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ANALYSIS OF THE PID CONTROLLER PARAMETERS FOR A SURFACE MOBILITY PLATFORM MOBILE ROBOT

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ABSTRACT

Surface mobility control is a fundamental challenge in robotics, and its applications range from autonomous vehicles to industrial automation. The main aim of the paper is to analyse the PID controller parameters for the speed control of a surface mobility platform mobile robot. MATLAB simulation toolbox and mathematical model of the DC motor are used to find the optimal PID controller parameters to complete the DC motor speed control system. For the SMP motion control system, the mobile robot kinematic model is supported as a differential drive system. In this paper, the PID controller parameters for the DC motor control system are analysed with simulation results using various KP, KI, KD gains. The experimental results of the SMP mobile robot with optimal PID controller parameters are analysed by driving on the rough, slope and even terrains. According to simulation results and experimental tests, the proposed system effectively controls the speed of the SMP mobile robot, demonstrating satisfactory performance in terms of settling time, rise time, and system overshoot. Among PI and PID controllers, the designed PID controller can quickly control to reach the desired DC motor speed. Using the optimal PID coefficient parameters, all motors reached their desired speed in 0.12 seconds during simulations. In the experimental tests on various terrain (even, slope and rough), all motors achieved their desired speed simultaneously within 25 seconds.

Keywords: *differential drive, PID controller, motion trajectory, real-time speed control, skid steering, SMP mobile robot, surface mobility control*

INTRODUCTION

Mobile robots are one of the most important fields of science and technology. Robots can be substituted for humans in various fields due to their abilities. Applications include surveillance, planetary exploration, patrolling, emergency rescue operations, reconnaissance, petrochemical applications, industrial automation, construction, entertainment, museum guides, personal services, intervention in extreme environments, transportation, medical care, and so on, as well as many other industrial and non-industrial applications [1]-[3]. Moment control of the mobile robot includes wheels, tracks, or legs. In the motion control for mobile robots, motors or other mechanisms are used as actuators. Mobile robot systems can vary significantly based on the drive systems, which refer to the mechanism that propels and controls the robot's movement. The drive system influences the robot's mobility, manoeuvrability, and performance in different environments. Some common variations of mobile robot systems based on the drive systems are differential drive robots, omnidirectional drive robots, holonomic and nonholonomic robots, tracked drive robots, legged drive robots, and four-wheeled drive robots.

Alternate surface mobility techniques that deviate from traditional wheeled reaction forces will continue to emerge in environments with different challenges; these include amphibious or aquatic targets and low-gravity surface travel in either unconsolidated or rocky media. The terrain is unsuitable for wheels to react against in both cases, and other locomotive methods are required [4]. Skid-steering mobile robots and surface mobility robots refer to similar concepts, both involving robots capable of manoeuvring across surfaces. The skid steering mobile robot has a simple and robust mechanical structure. SSMRs are widely used as outdoor mobile robots. They are suitable for terrain traversals such as loaders, farm machinery, mining and military applications due to their simple and robust mechanical structure, faster response, high manoeuvrability, strong traction, and high mobility [5]-[6]. The principle of skid steering is based on controlling the relative velocities of both tracks in a similar way to the control of differential wheeled vehicles. Since none of the wheels has a steering structure, the movement direction is changed by controlling the differential velocities of the left and right wheels [7]. The kinematics model of the skid-steering mobile robots was first designed based on instantaneous rotation centres (ICRs) [8]-[9].

DC motors are commonly used as actuators in many control systems because they provide a larger torque to the load and have good start performance and speed characteristics. Newton's second law and Kirchhoff's law of voltage (KVL) is used for DC motor control [10]. The DC motor model was designed with a PID controller to control the speed of the motor under the effect of load [11]-[13]. A DC motor is designed and placed on the robot's wheels for robotic mobility [14]. The angular rotational velocity of the wheels must be precisely controlled to minimise odometry errors [15].

This paper presents the analysis of the PID controller parameters of four DC motors for controlling a four-wheeled surface mobility platform SMP mobile robot. Both the PID auto-tuning method and the PID manual tuning method are utilised to determine the optimal PID parameters for the motion control of SMP mobile robots on even and rough terrain.

SYSTEM MODELING

The main idea of the proposed system is to identify the parameters of four DC motors and coefficient PID tuning parameters for driving the SMP mobile robot on even surfaces. These parameters are obtained by using the MATLAB simulation toolbox. Four DC motors with encoders, two dual-channel motor drivers, a main controller, and a 12-volt power supply are used to drive the mobile robot. The system is regarded as a differential drive system for motion control of the SMP mobile robot. The general block diagram for the proposed system is shown in Figure 1.

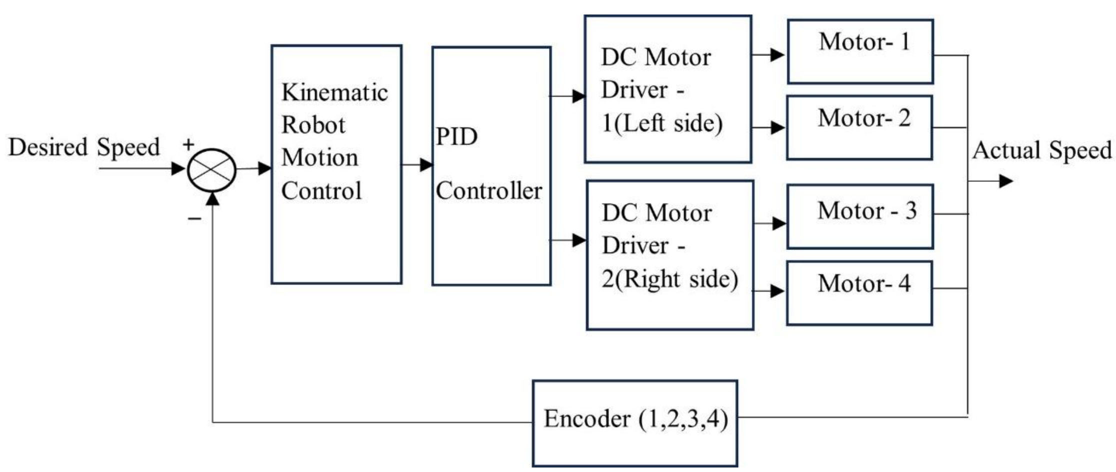


Figure 1 General block diagram for a proposed system

Kinematic Model of SMP Mobile Robot

For the kinematic modelling of the SMP mobile robot, it is assumed that the centre of mass (CG) is located at the geometric centre. The vehicle can only move on the two-dimensional plane of an SMP mobile robot, as shown in Figure 2.

Suppose the robot moves on a plane with a linear velocity expressed in the local and rotates with an angular velocity vector expressed as:

$$v = (v_x, v_y, \omega_z)^T \tag{1}$$

$$\omega = [0, 0, \omega_z]^T \tag{2}$$

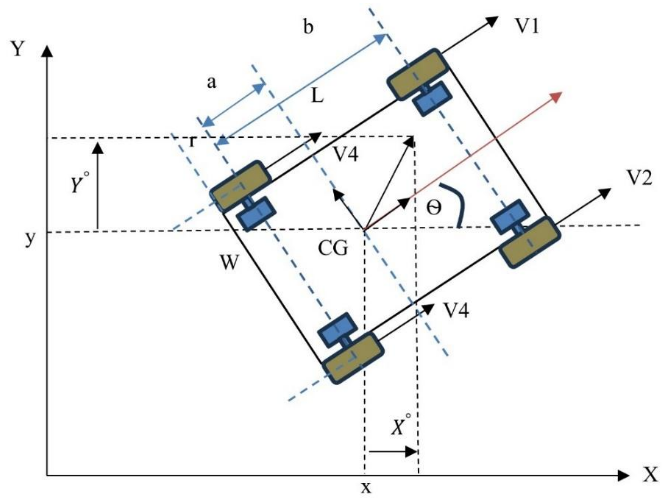


Figure 2 Free body diagram of SMP mobile robot

If $[X, Y, \theta]^T$ is the state vector describing the generalised coordinate of the robot (i.e., the CG position, X and Y, and the orientation of the local coordinate frame with respect to the inertial frame), then $[x°, y°, \theta°]^T$ denotes the vector of generalised velocities. It is straightforward to calculate the relationship of the robot velocities in both frames are calculated [16]. Mobile robot velocity is taken by kinematic modelling, and the velocity of each wheel is calculated as:

$$\begin{bmatrix} x^{\circ} \\ y^{\circ} \\ \theta^{\circ} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} \tag{3}$$

$$v_L = r\omega_L,\ v_R = r\omega_R \tag{4}$$

$$v_L = v_1 = v_3 \tag{5}$$

$$v_R = v_2 = v_4 \tag{6}$$

$$\omega = \frac{v_R - v_L}{W}, \tag{7}$$

$$v = \frac{v_R + v_L}{2} \tag{8}$$

where,

r = wheel radius
v = wheel linear velocity
v_R = right wheel velocity
v_L = left wheel velocity
ω = wheel angular velocity
ω_L = left wheel angular velocity
ω_R = right wheel angular velocity
W = width of mobile robot

Dynamic Model of a DC Motor

Due to its simplicity, reliability, and controllability, DC motors are used in various industries and applications, ranging from robotics to automotive systems. Modelling motors are essential for understanding the behaviour, designing control systems, and optimising performance. Modelling a DC motor involves representing its electrical and mechanical characteristics mathematically. Modelling a DC motor can be achieved through various techniques, including first principles modelling, empirical modelling, and system identification. In this paper, system identification techniques are used to identify the parameters of a DC motor. System identification techniques utilise input-output data to estimate model parameters, enabling accurate representation of motor dynamics. The applied voltage directly affects the DC motor's speed and motor torque is proportional to current. Therefore, the speed of the DC motor can be adjusted by changing the supply voltage [17]-[18].

The dynamic model and speed control block diagram of the DC motor are shown in Figures 3 and 4. The DC motor closed loop and dynamic equation are equated as:

$$\mathrm{J}\frac{d\omega}{dt} + b\omega = k_t \mathrm{i}, \tag{9}$$

$$\mathrm{L}\frac{di}{dt} + Ri + k_e\omega = \mathrm{V} \tag{10}$$

$$G(s) = \frac{\theta(s)}{V_a(s)} = \frac{k_m}{s\left[(R_a + L_a s)(Js + b) + k_b k_m\right]} \tag{11}$$

where,

R_a = armature resistance (Ω)
L_a = armature inductance (mH)
T = motor friction torque (N m)
i = armature current (A)
$V_a(s)$ = armature voltage (V)
$b\omega$ = fraction of motor
J = motor inertia (kg m^2)
k_m = motor torque constant (Nm/A)
k_b = back emf constant (Vs)

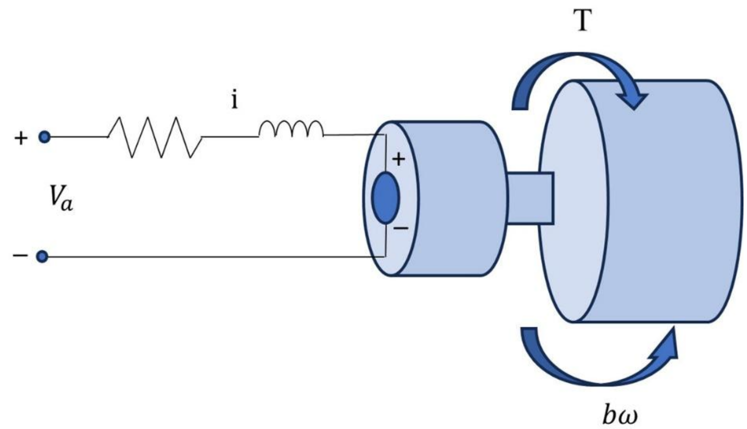


Figure 3 Dynamic model of a DC motor

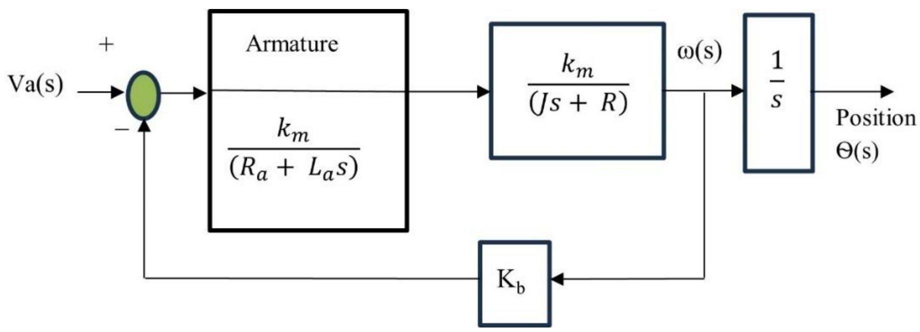


Figure 4 Block diagram of a DC motor closed-loop control system

CONTROL STRUCTURE AND METHODOLOGY

In this paper, controlling a four-wheeled mobile robot considers the assumption that the ground surface is rigid, horizontal, and even, that all wheels have contact with the surface, and that the robot does not rotate about the x and y-axis. Four DC motors with gear ratio according to the motor datasheet are 65.5:1. All the motors are placed on each wheel of the mobile robot for mobility. A mathematical model of a mobile robot system is used as a differential drive system, and a DC motor mathematical model is used as a drive system for system modelling development. The schematic diagram for the proposed system is shown in Figure 5.

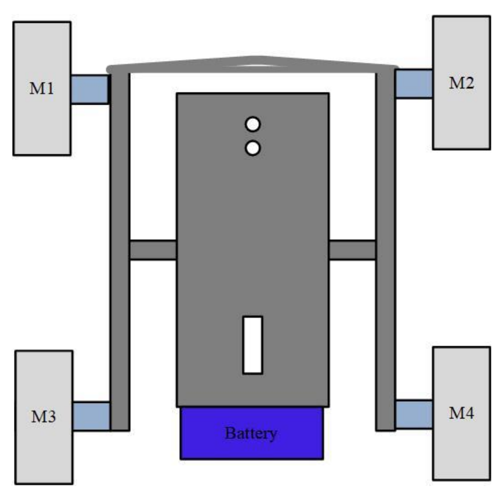


Figure 5 Schematic diagram of SMP mobile robot

The robot will be moved forward when all motors are synchronised at the same speed, and it will be reversed when all motors have equal speeds but in opposite directions. The robot will be turned left when the speed of the right motors, M2 and M4, is slower than that of the left motors, M1 and M4. The mobile robot will be turned right when the velocity of the left motors, specifically M1 and M3, exceeds that of the right motors, M2 and M4.

PID Controller Implementation

In the proposed SMP mobile robot system, PID tuning is a common method used to optimise the control system of the mobile robots. PID controllers are used to regulate the robot's motion and ensure that it follows a desired trajectory or maintains a specific position. The "P" term varies directly with the present error, representing the disparity between the desired and current states. It provides a corrective response directly proportional to the magnitude of the error. By increasing the "P" gain, the system becomes more responsive to errors, but it's important to watch out for overshooting. The "I" term accounts for accumulated past errors over time. It helps eliminate steady-state errors and corrects for prolonged deviations from the desired trajectory. It is necessary to adjust the "I" gain to reduce steady-state errors. The" D" term anticipates future errors by considering the rate of change of the error. It dampens oscillations and prevents overshooting. By raising the "D" gain, the system adds damping and improves stability. However, damping should be avoided, as it might slow down the system's response [19]. For a four-wheeled mobile robot system, the PID tuning method is applied to control individual wheel velocities to achieve desired movements. This paper compares the experimental results of four DC motor speed controls for SMP mobile robot control with the PID tuning method simulation results. The closed-loop system of PID implementation for the DC motor speed control system is shown in Figure 6.

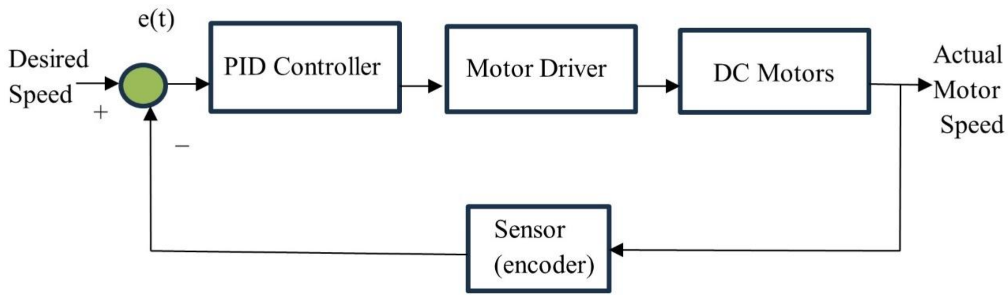


Figure 6 Block diagram of a DC motor closed loop system with PID implementation

The Procedure of the PID Parameter Tuning Method

In a DC motor with an encoder, tuning PID parameters are derived by adjusting the proportional, integral, and derivative gains to achieve the desired speed performance. Depending on the behavior of the motor, the PID controller is supported by adjusting the voltage applied to the motor based on the difference between the desired and actual speed [20]. The PID optimal parameters depend on the specific characteristics of the DC motor and the load and control requirements of the application. PID coefficient parameter equations for the DC motor are calculated as:

$$U(t) = K_P\, e(t) + K_I \int_0^{\tau} e(t)d(t) + K_D \frac{d(e)}{d(t)} \qquad (12)$$

where,

$U(t)$ = control signal
$e(t)$ = error signal
K_P = proportional gain
K_I = Integral gain
K_D = The derivative gain

For the proposed system, PID coefficient parameters are derived using two methods. The first is the PID auto-tuning method, and the second is the PID manual tuning method, which uses the DC motor model used in the SMP mobile robot. In the proposed system, the MATLAB system identification toolbox is used to automatically tune a PID controller for a DC motor control system to reach the desired speed. The DC motor Simulink model with the DC motor system for the SMP mobile robot is used for auto-tuning operation. For auto-tuning and manual tuning of the PID controller for a DC motor in MATLAB, the system used the electrical and mechanical parameters of DC motors shown in Table 1. After using PID auto-tuning and manual tuning methods, the coefficient parameter values (K_P, K_I, K_D) required for the SMP mobile robot were obtained as shown in Tables 2 and 3.

In an SMP mobile robot, four motor behaviours, such as the parameters of inertia (J), back emf constant (K), inductance(L), and damping (b), are different. Therefore, the result of PID tuning parameters is not the same for each motor, as shown in Table 1. This result is obtained using the DC motor's mathematical model in the MATLAB simulation toolbox. The PID controller for the proposed system is shown in Figure 7.

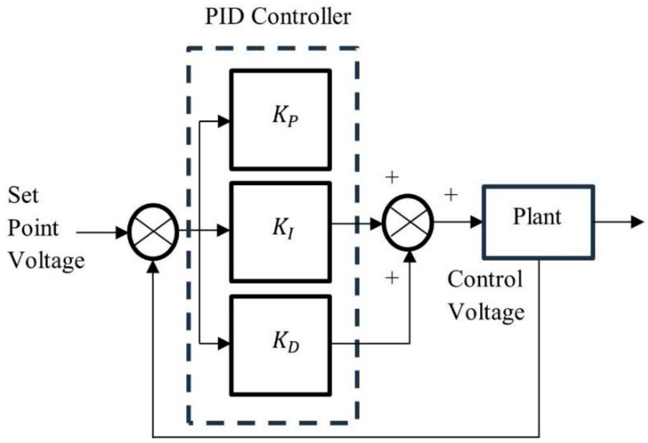


Figure 7 Block diagram of PID controller

EXPERIMENTAL INVESTIGATIONS OF CONTROLLER PERFORMANCE

For the control system, the DC motor model is created using the Matlab/Simulink package. In this paper, the parameters of DC motors (J, b, K, L) derived from the MATLAB simulation toolbox are implemented, as shown in Table 1. The parameters of DC motors are shown in Table 1. The R parameters are acquired through the utilisation of a multimeter. Motor M4 exhibits the lowest resistance value, while motor M1 displays the highest resistance value, as shown in Table 1.

A PID controller is used to gear a DC motor with the encoder in order to control the speed of the motor's wheel actuators. The gear DC motor encoder is used to detect the error between the actual and desired speed of the DC motor, and the error signals are used to update the PID controller gains. PID gains K_P, K_I, and K_D are tuned to reach the desired speed, as shown in Table 2.

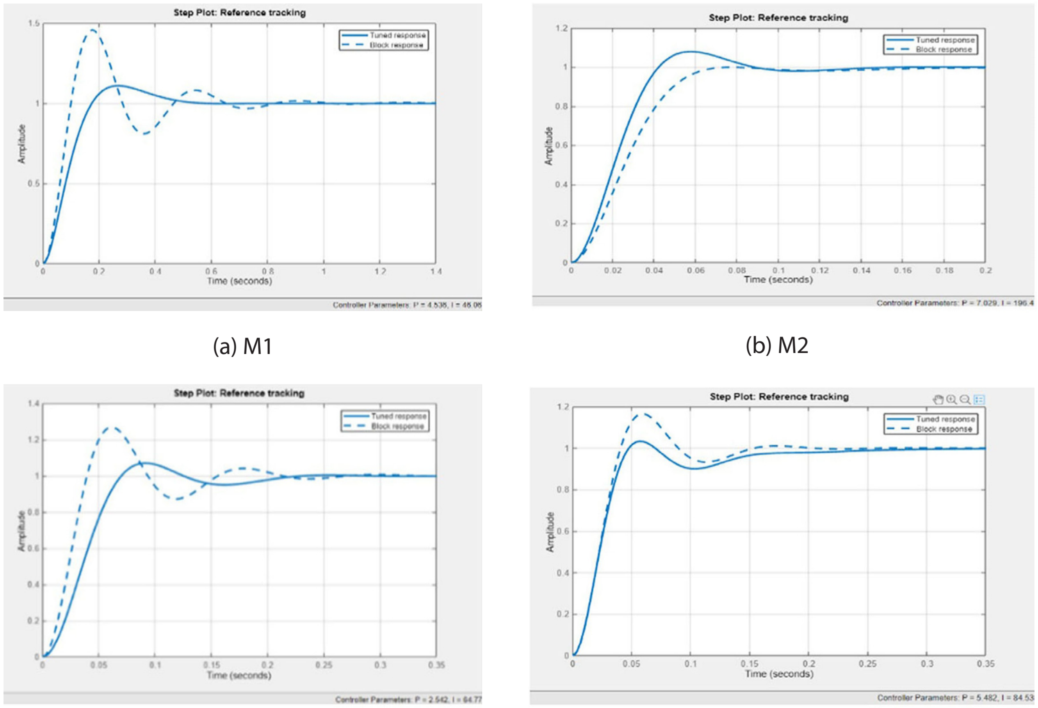
The simulation results for four DC motors using two methods (block response and tune response) are shown in Figure 8. In the response curve, the PI controller is used to control the motor. The "tune response" and "block response" refer to two different approaches for tuning the PID controller parameters to achieve desired performance, especially to reach the target speed. All the motors have high overshoot, and the settling times of M3 and M4 are over 0.25 seconds. Therefore, the PID controller is needed to use for the proposed system.

Table 1 Result of estimated parameters of DC motors used in SMP

Motor No.	J	K	L	R	b
1	1.13E-05	0.0110	0.3099	12.9190	2.40E-05
2	6.60E-05	0.0018	0.0675	4.5516	2.23E-05
3	1.40E-05	0.0301	0.0638	3.2843	5.53E-05
4	2.21E-05	0.0353	0.0400	2.7031	6.45E-05

Table 2 Result of estimated PID gain values used in the proposed system (auto-tuning)

Motor No.	K_P	K_I	K_D
1	5.6118	137.8855	0.0553
2	7.7383	252.5987	0.0532
3	5.5694	137.7014	0.0531
4	5.665	158.2641	0.0492

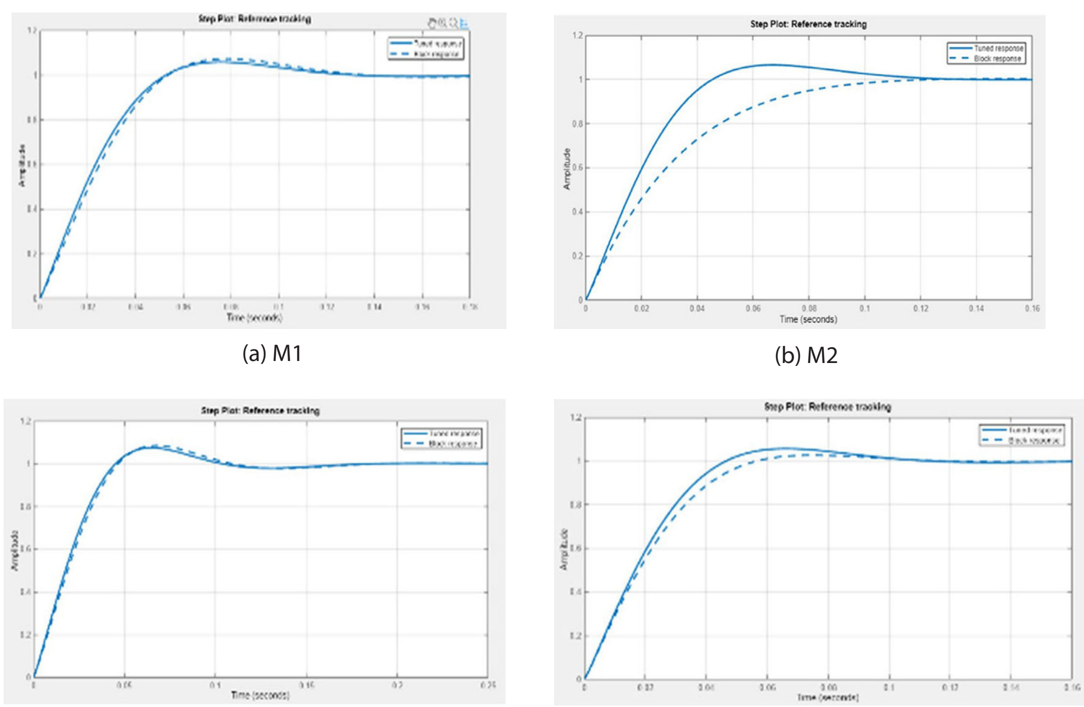


(a) M1 (b) M2

(c) M3 M4

Figure 8 Simulation response curve for four DC motor with PI controller

The simulation result of four DC motors with PID controller are shown in Figure 9. The response curves show that motors M1 and M2 reach their desired speed of about 0.12 seconds, although DC motors M3 and M4 reach their desired speed of about 0.15 seconds and 0.1 seconds, respectively. Besides, the response curves



(a) M1 (b) M2

(c) M3 M4

Figure 9 Simulation response curve for four DC motors (with auto-tuning coefficient PID parameters) (block and tune response) of motors M2 and M4 do not coincide, as seen in Figure 9.

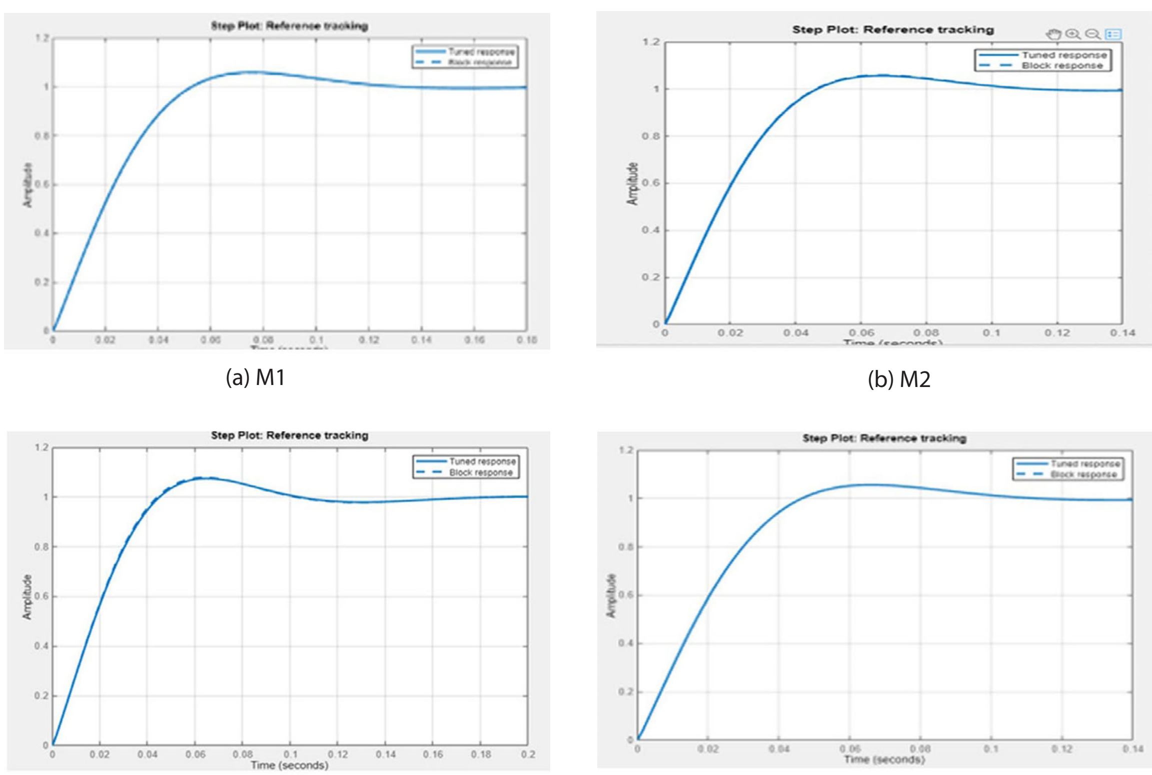
All the motors have different settling times and overshoot. As a result, although the motors are driven at the same speed, the robot cannot move straight on the ground. Therefore, it is required to tune the optimal values of PID parameters for all DC motors and tunned again to coincide with the two response results. Consequently, the response curves of all DC motors achieve a settling time of 0.12 seconds. The resultant coefficient parameters of the second fine-tuning are shown in Table 3.

Table 3 Result of estimated PID gain values used in the proposed system (manual tuning)

Motor No.	K_P	K_I	K_D
1	5.61	137	0.055
2	5.66	160	0.049
3	5.40	140	0.065
4	7.00	158	0.049

The simulation response curve using PID coefficient parameter values is shown in Figure 10. All four response curves exhibit slight overshoot but consistently achieve a settling time of 0.12 seconds and possess almost identical rise times.

After applying auto-tuning coefficient parameter values (K_p, K_I, K_D) for each motor, test the SMP mobile robot on an even surface. According to changing disturbances and frictions of each motor, the settling



(a) M1

(b) M2

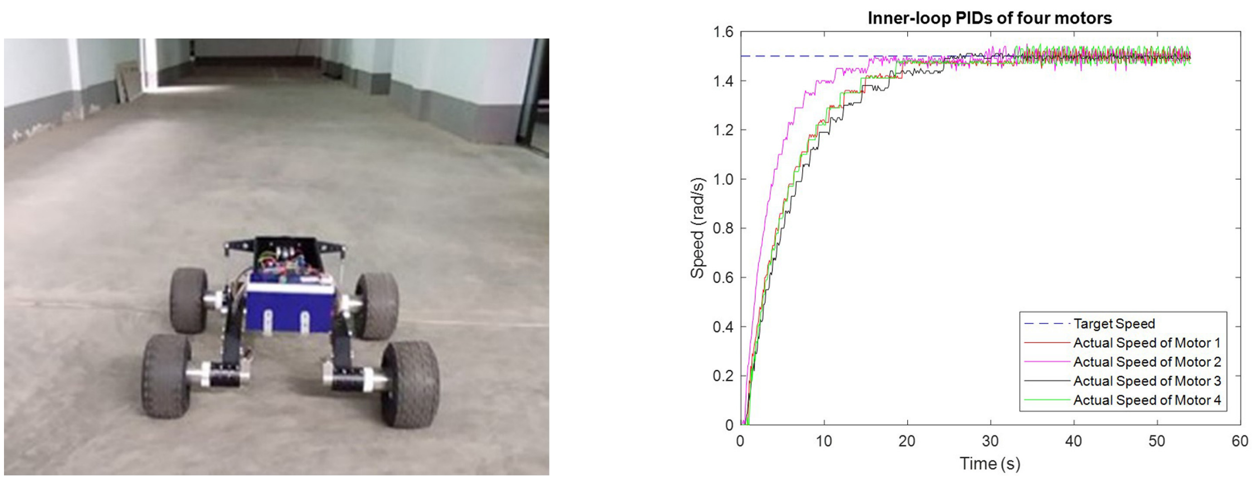
(c) M3

(d) M4

Figure 10 Simulation response curve for four DC motors (second tuning coefficient PID parameters) time to reach the desired speed is a little gap on each motor, as shown in Figure 11.

To achieve optimal performance, the proposed system utilises the manual tuning method. The real-time testing result in SMP mobile on even terrain using manual tuning parameters and values of PID is shown in Figure 12. After applying the new coefficient PID parameters values, all the motors have the same rise time settling times and reach the desired speed over 20 seconds, respectively. There is friction and other disturbances on the ground. The real-time testing result on even ground has noise, and the settling time to reach the desired speed slightly differs from the simulation result.

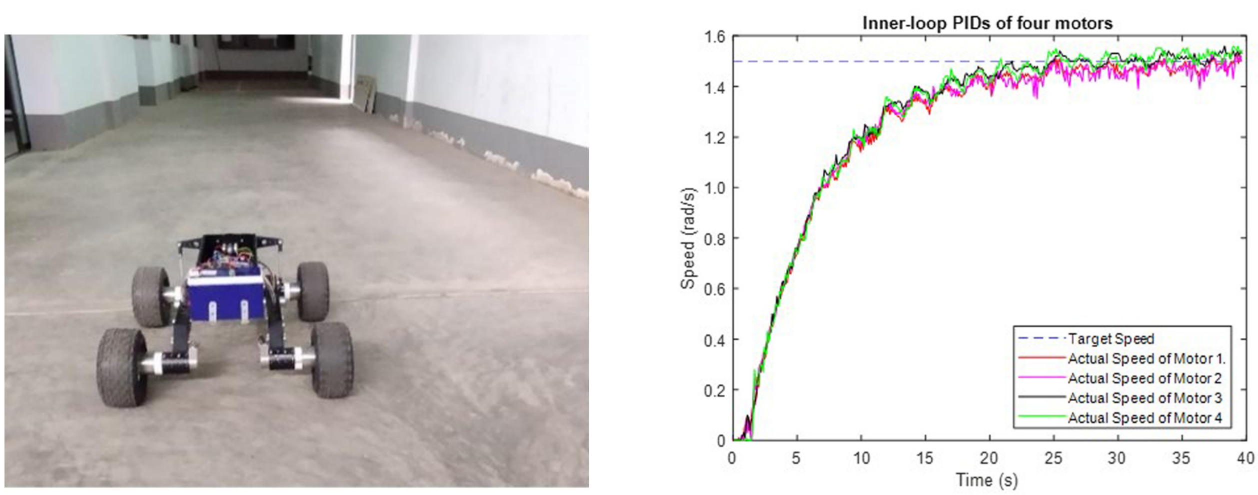
The real-time testing of SMP on an inclined surface in a downward condition is shown in Figure 13, and the upward condition is shown in Figure 14. When the robot moves on inclined conditions due to surface irregularities and other ground disturbances, the response curve exhibits significant noise. However, all the DC motors achieve the same settling time and reach their target speed over 20 seconds.



(a) Test on even terrain

(b) Response curve

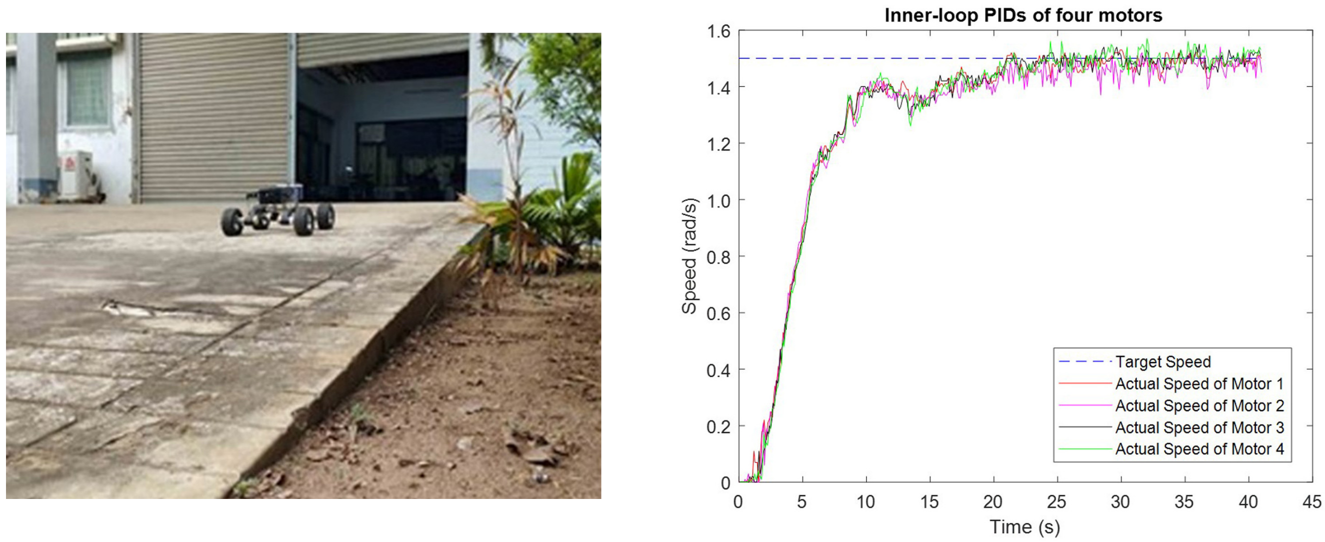
Figure 11 Comparison of desired and actual speed of four DC motors with PID controller (auto-tuning) in real-time testing result on even terrain



(a) Test on even terrain

(b) Response curve

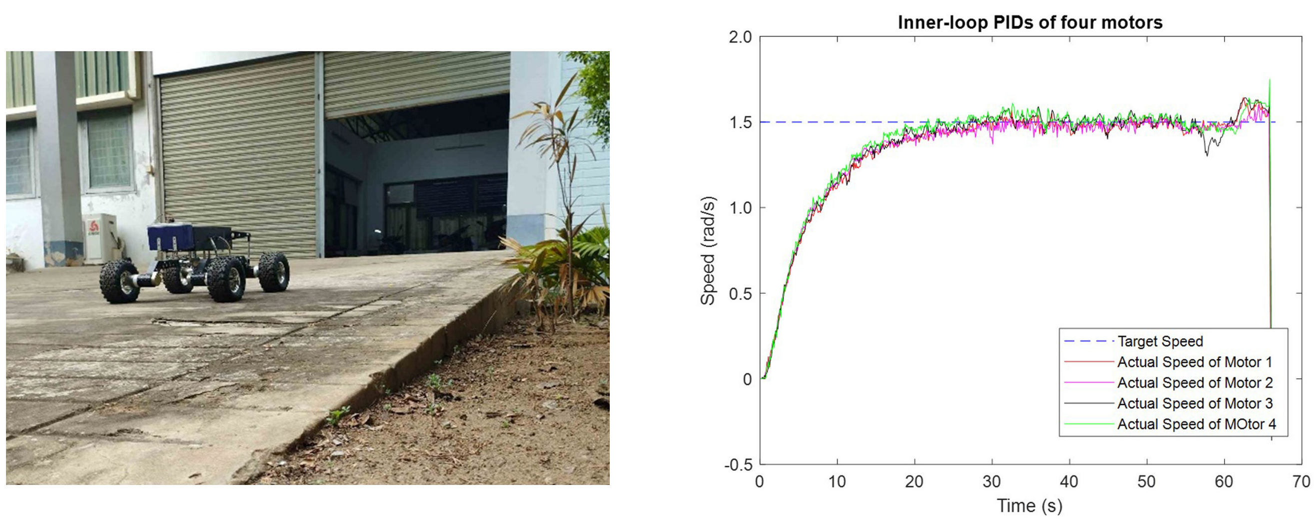
Figure 12 Comparison of desired speed and actual speed of four DC motors with PID controller (manual tuning) in real-time testing result on even terrain



(a) Test on downward condition

(b) Response curve

Figure 13 Comparison of desired speed and actual speed of four DC motors with PID controller (manual tuning) in real time testing result on inclined motion (with PID manual tuning parameters)



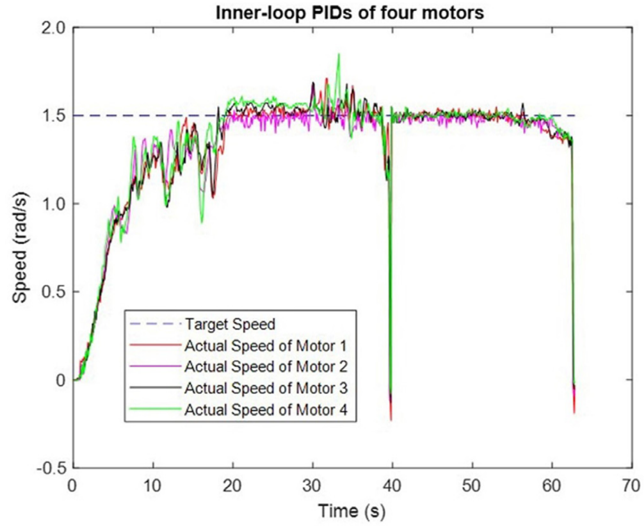
(a) Test on upward condition

(b) Response curve

Figure 14 Comparison of desired speed and actual speed of four DC motors with PID controller (manual tuning) in real-time testing result on inclined motion (with PID manual tuning parameters)

A comparison of the desired speed and actual speed of four DC motors for SMP mobile robot drive on rough terrain is shown in Figure 15. When the robot navigates on rough terrain, the friction coefficient can vary widely due to different surface materials and unexpected holes and slopes, and the robot can alter its speed and stability. In the SMP mobile robot test on rough terrain depicted in Figure 15a, all the motors reach their desired speed within 20 seconds. At 40 seconds during the running time of the SMP mobile robot, the robot encounters a 7.6 cm step. The robot can ascend the step without a speed reduction, and all the motors regain their desired speed within 1 second. According to the response curves, the proposed system successfully maintains the stability and accuracy of the desired speed for all motors of the SMP mobile robot.

(a) Test on rough terrain



(b) Response curve

Figure 15 Comparison of desired speed and actual speed of four DC motors with PID controller (manual tuning) in real-time testing result motion on rough terrain (with PID manual tuning parameters)

CONCLUSION

The proposed system employs four-gear DC motors for the mobility of the SMP mobile robot and uses the PID controller to regulate the motor speed. The forward motion trajectory is predicted based on the kinematic model. Based to simulation results obtained in MATLAB and experimental test, the proposed system can effectively control the speed of the SMP mobile robot with settling time, rise time, and system overshoot. Among PI and PID controllers, the designed PID controller can quickly control to reach the desired DC motor speed. Vibrations are present in the resulting curve due to friction and noise, but the motion control of the SMP mobile robot remains exceptionally smooth during many terrains testing.

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REFERENCES

[1] F. Rubio, F. Valero, and C. Llopis-Albert, "A review of mobile robots: Concepts, methods, theoretical framework, and applications", *International Journal of Advanced Robotic Systems*, vol 16, no. 2, 2019, doi:10.1177/1729881419839596.

[2] S.G. Tzafestas, "Mobile Robot Control and Navigation: A Global Overview", *J Intell Robot Syst.*, vol. 91, pp. 35–58, 2018, doi: 10.1007/s10846-018-0805-9.

[3] G. Yang and S. Hu, "Review of Robotics Technologies and Its Applications," *2023 International Conference on Advanced Robotics and Mechatronics (ICARM)*, 2023, pp. 322-329, doi: 10.1109/ICARM58088.2023.10218815.

[4] A. Thoesen and H. Marvi, "Planetary Surface Mobility and Exploration: A Review", *Curr Robot Rep,* vol. 2, pp. 239–249, 2021, doi: 10.1007/s43154-021-00056-3.

[5] W. Yu, O. Y. Chuy, E. G. Collins, and P. Hollis, "Analysis and experimental verification for dynamic modelling of a skid-steered wheeled vehicle," *IEEE Transactions on Robotics*, vol. 26, no. 2, pp. 341–353, 2010

[6] X. Yue, J. Chen, J., and Y. Li, "Path Tracking Control of Skid-steered Mobile Robot on the Slope Based on Fuzzy System and Model Predictive Control", *Int. J. Control Autom. Syst.*, vol. 20, pp. 1365–1376, 2022, doi: 10.1007/s12555-021-0203-0

[7] B. Ramkumar, H.M. Kittur, and P. M. Kannan, "ASIC implementation of modified faster carry save adder," *Eur. J. Sci. Res.,* vol. 42, no. 1, pp.53–58, 2010

[8] C. Yang, W. Yao, Z. Wei, and D. Shaoyi, "Kinematics Model Estimation of 4W Skid-Steering Mobile Robots Using Visual Terrain Classification," *Journal of Robotics*, 2023, doi: 10.1155/2023/1632563.

[9] J. L. Martínez, J. Morales, A. Mandow, S. Pedraza, and A. García-Cerezo, "Inertia-based ICR kinematic model for tracked skid-steer robots," in *2017 IEEE International Symposium on Safety, Security and Rescue Robotics (SSRR)*, Shanghai, China, 2017, pp. 166-171, doi: 10.1109/SSRR.2017.8088158.

[10] P. Zhang and Z. Wang, Improvements of direct current motor control and motion trajectory algorithm development for automated guided vehicle", *Advances in Mechanical Engineering,* Vol. 11, no. 2. 2019, doi:10.1177/1687814018824937

[11] A. Mohammad and P. Balabanov, "Speed Control of Dc Motor using PID Controller Based on Matlab", *Vestnik Tambovskogo gosudarstvennogo tehnicheskogo universiteta*, vol. 27, pp. 195-202, 2021, doi: 10.17277/vestnik.2021.02.

[12] R. Bitriá, and J. Palacín, "Optimal PID Control of a Brushed DC Motor with an Embedded Low-Cost Magnetic Quadrature Encoder for Improved Step Overshoot and Undershoot Responses in a Mobile Robot Application", *Sensors (Basel)*, vol. 22, no. 20, p. 7817, 2022, doi: 10.3390/s22207817.

[13] J. Palacín and D. Martínez, "Improving the Angular Velocity Measured with a Low-Cost Magnetic Rotary Encoder Attached to a Brushed DC Motor by Compensating Magnet and Hall-Effect Sensor Misalignments", *Sensors,* vol. 21, no.14, p. 4763, 2021; doi: 10.3390/s21144763.

[14] H. Khan, S. Khatoon, P. Gaur, M. Abbas, C.A. Saleel, and S.A. Khan, "Speed Control of Wheeled Mobile Robot by Nature-Inspired Social Spider Algorithm-Based PID Controller", Processes, vol. 11, p. 1202. 2023, doi: 10.3390/pr11041202

[15] J. Palacín, E. Rubies, E. Clotet, and D. Martínez, "Evaluation of the Path-Tracking Accuracy of a Three-Wheeled Omnidirectional Mobile Robot Designed as a Personal Assistant", *Sensors,* vol. 21, p. 7216. 2021, doi: 10.3390/s21217216.

[16] P. Nourizadeh and F.J.S. McFadden, and W.N. Browne, "Trajectory Tracking Control of Skid-Steering Mobile Robots with Slip and Skid Compensation using Sliding-Mode Control and Deep Learning", *ArXiv,* 2023, doi: 10.48550/arXiv.2309.08863.

[17] S. K. Suman and V. K. Giri, "Speed control of DC motor using optimisation techniques based PID Controller," in Proc. 2nd IEEE Int. Conf. Eng. Technol. ICETECH 2016, 2016, no. March, pp. 581–587.

[18] W. M. Elsrogy, M. A. Fkirin, and M. A. M. Hassan, "Speed control of DC motor using PID controller based on artificial intelligence techniques," in *2013 International Conference on Control, Decision and Information Technologies (CoDIT),* Hammamet, Tunisia, 2013, pp. 196-201, doi: 10.1109/CoDIT.2013.6689543.

[19] B. Alexandru, "Position Control of a Mobile Robot through PID Controller", *Acta Universitatis Cibiniensis. Technical Series*, vol. 71, pp. 14-20, 2019, doi: 10.2478/aucts-2019-0004.

[20] H. Khan, S. Khatoon, and P. Gaur, "Comparison of various controller design for the speed control of DC motors used in two-wheeled mobile robots", *Int. J. Inf. Tecnol.*, vol. 13, pp. 713–720, 2021, doi: 10. 1007/s41870-020-00577-8.