DEVELOPMENT OF SELF BALANCING ROBOT WITH PID CONTROL

Debdipto Biswas
21BPS1265
SCOPE VIT CHENNAI
Chennai, India
debdipto.biswas2021@vitstudent.ac.in

Vivek Kumar Tiwari
21BPS1117
SCOPE VIT CHENNAI
Chennai, India
vivekkumar.tiwari2021@vitstudent.ac.in

Utkarsh Sharma
21BPS1170
SCOPE VIT CHENNAI
Chennai, India
utkarshdharmendra.sharma2021@vitstudent.ac.in

Viral Upadhyay
21BPS1266
SCOPE VIT CHENNAI
Chennai, India
viral.upadhyay2021@vitstudent.ac.in

Abhinav Maurya
21BPS1496
SCOPE VIT CHENNAI
Chennai, India
abhinav.maurya2021@vitstudent.ac.in

***Abstract*—This paper addresses the application of the classical inverted pendulum problem in developing a self-balancing robot. The robot here under discussion is a type of two-wheeled vehicle and is designed with structural, mechanical, and electronic components that create an inherently unstable platform, making it prone to tipping along one axis. The robot wheel is independently driven by a high-torque DC motor. A 6DOF IMU sensor gathers the angle of the device relative to the ground. Information from the IMU is processed and filtered into a stable, accurate read that is sent to a processor onboard. A PID algorithm in the processor is then used to generate position-control signals and apply proportional forces to the motors according to program logic to maintain or regain the position of the robot if it has toppled. Such two-wheeled balancing robots have extensive applications; they can work as intelligent gardening robots or even be used as autonomous trolleys in hospitals and can be used as transporters in malls, offices, and airports.**

Keywords—*Inverted Pendulum, Sensor, Two Wheeled Vehicle, and PID Control*

I. Introduction

The self-balancing robot works on an electronic device with Integrated control based on the model of the Inverted Pendulum (IP). The key is living tilt angle data for balancing the two-wheeled inverted pendulum robot. Therefore, there is a need for a controller that compensates for deviation in tilt, as elaborated in Sugie & Fujimoto (1998), Nuo & Hui (2008), Tomasic et al. (2013), Jin (2015), and Pillai et al. (2016). In a nutshell, the inverted pendulum is the quintessence of the control problem: a nonlinear system that is unstable with a single input and multiple outputs and therefore leads to an almost impossible condition for balance without outside help.

The self-balancing robot works on an electronic device with Integrated control based on the model of the Inverted Pendulum (IP). The key is living tilt angle data for balancing the two-wheeled inverted pendulum robot. Therefore, there is a need for a controller that compensates for deviation in tilt, as elaborated in Sugie & Fujimoto (1998), Nuo & Hui (2008), Tomasic et al. (2013), Jin (2015), and Pillai et al. (2016). In a nutshell, the inverted pendulum is the quintessence of the control problem: a nonlinear system that is unstable with a single input and multiple outputs and therefore leads to an almost impossible condition for balance without outside help. A Single-Input Single-Output (SISO) PID controller is usually sufficient to control the angle of the pendulum, but if one aspires to control both position and angle simultaneously-that is, making the system a Multiple-Input Multiple-Output (MIMO) system-then a single PID controller alone is not enough; it rather requires a more complex state-space controller instead.

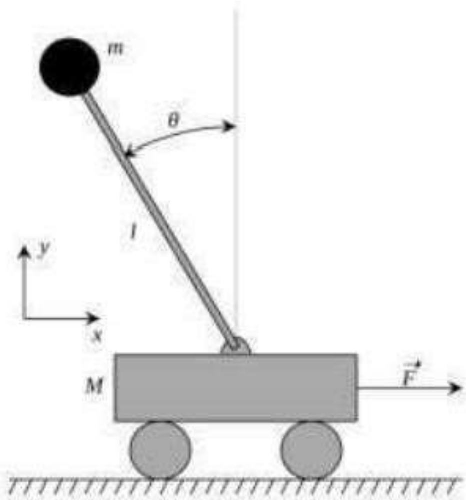
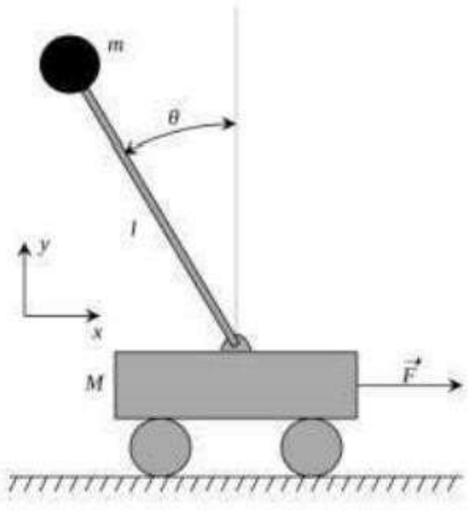


Fig 1: Inverented Pendulum

CPSD Digital assignment-2
Link-
https://drive.google.com/file/d/1G-m1qAR6pkmzoCKvdRB5HqSQj0-kKuNh/view?usp=sharing



Engineers and researchers focus attention on the inverted pendulum due to its unstable nature and use in designing wheeled mobile self-balancing robots, such as the Segway. Companies design and innovate in the creation of a robot, such as the LegWay robot designed by Lego, which utilizes differential driving mechanisms for mobility on an inclined or unbalanced surface with remote control.

II. SYSTEM DESCRIPTION

The bot has three stacked platforms.

Top Platform: The IMU is located inside.

Middle Platform: Is equipped with a microcontroller that is compatible with Arduino Pro Mini

Base Platform: It contains the motor driver.

At the top end of the base platform, the batteries are fitted, whereas on the lower end two high-torque motors (0.4 kg-cm, 200 rpm) are clamped. The wheels are fitted on motor shafts designed to incorporate the necessary amount of grip and friction to stabilize the vehicle. The platforms have acrylic board sizes of 22.5 cm x 7 cm with a 5 cm gap between the platforms.

Fig 2: Mechanical Structure of Self Balancing Bot

III. ELECTRICAL SYSTEM DESIGN

A. *Inertial Measuring Unit (IMU)*

The Inertial Measurement Unit (IMU) consists of a Micro Electro Mechanical System (MEMS) accelerometer and a MEMS gyroscope integrated into a single chip, offering high accuracy. It features 16-bit analog to digital converters for each channel, enabling simultaneous capture of data along the x, y, and z axes. Communication with the microcontroller is facilitated through the I2C bus. The sensor operates continuously as its sleep mode is disabled, and data from the accelerometer and gyro registers are continuously read. Additionally, it includes a 1024 byte FIFO (First In, First Out) buffer that stores sensor data, which the microcontroller accesses as needed. The IMU uses interrupts to signal the microcontroller when new data is available in the FIFO buffer for processing.

B. *Sensor Fusion:*

The IMU incorporates two types of sensors: a tri-axial accelerometer and a gyroscope. The accelerometer measures acceleration forces along three axes and is prone to noise. The gyroscope measures angular velocity across three axes but tends to drift over time. This drift makes sensor fusion essential, as relying on data from either sensor alone could lead to inaccuracies. The IMU includes a Digital Motion Processor (DMP), which can execute complex calculations on the chip, thus reducing the computational load on the microcontroller. The DMP processes data from both the accelerometer and gyroscope, providing essential vehicle orientation metrics such as yaw, pitch, and roll. For this application, the pitch is particularly important as it indicates the vehicle's tilt along the axis of interest.

C. *Algorithm – PID Control:*

The balancing mechanism of the autonomous two-wheeled robot is managed by a PID (Proportional, Integral, Derivative) controller. This three-term controller uses constants known as Kp, Ki, and Kd for the proportional, integral, and derivative terms, respectively. The PID controller operates within a closed-loop, or negative feedback system, where it compares the desired set-point (in this case, a vertical position of zero degrees) with the actual output. The difference, or error, between these values is then processed by the PID algorithm in three stages: proportional, integral, and derivative. The proportional term addresses the present error, the integral term corrects accumulated past errors, and the derivative term anticipates future errors based on current rate of change. The output from the PID controller, the control signal 'u', drives the robot toward the desired set-point, aiming to maintain or return to a balanced state. The mathematical modeling of the PID algorithm allows for precise adjustments to be made based on the error values, ensuring effective control over the robot′s balance.

PID was used to calculate the "correction factor" as shown below:

$$correction = Kp * E + Ki * \int E(t)\, dt + Kd * [dE(t)/dt]$$

Kp, Ki, and **Kd** which are specific error constants, are set experimentally

E is the error signal constant

The integral term was simply the summation of all previous deviations and called this Integral as–"total error". The derivative was the difference between the current deviation and the previous deviation

Following was the code for evaluating the correction. These lines were run in each iteration:

Correction=Kp*D + Ki*[(DT)*dt] + Kd[(D-D0)*dt]

D0=D

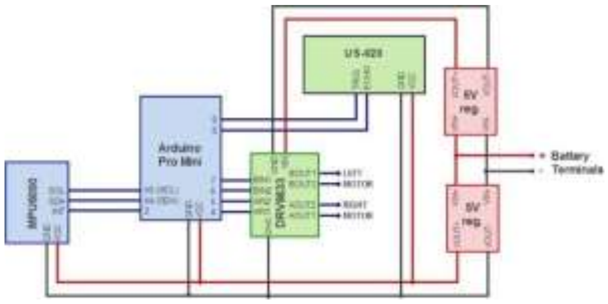
DT=D+DT

Where **'D'** is the deviation, **'D0'** is the previous deviation, **'DT'** is the total deviation or accumulated deviation and **'dt'** is the sampling time.

It was assumed that if only the first term had been used to calculate the correction, the robot would have reacted in the same way as in the classical line following algorithm. These cond term forced the robot to move towards the mean position faster. The third term resisted sudden change in deviation (Figure 3).

Fig 3: Balancing Technique of Bot

D. Overall System Block Design



The IMU sensor positioned atop the vehicle captures acceleration and angular velocity across the x, y, and z axes. This data is processed by the Digital Motion Processor (DMP), which converts these readings into the more manageable orientation metrics: yaw, pitch, and roll. In this setup, the pitch value is critical as it indicates the tilt along the axis in question. This pitch data serves as feedback to the microcontroller, which processes it according to predefined algorithms.The microcontroller evaluates the current pitch against a predetermined set value. If a discrepancy is detected, it calculates the error and forwards this information to the PID controller. The PID controller then applies its algorithm to generate a proportional control signal that adjusts the force exerted by the motors, aiming to realign the vehicle to its original vertical stance.This control signal is transmitted to the motor controller, specifically an L298N, which then adjusts the motors' speed, torque, and direction to correct the tilt, as depicted in Figure 4. This systematic approach ensures the vehicle maintains stability and proper orientation.

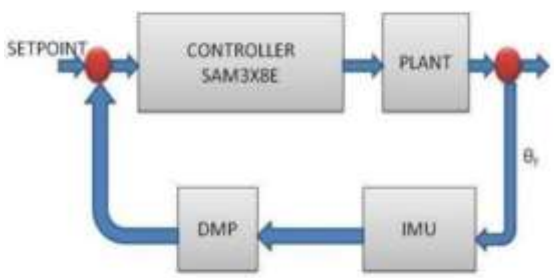


Fig 4: System Schematics

IV.LITERATURE REVIEW

1) https://www.researchgate.net/publication/326294136_Development_of_Self_Balancing_Robot

Main topic: This research paper explores the design and development of two-wheeled balancing robots, focusing on the inverted pendulum principle and PID control system for maintaining stability.

Key points:

- Motivation: Two-wheeled robots offer unique locomotion possibilities and stability control challenges compared to traditional robots.
- Inverted pendulum principle: The robot's body behaves like an inverted pendulum, requiring constant adjustment of the wheels to maintain balance.
- PID control system: This algorithm uses proportional, integral, and derivative terms to respond to the robot's tilt angle and adjust motor power accordingly.
- Components: The robot typically consists of sensors (gyroscope, accelerometer), motors, motor drivers, microcontrollers, and power sources.
- Design considerations: Factors like friction, wheel size, motor type, and sensor selection impact the robot's performance and stability.
- Existing robots: The paper discusses commercially available robots like Segway and Emiew, along with DIY projects like nBot.
- Future improvements: The authors suggest incorporating additional sensors and tuning the PID constants for better precision and stability.
- Potential applications: These robots have potential uses in agriculture, healthcare, logistics, and various service industries.

Overall, this review provides a comprehensive overview of two-wheeled balancing robots, including their technology, challenges, and promising future applications.

2) https://www.ijert.org/self-balancing-robot

Main focus: Design and construction of a two-wheeled self-balancing robot using PID control and sensor fusion (accelerometer and gyroscope).

Key points:

- Concept: Inspired by the inverted pendulum principle, where the unstable system maintains balance through continuous feedback and motor adjustments.
- Hardware: ATmega328P microcontroller, MPU6050 inertial measurement unit (IMU), L298N motor driver, DC motors.
- Software: PID algorithm for adjusting motor speeds based on sensor data (angle, angular velocity).
- Challenges: Sensor drift, gyro noise, tuning PID constants for optimal balance and responsiveness.
- Results: Robot successfully balances itself when tilted forward or backward.
- Future improvements: Enhance motor speed readings for better stability, implement wireless control for remote operation.

Research gaps identified:

- Limited sensor accuracy: The reliance on accelerometer and gyroscope data creates susceptibility to drift and noise, potentially influencing balance control.

- PID tuning optimization: While the paper describes a trial-and-error approach for PID constants, a more systematic and efficient method could be explored.
- Advanced control algorithms: Exploring alternative or complementary control strategies like fuzzy logic or adaptive control could be beneficial for handling external disturbances and improving manoeuvrability.
- Application exploration: Beyond the mentioned examples (smart gardening, autonomous trolleys), investigating further applications for self-balancing robots in challenging environments or specialized tasks could be valuable.

Overall, this paper presents a well-designed and functional self-balancing robot prototype. However, addressing the identified research gaps can lead to further performance improvements, adaptability, and diverse applications for this technology.

3) https://core.ac.uk/reader/11036400

In the field of mechatronics and robotics, Kealeboga Mokonopi's dissertation offers a thorough analysis of sensor fusion, control techniques, and balancing robots. The paper examines methods of stabilizing an intrinsically unstable system and examines pertinent literature to guide the development of a two-wheeled balancing robot. Covered subjects include hardware configurations, sensor fusion algorithms, and traditional and contemporary control techniques. The dissertation establishes the foundation for the creation of precise control techniques necessary to achieve upright stability and autonomous movement in such systems by combining prior research.

4)https://indusedu.org/pdfs/IJREISS/IJREISS_3094_97729.pdf

This work's research article emphasizes the importance of creating a self-balancing robot in the context of robotics and control theory. By utilizing well-known benchmarks such as the inverted pendulum, the study highlights the usefulness of theoretical concepts presented in Control Systems classes. Notably, the initiative emphasizes the necessity of actual experimentation by attempting to close the gap between theoretical simulations and real-world behavior. The review also recognizes the use of Kalman Filters in sensor fusion, which allows for more accurate tilt angle estimation—a critical component of self-balancing robots. The project also takes into account the more general developments in robotic mobility technology, such as the rising popularity of autonomous systems and open-source robotics. Overall, the paper sets the stage for the project's objectives by contextualizing the importance of self-balancing robots in contemporary research and applications.

5) https://news.mit.edu/2019/particle-robot-cluster-simple-units-0320#:~:text=This%20so%2Dcalled%20%E2%80%9Cparticle%20robotics,their%20perimeters%2C%20and%20each%20unit

Numerous articles and research papers discuss the project and how it operates. According to an article titled "Particle robot - works as a cluster of simple units," in the future, various system components will collaborate to accomplish tasks and reach goals in the form of clusters. Particle robot theory also discusses how the modular approach to robotics will lead to future robots that are more reliable and effective. Furthermore in a different research report.Through this article, "Self-balancing robot implementing the inverted pendulum concept," we were able to derive the notion that robots might be used to both avoid objects and act as an example of the inverted pendulum theory.

6) https://www.divaportal.org/smash/get/diva2:916184/FULLTEXT01.pdf%20Page%205

The paper explores the design and implementation of a two-wheeled self-balancing robot using an Arduino Uno microcontroller board. It begins by discussing the significance of inverted pendulum systems in various applications, emphasizing the need for active control mechanisms. Leveraging open-source resources, the project utilizes the Arduino platform for its flexibility and accessibility. Control theory concepts, including PID controllers and state space controllers, are employed to stabilize and control the robot's motion. Additionally, the paper introduces Linear Quadratic Regulators (LQR) as an efficient control strategy. Theoretical derivations of dynamical equations and transfer functions provide a theoretical framework for the experimental work. The implementation involves hardware components such as motors, sensors, and an IMU (Inertial Measurement Unit) for feedback. Through experimental testing and validation, the effectiveness of the designed control system is demonstrated in maintaining the robot's balance and executing desired movements. Overall, the paper contributes to the field of robotics by presenting a comprehensive approach to designing and controlling two-wheeled self-balancing robots using affordable and accessible hardware and control strategies.

Research gap: While the paper provides a thorough exploration of designing and controlling a two-wheeled self-balancing robot using the Arduino platform, several potential research gaps remain unaddressed. Firstly, although the paper discusses the implementation of PID controllers and Linear Quadratic Regulators (LQR), it could delve deeper into comparative analyses of different control strategies to assess their respective advantages and limitations in specific scenarios. Additionally, the paper focuses on hardware implementation and control algorithms but lacks discussion on advanced topics such as trajectory planning, obstacle avoidance, or robustness to external disturbances. Furthermore, the experimental validation primarily emphasizes the robot's balance maintenance and basic movements; however, more extensive testing under varying conditions and environments could provide deeper insights into the system's performance and limitations. Lastly, while the paper emphasizes affordability and accessibility by utilizing the Arduino platform, exploring scalability and performance enhancements for more complex systems could be an interesting avenue for future research. Addressing these gaps could contribute to advancing the state-of-the-art in two-wheeled self-balancing robot design and control.

7) https://ijarsct.co.in/Paper2144.pdf

The paper titled "Self Balancing Robot" presents the design and implementation of a two-wheeled self-balancing robot using open-source microcontrollers and sensors. The project aims to develop an affordable and versatile robot capable of maintaining balance and avoiding obstacles in real-time. By utilizing components such as the Arduino NANO, MPU6050 sensor, motor driver (TB6612FNG), ultrasonic sensor, IR sensor, Bluetooth module, and encoder motors, the system achieves stability and adaptability.

The literature review highlights the relevance of modular robotics approaches and inverted pendulum concepts in robotics development. Additionally, the paper outlines the aims and objectives, hardware and software details, implementation methodology, and results of the project. Through detailed hardware configurations and software programming using Arduino IDE and Android Studio, the robot achieves self-balancing and obstacle avoidance capabilities.

The project's success lies in its ability to provide an affordable solution for self-balancing robotics, suitable for both industrial and domestic applications. Future developments could include enhancements such as integrating vision systems for object detection and miniaturization for humanoid robot applications. Overall, the paper contributes to advancing the field of robotics by demonstrating practical implementation and addressing key challenges in self-balancing robot design and control.

8) https://www.researchgate.net/publication/350778948_Design_and_control_of_a_two-wheel_self-balancing_robot

The paper presents a novel approach to designing and controlling a two-wheeled self-balancing robot, focusing on achieving stability without complex control systems. The robot's structure incorporates vertical straight-line motion to enhance stability during movement over different terrains. Mathematical modelling using Lagrange's equation and simulation in Matlab Simulink are employed to analyse the system's behavior under various input conditions. Initially, instability is observed due to positive Eigen values, addressed through methods like pole placement and Linear Quadratic Regulation (LQR). Further enhancement is achieved with the integration of a PID controller, resulting in precise manoeuvrability and negligible error in response to step, ramp, and sine wave inputs. However, while the study provides comprehensive insights into the design and control of the two-wheeled robot, several research gaps remain. Firstly, the paper lacks detailed exploration of real-world implementation and validation of the proposed design. Additionally, the robustness of the control system under varying environmental conditions and external disturbances is not thoroughly investigated. Future research could focus on experimental validation and robustness analysis to bridge these gaps and further enhance the practical applicability of the proposed design.

9) https://abhivruddhi.mituniversity.ac.in/journals/2021/Mechanical/Review%20on%20Self%20Balancing%20Robot%20Navigation.pdf

The research paper presents an overview of the technologies and evolution of self-balancing robot navigation. It includes both sophisticated approaches like LiDAR and image processing as well as basic control strategies like PID and fuzzy logic. The potential of the robot for providing human assistance and service delivery is shown by the exploration of applications in industries such as hospitality and healthcare. Development of controllers, integration of sensors, and use of programming languages are research contributions. Obstacle avoidance and stability in unsteady terrain are still problems despite progress. Advanced control techniques, intelligent sensor integration, and algorithm optimization for practical applications are some of the areas that future study will focus on. The study highlights the need for better stability and obstacle avoidance while pointing out gaps in the body of current research. All things considered, it offers insightful information on the present and potential futures of self-balancing robot navigation technologies.

Research gap:

- Stability on Rough Terrain: Despite advancements in control strategies, the paper highlights a significant challenge in maintaining stability on rough surfaces. Further research is needed to develop robust control algorithms that can adapt to various terrains and environmental conditions.
- Obstacle Avoidance: While some research efforts have focused on obstacle avoidance using sensors like LiDAR and ultrasonic sensors, there is still room for improvement. Future studies could explore more sophisticated obstacle detection and avoidance techniques to enhance the robot's navigation capabilities in complex environments.
- Real-World Application Validation: While the paper discusses potential applications of self-balancing robots in industries like hospitality and healthcare, there is a lack of empirical validation in real-world scenarios. Future research could involve field tests and pilot studies to assess the practical feasibility and effectiveness of deploying these robots in different settings.
- Integration of Intelligent Sensors: The paper briefly mentions the use of intelligent sensors like gyroscopes and accelerometers but does not delve deeply into their integration for navigation purposes. Further research could explore the integration of advanced sensor technologies and their impact on enhancing navigation accuracy and reliability.

10) https://www.mdpi.com/1424-8220/23/5/2489

The paper introduces a novel approach to enhance inspection and monitoring of equipment in coal mine pump rooms using a two-wheel self-balancing inspection robot based on laser SLAM (Simultaneous Localization and Mapping). The robot's mechanical structure is designed using SolidWorks, with finite element static analysis ensuring its stability. A kinematics model and a multi-closed-loop PID controller are employed for self-balancing control, while the 2D LiDAR-based Gmapping algorithm facilitates robot localization and map construction. Tests confirm the algorithm's anti-jamming ability and robustness, with simulation experiments validating the importance of particle number selection for map accuracy improvement. The constructed map demonstrates high accuracy. The research addresses the need for unmanned inspection solutions in coal mines, offering a lightweight, maneuverable robot capable of precise positioning and mapping. Finite element analysis verifies the mechanical structure's stability and strength, while mathematical modeling and analysis aid in designing a self-balancing algorithm ensuring the robot's stability. This work significantly contributes to improving indoor inspection efficiency and workers' safety in challenging environments.

V. CONCLUSIONS

The project leverages the classical inverted pendulum problem, adapting it to develop a self-balancing robot that maintains equilibrium when pushed forward or backward. The structure, operation, and integration of the components are thoroughly detailed. This concept, inspired by the Segway, suggests potential enhancements through the integration of quadrature optical encoders to increase the precision of motor speed readings, thereby enhancing stability. Additionally, the use of potentiometers could fine-tune the error constants in the PID control system. Although these improvements were not implemented due to time constraints, they are recommended for future versions to boost system efficiency.Furthermore, the utility of two-wheeled balancing robots extends beyond mere transportation, with potential applications as intelligent gardeners in agriculture, autonomous trolleys in hospitals, shopping malls, offices, airports, and healthcare settings. They could also serve as aides for guiding individuals who are blind or have disabilities, showcasing the versatility and broad applicability of this technology in various domains.

VI.EXPERIMENTAL RESULTS

Spending a bit more time on tweaking the PID constants would give us a better result. The size of our robot also limits the level of stability we can achieve. As we are using micro gear 6v motors, we know that they are low on rpm but good with torque. It is important to keep the weight of overall project as less as possible. That is why we are using Arduino pro mini instead of Arduino uno or Arduino Nano.

ACKNOWLEDGMENT *(Heading 5)*

This paper, titled "Development of Self-Balancing Bot with PID Control," represents the research conducted at the Embeddded Systems Lab, which is part of the Department of SCOPE at Vellore Institute of Technology Chennai, Kelambakkam, in Tamil Nadu, India. We extend our gratitude to the university and out faculty Dr. Balakrishnan R for invaluable support and encouragement throughout this project.

REFERENCES

1. Pillai R., Sondhia S., Hegde S. S., Chakole S. & Vora V. (2016). Project report on self balancing robot using PID control. Motion Analysis Lab, Department of Mechatronics, SRM University Kattankulathur, Tamil Nadu, India
2. Ferdinando, H., Khoswanto H., & Tjokro, S. (2011). Design and evaluation of two-wheeled balancing robot chassis. IEEE International Conference on Communications, Computing and Control Applications, pp. 1-6.
3. Grasser, F., Arrigo, A. D., & ColombiS. (2002). JOE: Amobile, inverted pendulum.I EEE Transaction on Industrial Electronics 49, 107-114.
4. Grepl, R., Zouhar, F., Stepanek, J., & Horak, P. (2016). The development of a self-balancing vehicle: A platform for education in mechatronics. Faculty of Mechanical Engineering, Brno University of Technology. http://dsp.vscht.cz/konference_matlab/MATLAB11/prispevky/040_grepl.pdf(Accessed 16 February 2017).
5. http://www. art-of-invention. com/robotics
6. http://www. segway. com.
7. http://www. teamhassenplug. org/robot/legway.
8. 8Jin, D. (2015). Development of a stable control system for a segway. Available at: http://www.raysforexcellence.se/wpcontent/uploads/2013/01/Dennis-Jin-Developmentof-a- stable-control-system-for-a-segway.pdf.[Accessed 02 May, 2015]
9. Kim, S. & Kwom S. (2011). SDRE based non linear optimal control of a two-wheeled balancing robot. Journal of Institute of Control, Robotics and Systems, 17, 1037-1043.
10. Sun, L., & Gan, J. (2010).Research in g of two-wheeled self-balancing robot based on LQR combined with PID. International Workshop on Intelligent systems and Applications, pp. 1-5.
11. Lin, S.C., & Tsai, C.C. (2009).Develop of a self-balancing human transportation vehicle for the teaching of feedback control. IEEE Transaction Education, 52(1)157-168.
12. MathWorks, (2012). Control Tutorials for MATLAB and SIMULINK, Inverted Pendulum. Available at: http://ctms.engin.umich.edu/CTMS/index.php.exampleInvertedPendulum section-System Modeling. [Accessed 21 April 2015]
13. Nuo, J. & Hui, W. (2008). Nonlinear control of an inverted pendulum system based on sliding mode method. ACTA Analysis Functionalis Applicata, 9 (3), 234-237.
14. Sugie, T. & Fujimoto, K. (1998). Controller design for an inverted pendulum based on approximate linearization. International Journal of Robust and Nonlinear Control, 8(7), 585-597.
15. Takei, T., lmamura, R. & Yuta, S. (2009). Baggage transportation and navigation by a wheel inverted pendulum mobile robot. IEEE Transaction on Industrial Electronics, 56, 3985-3994.
16. Tomasic, T., Demetlika, A., & Crnekovic, M. (2012). Self-balance mobile robot tilter. Transactions of FAMENA, 36 (3), 23-32.