

Comparison of PID and EPID Controllers in Self Balancing Robot

Swapna Sanapala¹, Deepa K², Lekshmi S³, Alper Nabi Akpolat⁴

^{1,2,3} Department of Electrical and Electronics Engineering, Amrita School of Engineering, Bengaluru
Amrita Vishwa Vidyapeetham, India

⁴ Department of Electrical-Electronics Engineering, Faculty of Technology, Marmara University, Istanbul, Türkiye

¹bl.en.p2ebs22002@bl.students.amrita.edu, ²k_deepa@blr.amrita.edu, ³s_lekshmi@blr.amrita.edu ⁴alper.nabi@marmara.edu.tr

Abstract—Two wheeled Self balancing robots have become more popular in recent times and used in many applications, commonly used in transportation as these balancing robots are faster and apparently stable. Balancing is achieved by using controllers tuned for the system. Inverted pendulum principle is used in these robots. This paper proposes the use of two control methods, namely Proportional-Integral-Derivative (PID) and Extended PID (EPID), for maintaining the balance of two-wheeled and self-balancing robots, even when slightly tilted, thus preventing them from falling. PID control theory generally depends up on transfer functions, this paper extends the theory using EPID. EPID provides a new perspective on the working principle of PID control and its relationship with other control theories, such as tracking control and disturbance observer. This approach is illustrated using the fundamental principle of inverted pendulum technology. The key advantage of these robots over other mobile robots is their increased stability due to zero turning radius, which allows for smoother rotations during changes in direction.

Keywords— Proportional – Integral - Derivative controller, Enhanced Proportional Integral Derivative controller, Self-balancing robot, Inverted pendulum, Self-balancing robot

I. INTRODUCTION

In recent years, robots have been increasingly adopted as a new type of production tool in numerous industries. Self-balancing robots are a class of robots that employ sensor technology and advanced control algorithms to achieve and sustain equilibrium on two wheels [12]. An open loop system is unstable, so as to maintain stability PID and EPID controllers are used in this system. This unique capability enables the robot to maintain its upright posture, even in the face of external disturbances or uneven terrain. The robotic system [15] maintains its stability and balance by dynamically adapting its position and movements ensuring that its centre of gravity remains over its wheels despite its external disturbances such as bumps [13]. This behavior helps the robot to navigate challenging environments and perform tasks with precision and efficiency.

Fig.1 illustrates the control flow of the system. Self-balancing robots can maintain an upright position without the need for external support and control, which is achieved through the use of control system [14] that enables the robot to sense its orientation and make the necessary adjustments to maintain its balance. This capability allows robot to operate autonomously and perform tasks with greater efficiency and reliability. Multiple control techniques such as PID, FUZZY- PID and Enhanced PID controllers can be utilized to accomplish the

objective of self-balancing [3]. Each of these methods offers distinct advantages that can be exploited to enhance the performance of the self-balancing robot by appropriately selecting and tuning the controller parameters, the robot can maintain its balance and stability in diverse environmental conditions [5].

The PID control is known for its simplicity and effectiveness. Nevertheless, in systems with nonlinearity, time-varying parameters, and considerable disturbances, the PID controller's performance may be limited. To address these challenges several Enhanced PID control methods have been developed, including fuzzy PID, neural network PID, and adaptive PID. These approaches incorporate additional control strategies to compensate for the PID gains based on the system's conditions, making it more adaptable to changes in system behavior and better suited for nonlinear systems. In this paper a comparison between PID and Enhanced PID algorithms have been done.

The PID controller is a stable and easy-to-design controller that is well-suited for slow processes, as it offers fast dynamic response and minimal overshoot. However, its dynamic response is limited when it comes to more complex systems, which rely on linear, fixed gains K_p , K_i , and K_d [11]. On the other hand, the Extended PID (EPID) control framework is an extension of PID control that leverages the state-space model description. In contrast to PID control, EPID replaces the output error with state error, thereby improving its ability to handle more complex systems. EPID is a nonlinear controller which gives better stable performance than PID controllers with linear systems and it deals with nonlinear systems too and gives a stable response. EPID is simply the classic linear PID enhanced with filters and additional control loops to form an extended control structure with the ability to control nonlinear systems. EPID controller has high robustness against noise. Simulation performed on both PID and Enhanced PID, which demonstrates the improved performance of EPID over traditional PID controllers.

Self-balancing robots with PID controllers are used in various fields few of them are as follows:

Entertainment: self-balancing robots with PID controllers are used in amusement parks, events and exhibitions as a source of entertainment.

Industrial automation: these systems are used in manufacturing industries to move materials and products which in turn increases the productivity and reduces human labor.

Medical applications: These are used in medical field to transport medical equipment and supplies.

This paper offers novel insights into PID control based on the Extended PID (EPID) control framework. Specifically, it highlights the potential benefits of setting a high integral gain for minimum phase systems, which can improve tracking accuracy and disturbance rejection without compromising system stability [9]. The EPID approach offers a comprehensive understanding of PID control and its relationship. It is worth noting that PID control is a particular instance of EPID, for first-order SISO systems.

II. SYSTEM MODELLING

A. Inverted pendulum

For a cart its characterized by a mathematical model that is derived from the fundamental equations that describe the correlation between the angle and total mass of the pendulum and cart, the frictional force between the cart and the surface, as well as the external forces acting on the cart and the pendulum, which include the force of gravity [2,10]. By analyzing these factors and formulating the appropriate mathematical equations, it is possible to accurately model the behaviour of the inverted pendulum on a cart and design effective control systems to maintain its stability[4].

From [6] the equations governing the mathematical model of inverted pendulum are stated in Equ. (1) –(4).

$$\ddot{x} = \frac{1}{M} (F - N - b\dot{x}) \quad (1)$$

$$\ddot{\theta} = \frac{1}{I} (-Nl \cos\theta - Pl \sin\theta) \quad (2)$$

$$N = m(\ddot{x} - l\dot{\theta}^2 \sin\theta + l\ddot{\theta} \cos\theta) \quad (3)$$

$$P = m(l\dot{\theta}^2 \cos\theta + l\ddot{\theta} \sin\theta + g) \quad (4)$$

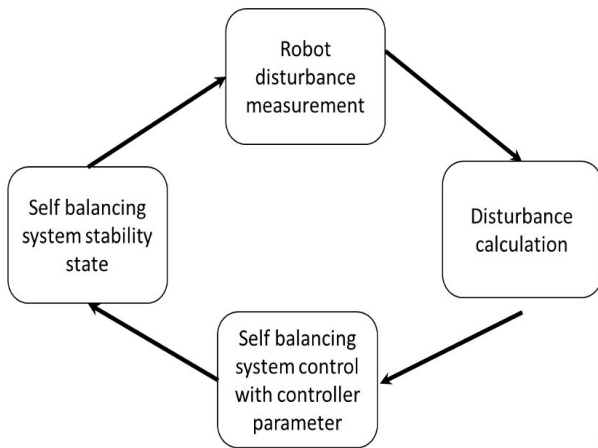


Fig.1 Control flow of system

III. CONTROLLER DESIGN

A. PID Controller

One of the most frequently used control mechanism in engineering is the proportional-integral-derivative control [16]. It operates as a feedback loop that continuously computes the error value, denoted as $e(t)$, by comparing set point to a measured process variable., and subsequently directs a corrective action that considers the proportional, integral, and derivative terms. This dynamic approach enables the controller to effectively regulate the system, providing accurate and stable control [17].

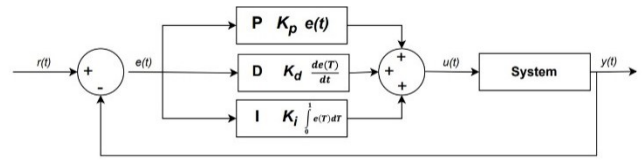


Fig.2 PID Framework

Fig.2 shows framework of the PID controller. The PID controller's inherent stability and versatility make it popular choice among control engineers for a broad range of practical control applications. This is due to its ease of comprehension and robustness, allowing for straightforward implementation in various real-world control scenarios. Currently, PID control systems are widely utilized in industrial control loops Equ.(5), with over 90% of such loops relying on this technology. Equation (5) represents PID controller output where K_p , K_d , K_i are proportional gain, derivative gain and integral gain respectively.

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de}{dt} \quad (5)$$

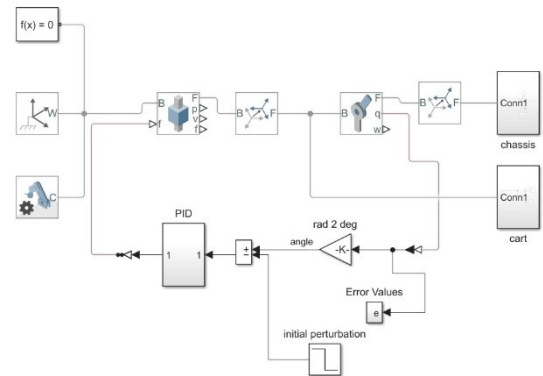


Fig.3 PID controlled inverted pendulum model.

Where PID design parameters are K_p, K_i, K_d and $e(t)$ is the error value. The error value is the deviation of the output to the set point of the system. The angle of pendulum is fed as feedback to the controller, the set point is set to 0. Assuming that at zero degree the pendulum is perpendicular to the cart. The integral gain overcomes the steady state error introduced by proportional gain, but the system has sustained oscillations. The derivative gain dampens the oscillations introduced by integral gain. Table I shows how proportional, integral and derivative terms effect on the system.

TABLE I PID PARAMETERS TUNING

Parameter	Overshoot	Settling time	Steady state error	Raise time
K_p	Decreases	Decrease	No effect	Minor change
K_i	Increase	Increase	Eliminate	Decrease
K_d	Increase	Minor change	Decrease	Decrease

Fig.3 is the Simulink model with PID controller and impulse signal added to the force value. The angle is taken as feedback

for the controller. Table II shows the PID parameters values in this current system.

TABLE II PID VALUES

PARAMETERS	VALUES
K_p	2
K_i	5
K_d	0.01

B. EPID Controller

From PID controller based systems it is observed that settling time can be still more improved and overshoot can be further reduced, which can be achieved by EPID controller where constants (whose values ranges between 0 and 1) are added in proportional and derivative to boost up the performance. Enhanced PID controller is an upgraded version of conventional PID controller that integrates supplementary control techniques to enhance its efficiency in managing nonlinearities, time-varying parameters, and significant disturbances in systems. The Enhanced PID (EPID) control framework is a modified version of PID [1]. Its integral part observers and addresses disturbances, but it cannot operate independently and must be paired with the proportional part. In this way, EPID both expands upon the existing PID control framework and serves as a linking element between various control techniques, offering deeper insights into their internal relationships.

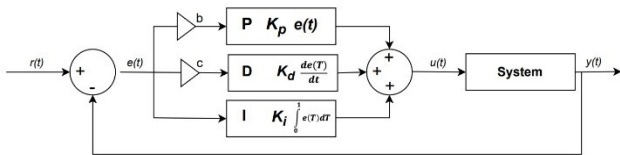


Fig.4 EPID Framework

Fig. 4 shows the Framework of the Enhanced PID controller. This paper provides a summary of the Extended PID (EPID) control framework and compares its performance with PID control system. By doing so, it offers a fresh perspective on the three parameters which are proportional, integral and derivative terms of PID control system. (Eqn. (6)). Specifically, the integral component utilizes past information and functions as a feedforward mechanism, while the derivative component, which was previously considered a prediction method, acts as a standard state feedback. Moreover, EPID is shown to have strong connections with various other control techniques, such as tracking control, iterative learning control, and disturbance observer [8,11]. Equation (6) represents EPID output where proportional gain multiplied by constant b and derivative gain multiplied by constant c.

$$u(t) = k_n(e) (bK_p e(t) + K_i \int_0^t e(t) dt + cK_d \frac{de(t)}{dt}) \quad (6)$$

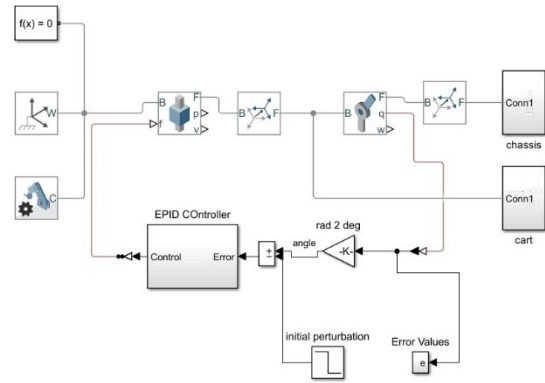


Fig.5 EPID controlled inverted pendulum model

TABLE III EPID VALUES

PARAMETERS	VALUES
k_t	3
K_i	0.1
K_d	0.1
B	0.75
C	0.67

Fig.5 is the Simulink model with EPID controller and impulse signal added to the force value. The angle is taken as feedback for the controller. Table. III shows the EPID parameters.

IV. RESULTS AND OBSERVATION

MATLAB Simulink is a software package that synergistically integrates the computational capabilities of MATLAB, a numerical computing environment with the graphical simulation and model-based design environment of Simulink. Simulink is frequently employed in engineering and scientific contexts to facilitate the creation, evaluation, and deployment of control systems through testing and implementation.

A. PID Controller Response

The Fig.6 and Fig.7 are the angle and angular velocity of the PID control system respectively, where oscillations can be observed. In Fig8, the distance is observed to be increasing and Fig9, is the linear velocity in which it is observed to have some oscillations which settles down after some time.

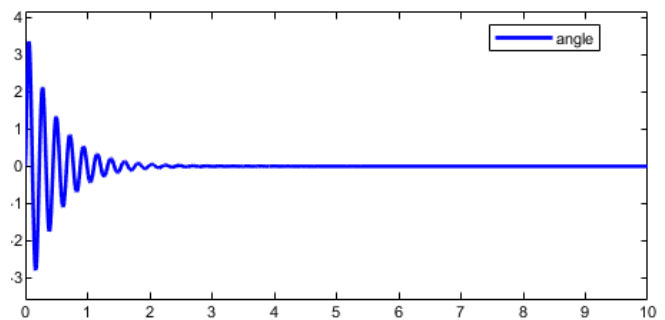


Fig.6 Angle of the system with PID

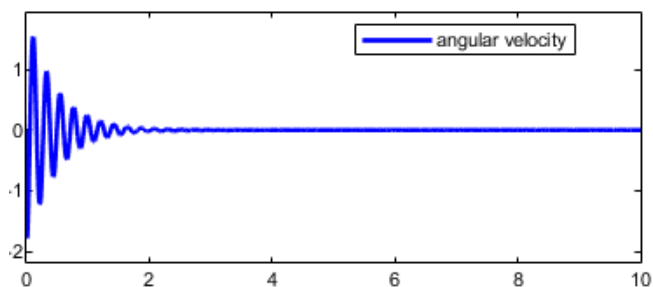


Fig.7 Angular velocity of the system with PID

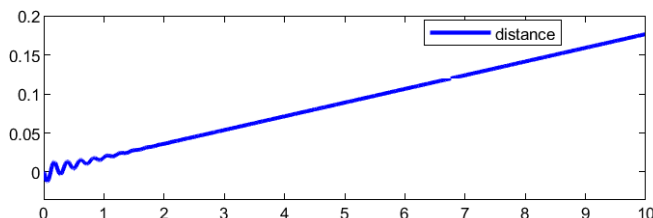


Fig.8 Distance of system with PID

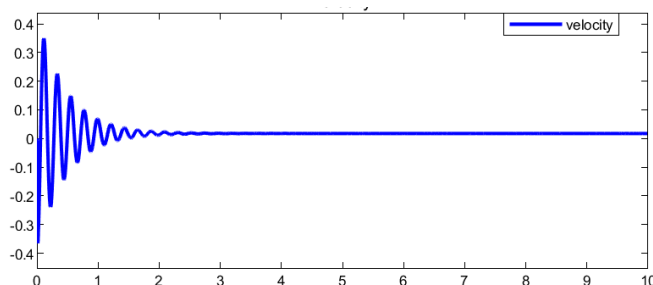


Fig.9 Linear velocity of system with PID

B. EPID Controller Response

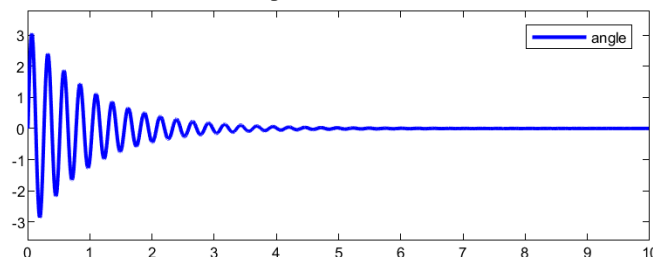


Fig.10 Angle of the system with EPID

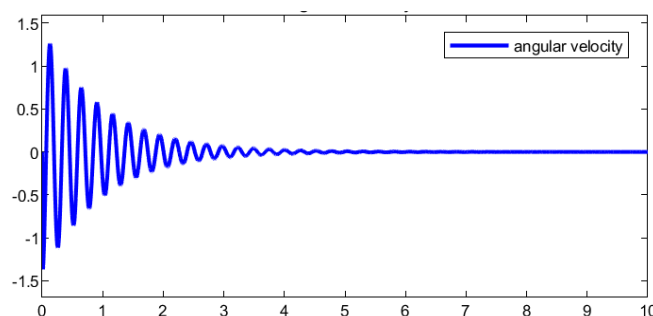


Fig.11 Angular velocity of the system with EPID

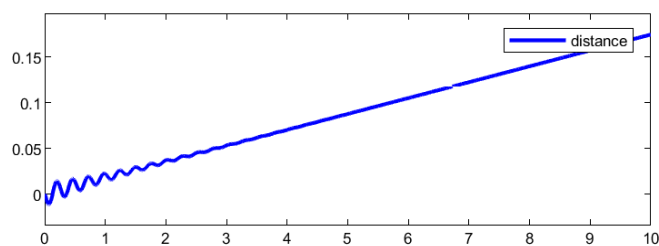


Fig.12 Distance of the system with EPID

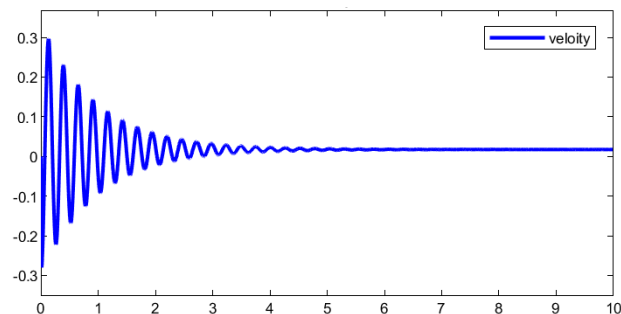


Fig.13 Velocity of system with EPID

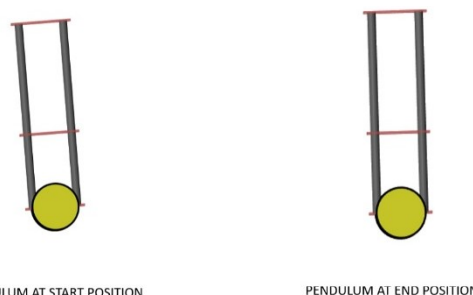


Fig.14 Initial and final position of self-balancing system

The Fig.10 is the angle output of the system for the impulse input. The time of the simulation is 100 seconds. The overshoot is observed at the time of the impulse signal and a undershoot occurs to settle down to zero. The Fig.12 is the linear distance of the system with EPID controller. The distance traveled by the cart keeps increasing as time progresses. From the figure.12 it is observed that the distance keeps increasing to maintain the stability angle. From fig.14, it is evident that the system is able to attain and maintain the stable angle with the help of the controller.

The errors from systems with PID and EPID controller is compared to determine the performance difference between the controller. The error criteria considered are IAE, ISE, ITAE [7].

The performance index is calculated using the equation (7- 9)

$$IAE = \int_0^{\infty} |e(t)| dt \quad (7)$$

$$ISE = \int_0^{\infty} e^2(t) dt \quad (8)$$

$$ITAE = \int_0^{\infty} t |e(t)| dt \quad (9)$$

TABLE IV ERROR VALUES

Error	IAE	ISE	ITAE
PID	0.0369	0.0008484	0.0366
EPID	0.02019	0.000526	0.00971

Fig.11, Fig.13 reveals the velocity and angular velocity of the system with EPID controller. The system settles after an overshoot and undershoot. The ISA, IAE, ITAE of the systems with PID and EPID controller are tabulated in Table IV. The EPID controller has less values for all the errors listed.

Fig.15 is the pictorial representation of inverted pendulum on a moving cart and the forces acting on it.

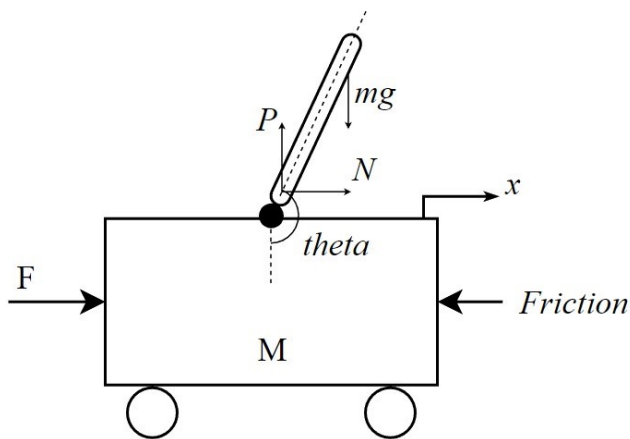


Fig.15 Inverted pendulum on a moving cart

V. CONCLUSION

In conclusion, this paper has explored the effectiveness of two different types of controllers, namely PID and EPID, in the context of a self-balancing robot. The results show that both controllers can achieve successful stabilization of the robot, with the EPID controller demonstrating slightly better performance in terms of settling time as well as steady-state error. Overall, the choice between PID and EPID controllers for a self-balancing robot will depend on the specific requirements of the application, as well as factors such as cost and ease of implementation. However, the results of this study indicates that the EPID controller may be a particularly promising option for applications that require fast and accurate stabilization.

Future research in this area could explore the performance of other types of controllers. The objective of this study is to examine how various tuning techniques affect the efficacy of PID and EPID controllers. Additionally, it may be valuable to test these controllers in more complex environments or with additional factors such as variable payloads. In summary, the outcomes of this investigation add to the expanding body of knowledge on control systems for self-balancing robots and offer significant findings for researchers and professionals operating in this domain.

REFERENCE

- [1] L. Ye, B. Liang and X. Wang, "An Extended PID Control Framework," 2021 IEEE Conference on Control Technology and Applications (CCTA), 2021, pp. 1069-1074.
- [2] N. T and P. K T, "PID Controller Based Two Wheeled Self Balancing Robot," 2021 5th International Conference on Trends in Electronics and Informatics (ICOEI), 2021, pp. 1-4.
- [3] R. Sadeghian and M. T. Masoule, "An experimental study on the PID and Fuzzy-PID controllers on a designed two-wheeled self-balancing autonomous robot," 2016 4th International Conference on Control, Instrumentation, and Automation (ICCIA), 2016, pp. 313-318.
- [4] Y. Gong, X. Wu and H. Ma, "Research on Control Strategy of Two-Wheeled Self-Balancing Robot," International Conference on Computer Science and Mechanical Automation (CSMA), 2015, pp. 281-284.
- [5] A.C. Unni, A. V. Mohan and W. Ongsakul, "PID, fuzzy and LQR controllers for magnetic levitation system," Int. Conf. on Cogeneration, Small Power Plants and District Energy (ICUE), 2016, pp. 1-5.
- [6] Jia-Jun Wang "Simulation studies of inverted pendulum based on PID controllers, Simulation Modelling Practice and Theory", Volume 19, Issue 1, 2011, Pages 440-449.
- [7] B. Prasad, R. Kumar and M. Singh, "Performance Analysis of Model Predictive Control for Cascaded Tank Level Control System," 2021 IEEE 2nd International Conference On Electrical Power and Energy Systems (ICEPES), Bhopal, India, 2021, pp. 1-6.
- [8] M. Sam and T. S. Angel, "Performance optimization of PID controllers using fuzzy logic," 2017 IEEE International Conference on Smart Technologies and Management for Computing, Communication, Controls, Energy and Materials (ICSTM), 2017, pp. 438-442.
- [9] C. K. Chandni, V. V. Sajith Variyar and K. Guruvayurappan, "Vision based closed loop pid controller design and implementation for autonomous car," International Conference on Advances in Computing, Communications and Informatics (ICACCI), 2017, pp. 1928-1933.
- [10] A. Lima-Pérez et al., "Robust Control of a Two-Wheeled Self-Balancing Mobile Robot," 2021 International Conference on Mechatronics, Electronics and Automotive Engineering (ICMEAE), Cuernavaca, Mexico, 2021, pp. 196-201.
- [11] V. Praveen and S. Pillai, A, "Modelling and Simulation of Quadcopter using PID Controller ", International Journal of Control Theory and Applications, vol.9, pp. 7151-7158, 2016
- [12] F. -C. Paulescu, I. Szeidert, I. Filip and C. Vasar, "Two-Wheeled Self-Balancing Robot," 2021 IEEE 15th International Symposium on Applied Computational Intelligence and Informatics (SACI), Timisoara, Romania, 2021, pp. 33-38.
- [13] Y. Liu, "Research on Tracking Control of Two Wheeled Self-balancing Vehicle," 2022 41st Chinese Control Conference (CCC), Hefei, China, 2022, pp. 1137-1142.
- [14] S. P. A and A. Mohan, "Design and Simulation of an Autonomous Indoor Robot for Elderly Assistance," 2022 IEEE 2nd Mysore Sub Section International Conference (MysuruCon), Mysuru, India, 2022, pp. 1-5, doi: 10.1109/MysuruCon55714.2022.9972508.
- [15] B. Shilpa, V. Indu and S. R. Rajasree, "Design of an underactuated self balancing robot using linear quadratic regulator and integral sliding mode controller," 2017 International Conference on Circuit, Power and Computing Technologies (ICCPCT), Kollam, India, 2017, pp. 1-6.
- [16] S. Likhith, S. Bhargavi, P. V. Manitha and S. Lekshmi, "DC-DC Converter for EV Charger with Controlling Unit," 2022 International Conference for Advancement in Technology (ICONAT), Goa, India, 2022, pp. 1-4.
- [17] B. Sahithi, P. V. Manitha and S. Lekshmi, "Design and Simulation of Washing Machine Equipped with Universal Motor," 2022 International Conference on Intelligent Innovations in Engineering and Technology (ICIET), Coimbatore, India, 2022, pp. 111-117.