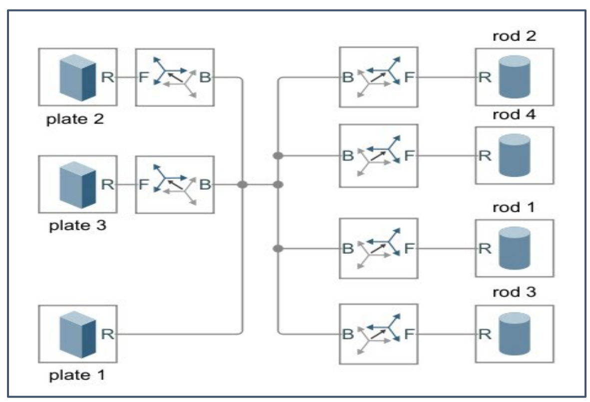


Fig.1: Modeling of robot chassis subsystem.

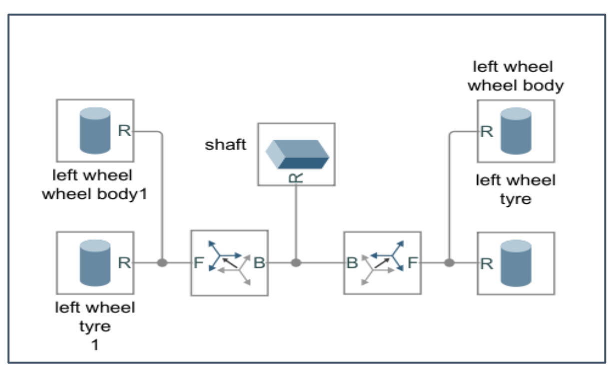


Fig.2: Modeling of robot cart subsystem.

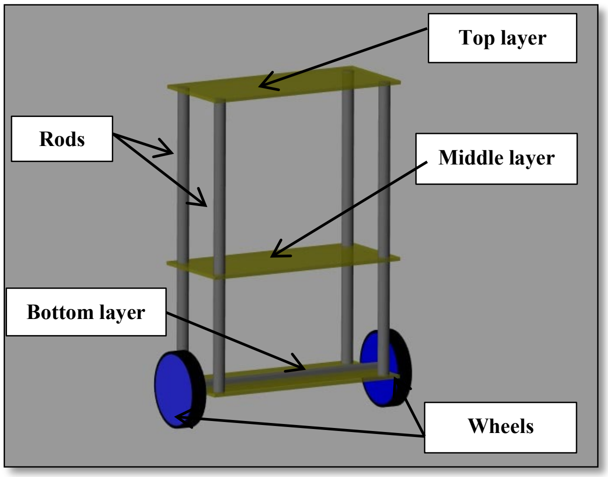


Fig.3: The structure of Two-Wheeled Self-Balanced Robot.

Figure 4 shows a designed TWSBR with Simscape Multibody Library. The external force and torque block is introduced to apply an external disturbance force on the robot body for controller evaluation as described in the following controller scheme.

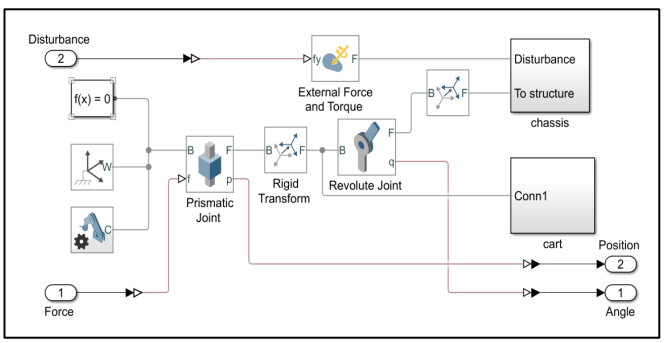


Fig.4: TWSBR open loop Simscape Multibody modeling

III. Controller Scheme

For the considered design of TWSBR, the wheels are moved back and forth to keep the robot's vertical angle close to zero. A stability criterion is given as: if the system is a Single Input Single Output (SISO) only, the robot body angle must be dependable; and if Single Input Multi Output (SIMO) system is used, it is able to control the robot position as well. The robot is challenged with several control primitives to achieve control objectives. The robot tilt angle (θ) and the wheel cart position (x) represent the current condition that needs to be controlled. These elements are discussed below.

A. PID Controller

The self-balance robot control system must be capable to reject external force perturbations from instability equilibrium to the initial vertical body position. Accordingly, it must provide the correct input to the prismatic joint to achieve the desired system behavior. To obtain the ideal input, a control loop is required with three parts: the actual robot inclination angle, the summation process to compare with the robot desired angle output, and the PID controller that provides the sufficient power to stabilize the robot. The Simulink into Physical signals (S-PS) converter has been used to mimic the functioning of a motor torque by estimating its ability to generate a linear actuation signal for translation motion after receiving feedback from the system rotational motion portion. According to [24] and [25], a classical PID controller is utilized for the proposed TWSBR. The PID control loop architecture is given by

$$U = K_p e + K_i \int_0^t e(t)dt + K_d \frac{de}{dt} \quad (1)$$

The required pitch angle for a vertical position is 0 degree. Pitch angle error is the difference between desired and measured angles. Based on these parameters the PID controller calculates the angle error gains *Kp, Ki* and *Kd*. If this assumption is correct, the PID controller output should be supplied to the S-PS converter which is configured as an actuator force action to apply on the plant to accomplish system balancing. Obviously, the Simscape plant senses the robot angle and feedbacks the deviation to the controller as an error under road disturbances effects. Figure 5 shows how to connect the 3D Simscape Multibody model of a TWSBR with controller Simulink environment. The project goal is to construct a robust design with the minimum response time while obtaining PID controllers optimal performance.
The PID auto-tuning tool software in MATLAB Simulink is successfully utilized to determine the best PID controller parameters [26]. The best parameters values obtained by using auto-tuner method as presented in Table I.

TABLE I
PID Controller Parameters of Auto-Tuning Method

PID Parameter	Value
Kp	0.563
Ki	1.552
Kd	0.02583

B. LQR controller

The robot moves back and forth under an inclination angle as implemented by the PID controller with uncontrolled position. TWSBR can be controlled using full-state feedback as described in [27]. The feedback control formula can be created by finding the gain matrix (k) and applying it to the Simscape Multibody system. The LQR method can be used to determine the robot position for improved target control [28]. The system can be given in the discrete state-space form as:

$$\boldsymbol{x}^{\cdot}(t) = \mathbf{A}x(t) + \mathbf{B}u(t) \quad (2)$$

$$\boldsymbol{y}(t) = \mathbf{C}x(t) + \mathbf{D}u(t) \quad (3)$$

The linearized system in the state-space model of TWSBR can be written in a mathematical form as [29], [30]:

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dot{\theta}\\ \ddot{\theta}\end{bmatrix}=\begin{bmatrix}0 & 1 & 0 & 0\\ 0 & \frac{-(I+ml^2)b}{I(M+m)+Mml^2} & \frac{m^2gl^2}{I(M+m)+Mml^2} & 0\\ 0 & 0 & 0 & 1\\ 0 & \frac{-mlb}{I(M+m)+Mml^2} & \frac{mgl(M+m)}{I(M+m)+Mml^2} & 0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \theta\\ \dot{\theta}\end{bmatrix}+\begin{bmatrix}\frac{I+ml^2}{I(M+m)+Mml^2}\\ \theta\\ \frac{ml}{I(M+m)+Mml^2}\end{bmatrix}U \quad (4)$$

$$y=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \theta\\ \dot{\theta}\end{bmatrix}+\begin{bmatrix}0\\ 0\end{bmatrix}u \quad (5)$$

LQR controller is used in this modeling technique to obtain the robot's chassis and cart parameters from the Simscape model that is configured when PID is employed. Figure 6 illustrates the LQR controller block diagram of TWSBR. The parameters of the TWSBR platform and their numerical values are listed in Table II. Small matrix R value is chosen since we selected high values in matrix Q to minimize the states x and θ. Resulting is getting a stronger control signal and faster robot response. Furthermore, the weights for the cost function Q and R are determined through trial and error.

$$Q = Diag([500 \quad 0 \quad 500 \quad 0]),\ R = [1]$$

The following MATLAB command is used to find gain matrix:

$$K = lqr(A, B, Q, R)$$

MATLAB Workspace was used to export a gains matrix into a TWSBR Simscape/Simulink model. Below are the gain values:

$$K = [-22.3607 \quad -14.3279 \quad 56.1181 \quad 6.0326]$$

All the two controller techniques results will be discussed in the simulation section.

TABLE II
Simscape Multibody Model Parameters of TWSBR

Symbol	Quantity	Value
M	mass of the chassis	1 Kg
m	mass of the wheels and shaft	0.2 Kg
I	moment of inertia of the chassis	0.0005 Kg/m^2
l	length to chassis center of mass	0.125 m
g	gravity	9.8 m/s^2

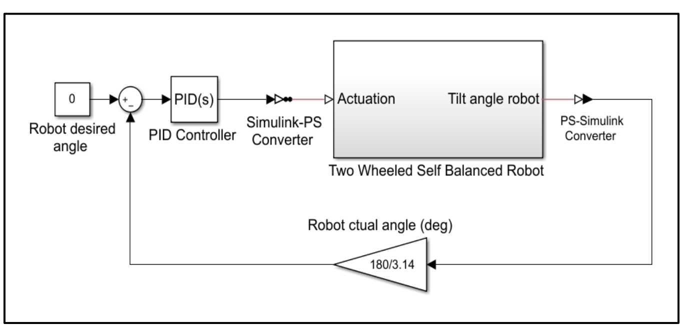


Fig.5: PID controller for TWSBR.

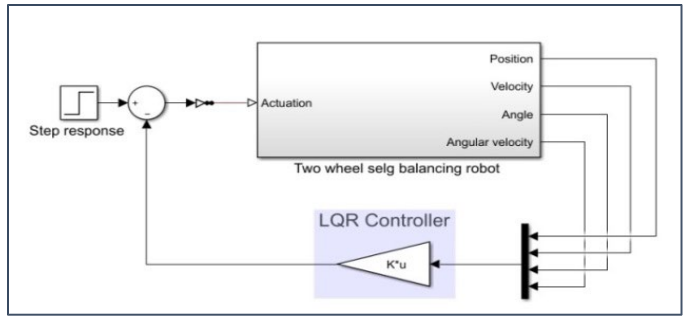


Fig.6: LQR controller for TWSBR.

IV. Simulation Results and Discussion

In this section, simulation results demonstrate how the system operates without the need for a complicated mathematical equation modeling of TWSBR by using the Simscape analysis method. This type of analysis reduced the requirement for the physical system to be implemented in real life with different control methods tested which is costly. Simulation studies are used to study the performance and robustness of the proposed TWSBR model in the presence of road disturbances. Four cases are studied: The first is an open-loop system in which the robot moves without using any controllers. The second is a closed-loop system that uses PID controllers, and the third is a closed-loop system that uses LQR controllers. The fourth, testing the controller robustness by adding weights to the robot's body. Simulation cases are discussed as below:

Case 1: open-loop system

There is no controller present in this looping system. The robot should be able to move vertically on the road and finish the movement without falling. Unfortunately, the robot cannot move in this case because it lost equilibrium and immediately fell down to the ground when the simulation started. TWSBR is in the initial position shown in Fig.7a when the simulation is starting to run. Also, Fig.7b demonstrates how TWSBR is falling down because its loop mechanism is not controlled.

Case 2: closed-loop using PID controller

The robot's tip is subjected to a single initial external force represented by 10° input angle disturbance. As a result, the controller is able to reveal the robot's original balancing in the upright position and track the robot movement in one direction. Figure 8a demonstrates how rapidly the system recovered its tilted angle after 0.56 seconds. The disturbance forces acting lead the robot angle to deviate before the controller starts. Once the controller starts, the robot angle returns to zero because it's beginning from zero condition and the wheel cart moves in a forward or backward direction at a constant speed as shown in Fig.8b.

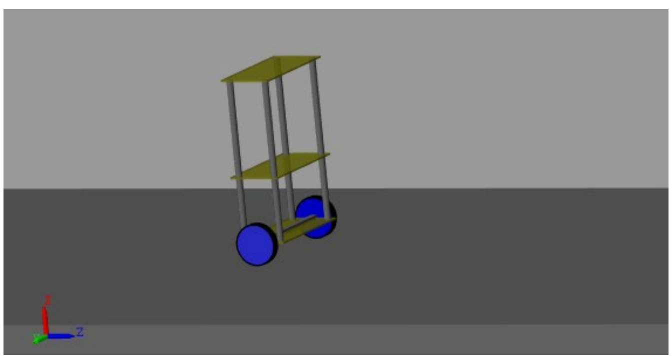
The simulation results also showed the controller's ability to reject multiple disturbance signals in different locations of the same motion simulation which confirms the controller robustness with respect to the behavior performance response system. Figure 9 shows the self-balancing behavior of simulated TWSBR model after being tilted 10° on the positive

Y-axis, $-10°$ on the negative Y-axis, and $5°$ on the positive Y-axis as disturbances subjected to robot structure.

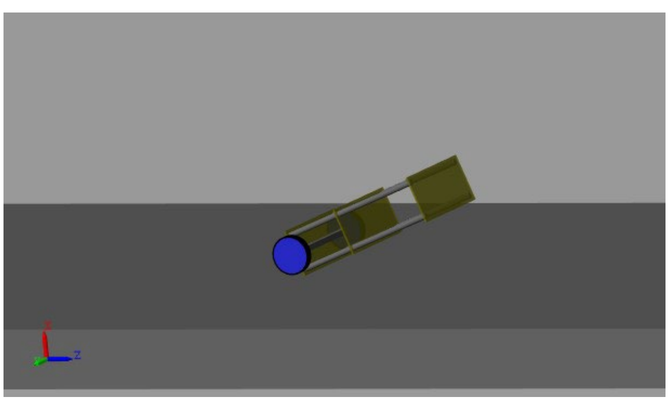
Case 3: closed-loop using LQR controller

According to the performance of the PID controller on the TWSBR Simscape Multibody model, it is clearly observed that the equilibrium is achieved correctly under road disturbance effects when the robot moves back and forth, but the position of the robot is uncontrollable. In order to give the TWSBR Simscape model access to a wider variety of control techniques and to let it take command of more system states. LQR controller is designed to be capable of controlling all four states of the system under control targets including robot wheel position, robot angle, robot velocity and the robot angle velocity.

A 10° degree disturbance angle at 0.1 seconds is applied to testing the Simscape plant. Figure 10 demonstrates the TWSBR full states system response. The controller capacity to track cart position is investigated as the wheel generates a control signal to move the wheeled robot to the desired position while keeping the robot body in the upright position. Figure10c shows the simulation results of robot position based on LQR controller were different desired position is established under external angle disturbance.

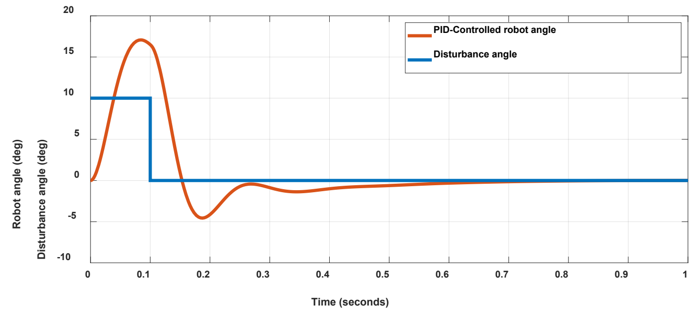


(a)

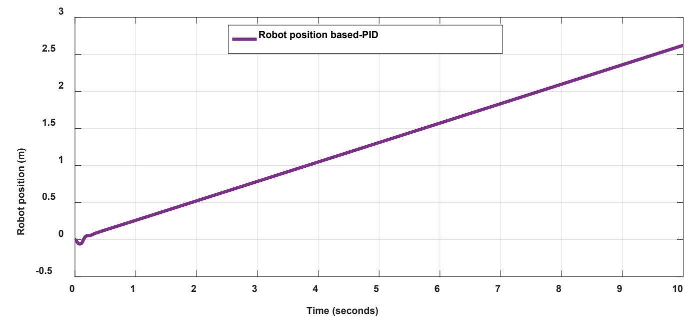


(b)

Fig.7: a) TWSBR is in the initial position. b) Showing a TWSBR falls down immediately without any controller is connected



(a)



(b)

Fig.8: TWSBR disturbance angle test. a: System response to the initial disturbance angle is applied. b: Robot Position indication.

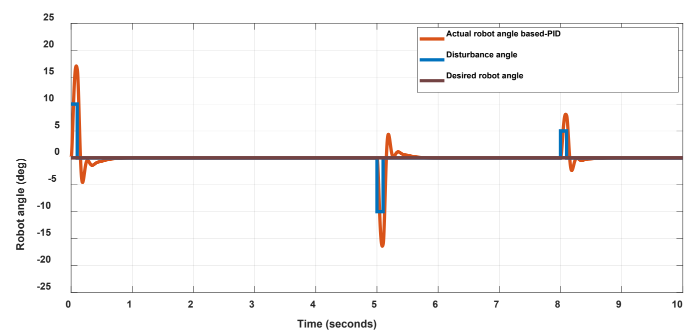
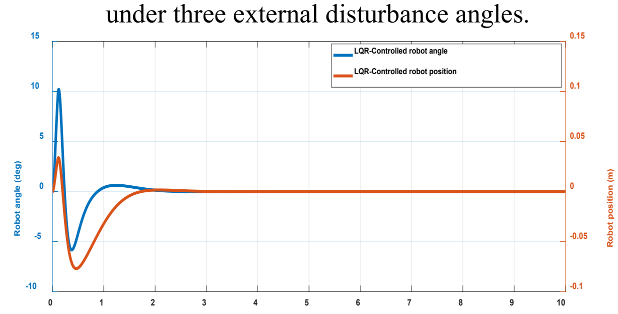
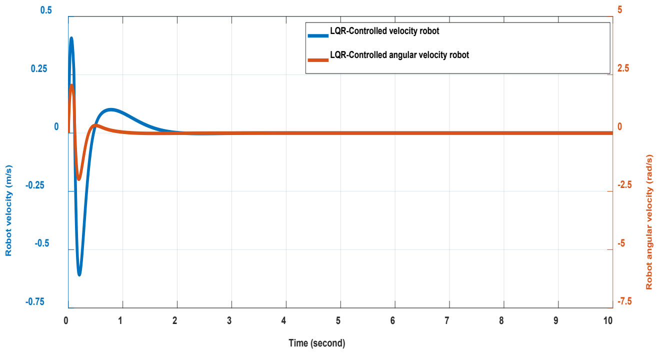


Fig.9: TWSBR inclination angle response with PID controller under three external disturbance angles.

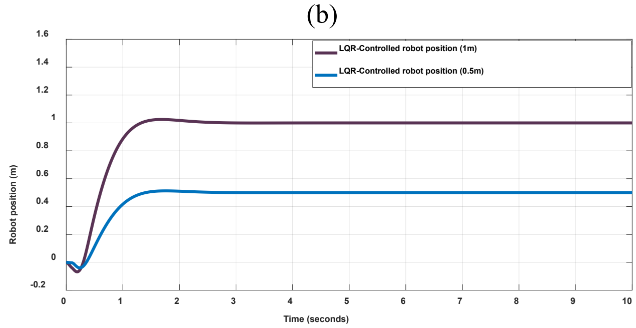


(a)

Fig.10: Full states of LQR controller responses for TWSBR a: position and body angle. b: velocity and angle velocity. c: Different desired positions are controlled by LQR controller.

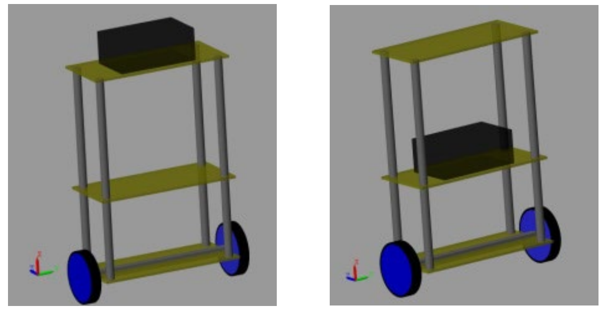


(b)

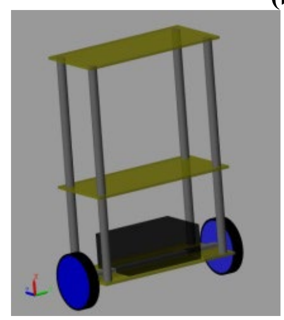


(c)

Fig.10: Continued.



(a) **(b)**



(c)

Fig.12: TWSBR 3D visualization with additional weight is loaded up. (a): on the top layer. (b): on the middle layer. (c): on the bottom layer

Case 4: Robustness test of proposed PID controller

The robustness of the proposed controller is studied by changing the carried weights on the TWSBR layers. In the three different cases 1kg, 2kg, and 3kg of additional weight are loaded to each layer of TWSBR, respectively as shown in Fig.12. Two disturbances are introduced to the controlled system in order to validate the robustness and effectiveness of the proposed controller. To evaluate the performance of the robustly designed controller, the top, middle, and bottom layers are compared in terms of their ability to handle the loaded extra weights and achieve the stability of these situations in the presence of two road disturbances. Figures 13, 14, and 15 show the PID control efforts and effectiveness for the three layers of the robot body construction when 0, 1, 2, and 3 kilograms are loaded. Furthermore, comparisons between the robot's desired angle and the robot's actual angle under two different scenarios of disturbance are used in road design. Based on the findings of the figures, the Tables III, IV and V shows the transient response of the simulation results to each robot layer for the self-balancing time (settling time), overshot, rise time, and steady-state error along with the corresponding suggested additional weights that are being loaded on three layers. When compared to the bottom layer, the top and middle robot layers have a faster self-balancing time when loading up extra weights. Moreover, they have a greater capacity for carrying and transferring the suggested additional loads of weight than the bottom layer.

TABLE III
The Key Values Response of Simulation Results for Top Layer.

Mass (kg)	Self-Balancing Time (seconds)	Rise Time (seconds)	Overshoot (%)	steady-state error
0	0.5	0.0278	61.6	0
1	0.765	0.0324	77.6	0
2	1.11	0.0329	97	0
3	1.62	0.033	125	0

TABLE IV
The Key Values Response of Simulation Results for Middle Layer.

Mass (kg)	Self-Balancing Time (seconds)	Rise Time (seconds)	Overshoot (%)	steady-state error
0	0.5	0.0278	61.6	0
1	0.774	0.0269	73.7	0
2	0.905	0.0267	88.4	0
3	1.63	0.0267	108	0

TABLE V
The Key Values Response of Simulation Results for Bottom Layer.

Mass (kg)	Self-Balancing Time (seconds)	Rise Time (seconds)	Overshoot (%)	steady-state error
0	0.5	0.0278	61.6	0
1	0.758	0.0438	82	0
2	1.88	0.0537	118	0
3	6.65	0.0606	164	0

V. Conclusions

The TWSBR Simscape Multibody (SimMechanics) model has been created as a different design environment in this paper. Also, the modeling and simulation in three dimensions are visualized with a robustness control approach by analyzing a TWSBR in Simscape library environment without depending on mathematical equation modeling to solve the balancing issue. The PID controller is designed for a TWSBR, and its optimal parameters are determined by an Auto-tuner tool software. The validity of the Simscape Multibody model is described by utilizing the TWSBR model state-space formula in the method of generating LQR controller optimal parameters and integrating them with the Simscape environment. According to simulation results, the PID controller is faster at the response and disturbance rejection than the LQR controller. However, the LQR controller has the ability to control all four states of the system under the control target, including wheel cart position and robot angle for the TWSBR Simscape model. For controller robustness verification purposes, three different weights have been added to each layer. The robustness of the controller was investigated by comparing the three layers to determine which of them can be suitable for carrying loaded weights while maintaining the fastest computed stability in the presence of road disturbances. The transient response for the key values of the simulation results was provided.

Conflict of Interest

The authors have no conflict of relevant interest to this article.

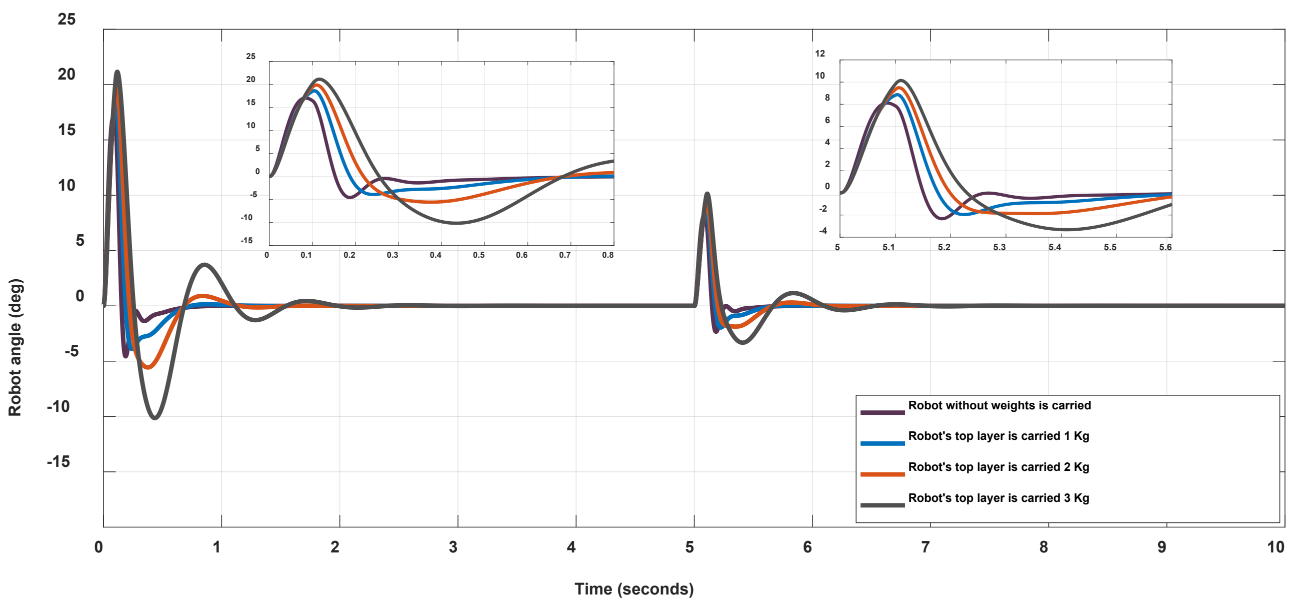


Fig.13: Robot inclination responses in three scenarios are 1, 2, 3 kg of extra weight are added to the top layer under road disturbances.

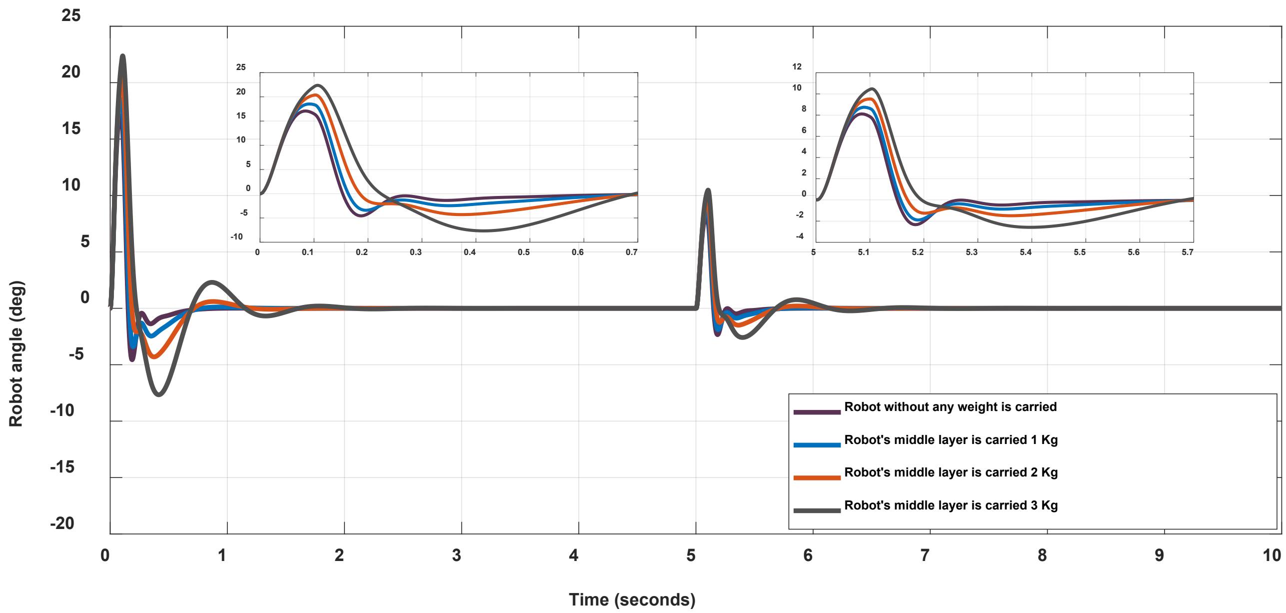


Fig.14: Robot inclination responses in three scenarios are 1, 2, 3 kg of extra weight are added to the middle layer under road disturbances.

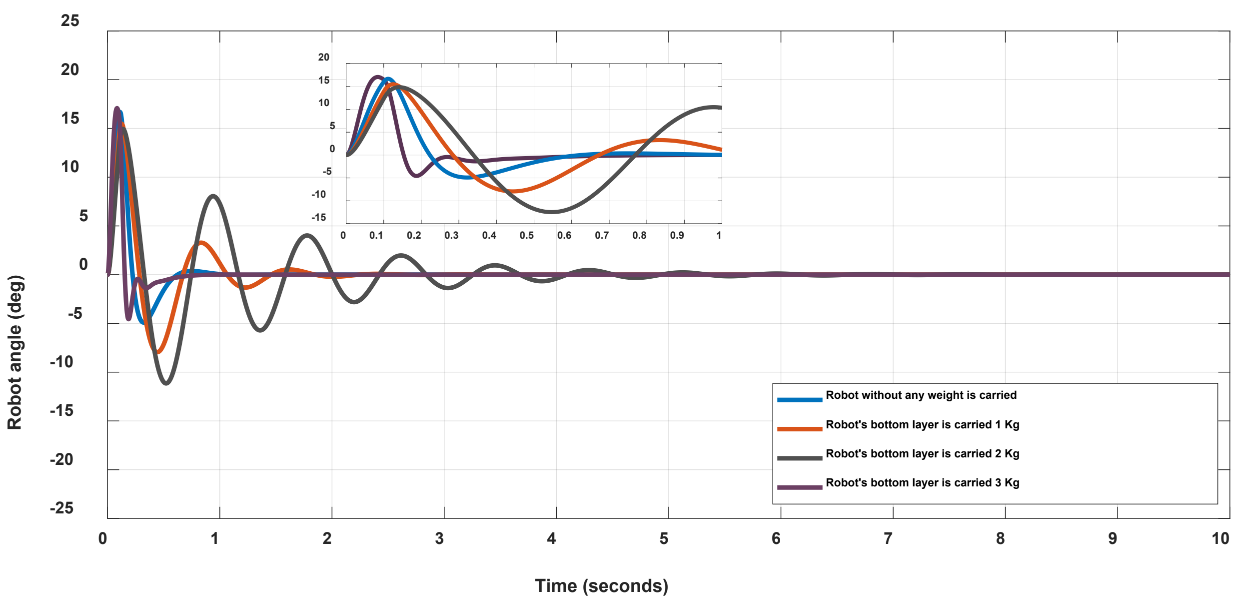


Fig.15: Robot inclination responses in three scenarios are 1, 2, 3 kg of extra weight are added to the bottom layer under road disturbances.

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