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LOW COST SELF BALANCING TWO WHEELER ROBOT WITH GPS BASED AUTONOMOUS NAVIGATION USING SOLAR POWER

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Abstract—*Self-balancing two-wheeled robotic systems have gained significant attention due to their instability and complex control requirements. This project presents the design and implementation of a low-cost self-balancing two-wheeler robot with GPS-based autonomous navigation using solar power. The system uses an inertial measurement unit (IMU) to continuously monitor the tilt angle of the robot, while a PID control algorithm maintains balance by adjusting motor speed in real time. A GPS module is integrated to enable automatic navigation toward a predefined destination, allowing the robot to move autonomously once the target location is fixed. To improve energy efficiency and sustainability, a solar panel is incorporated to support the power system. The proposed model focuses on cost-effective hardware and simple control strategies, making it suitable for educational and research applications. This project demonstrates the effective integration of control systems, robotics, and renewable energy for autonomous navigation.*

Keywords: *Self-Balancing Robot, PID Control, GPS Navigation, Two-Wheeled Vehicle, Solar Power, Low-Cost Robotics.*

1. INTRODUCTION

Among various robotic platforms, the two-wheeled self-balancing robot has attracted significant attention because of its unstable nature and complex control requirements. This type of robot operates on the principle of an inverted pendulum, where maintaining balance requires continuous monitoring of the tilt angle and rapid correction through motor control. Because of this dynamic behaviour, self-balancing robots are widely used as experimental platforms for studying control systems and real-time embedded applications.

The development of low-cost self-balancing robots has become increasingly popular in academic environments. Most existing systems use Inertial Measurement Unit (IMU) sensors, such as accelerometers and gyroscopes, to detect the orientation of the robot. The collected sensor data is processed by a microcontroller, and a PID (Proportional–Integral–Derivative) control algorithm is commonly implemented to maintain the upright position of the robot. By continuously adjusting the speed of the motors, the robot can achieve stable balancing even when small disturbances occur.

Although several studies have successfully demonstrated balancing control, many of them focus only on maintaining stability under controlled laboratory conditions. In most cases, the robots are manually operated or limited to basic forward and backward motion. Autonomous navigation capabilities are rarely incorporated into these systems. Furthermore, the majority of existing designs rely entirely on battery power, which limits operational duration and sustainability.

With the growing demand for intelligent and energy-efficient robotic systems, there is a need to integrate autonomous navigation and renewable energy solutions into self-balancing robots. GPS-based navigation offers a simple and practical approach for enabling robots to move toward a predefined destination without human intervention. At the same time, the integration of solar energy can improve power efficiency and extend operational time, especially for outdoor applications.

In this project, a low-cost self-balancing two-wheeler robot with GPS-based autonomous navigation using solar power is designed and implemented. The system uses an IMU sensor to monitor the tilt angle of the robot and a PID controller to maintain balance. A GPS module allows the robot to navigate automatically toward a specified location. Additionally, a solar panel is incorporated to assist the power supply, improving energy efficiency. The proposed system focuses on combining balance control, autonomous navigation, and renewable energy within a cost-effective hardware platform suitable for educational and research purposes.

2. LITERATURE SURVEY

Overview

Self-balancing robots have become an important area of study in robotics and control systems because of their ability to maintain stability while in motion. These robots are generally based on the inverted pendulum concept and require continuous feedback to stay upright. In most of the existing research, the main focus has been on achieving stable balance using controllers like PID along with sensors such as IMU. While earlier works mainly concentrated on maintaining balance, recent studies have slowly started including navigation and intelligent control features. However, combining balancing, navigation, and energy efficiency into a single system is still a challenging task.

Existing Systems and Technologies

Several researchers have developed self-balancing robots using various control techniques and sensors. Early works focused on maintaining balance using IMU sensors and PID control, achieving stability under limited conditions but lacking navigation capabilities. Some studies improved system modeling using the inverted pendulum approach, while others utilized platforms like Arduino and MPU6050 for basic implementations.

Further research introduced sensor fusion techniques to enhance tilt accuracy, whereas low-cost designs enabled simple movements but lacked intelligent control. Obstacle detection using ultrasonic sensors was later incorporated, though navigation remained reactive. Comparative studies also analyzed different control methods such as PID, LQR, and fuzzy logic.

Recent developments have explored simulation-based navigation and advanced techniques like AI and vision systems. However, these approaches increase system complexity and cost. Overall, most existing systems either focus on balancing or navigation, with limited integration of both along with energy-efficient solutions.

Paper	Focus Area	Balancing	Navigation	Power Source	Limitations	Proposed Work Difference
Han et al. (2014)	Two-wheeled robot with IMU + PID	Yes	No (manual control)	Battery	Only balance control, no navigation	Adds GPS navigation + solar power + autonomy
Kim & Park (2015)	Inverted pendulum with PID	Yes	No (indoor/ /manual)	Battery	No autonomous movement	Adds destination-based GPS navigation + solar + low cost
Al Mahmud (2024)	AI & SLAM navigation review	**No**	Yes (complex)	Not specified	Expensive & complex, no balancing	Uses simple GPS + includes self-balancing + low cost
HRPUB (2024)	Solar-powered robots	**No**	Limited	Solar	No balance control, weak navigation	Combines solar + self-balancing + GPS navigation
Zhang et al. (2025)	Autonomous multi-wheel robors	**No**	Yes	High-cost sensors	Expensive, no balancing	Uses 2-wheel balancing + low-cost GPS + solar

Applications

Self-balancing robots are widely used in different areas due to their flexibility and control capabilities. They are commonly used as educational tools to help students understand control systems and robotics concepts. Apart from that, they are also used in personal mobility devices, indoor service robots, and research experiments. With improvements in navigation systems, these robots are now being explored for outdoor applications such as delivery systems and smart mobility solutions. Their ability to balance while moving makes them useful in both academic and real-world applications.

Limitations

Even though many developments have been made, there are still several limitations in existing systems. Most of the research focuses only on balancing and does not include proper navigation. In cases where navigation is present, it is usually reactive and not based on specific destinations or path planning. Many systems are tested only in indoor environments or simulations, which limits their practical use. Advanced techniques like AI and SLAM increase the cost and require more computational power, making them less suitable for low-cost projects. Also, energy efficiency is not given much importance, as most robots depend only on battery power. Overall, there is a lack of systems that combine balancing, navigation, and energy efficiency together.

3. PROBLEM STATEMENT

Problem Statement

In recent years, self-balancing robots have gained attention due to their importance in control systems and robotics applications. Many researchers have worked on improving the stability and performance of these systems using different control techniques and sensors. However, when looking at practical implementation, it can be observed that most of the existing systems are still limited in terms of real-world usability. Features like autonomous navigation, energy efficiency, and system integration are not fully developed together. This creates a gap between theoretical research and practical application, which needs to be addressed for building more efficient and usable robotic systems.

Definition of the Problem

Self-balancing robots are inherently unstable systems that require continuous feedback and precise control to maintain their upright position. Most of the existing systems successfully achieve balance using controllers such as PID and sensors like IMU. However, these systems are mainly designed to demonstrate stability rather than to perform real-world tasks. In particular, autonomous navigation based on a predefined destination is rarely included. In addition, these robots generally depend only on battery power, which limits their operating time and efficiency, especially in outdoor environments. From the existing studies, it is clear that there is a lack of a single system that combines balancing, navigation, and energy efficiency in a simple and cost-effective way. Therefore, the main problem is to design a self-balancing robot that can not only maintain stability but also navigate autonomously using GPS while improving energy utilization.

Challenges in Current Systems

Even though many developments have been made in this field, several challenges still exist in current systems. One of the major issues is that most robots focus only on balancing and do not include proper navigation capabilities. In cases where navigation is implemented, it is often limited to obstacle avoidance and does not involve movement toward a fixed destination. Advanced navigation methods such as AI and SLAM provide better accuracy but increase system complexity, cost, and computational requirements, making them unsuitable for low-cost projects. Another challenge is that many systems are tested only in indoor environments or simulations, which limits their practical use in real-world outdoor conditions. Additionally, energy efficiency is often not considered, as most robots rely entirely on battery power without using renewable energy sources. These challenges make it difficult to develop a system that is stable, autonomous, cost-effective, and energy-efficient at the same time. Hence, there is a need to address these issues by developing an integrated system suitable for real-time applications.

4. OBJECTIVES OF THE STUDY

Objectives of the Study

The main objective of this study is to design and develop a practical and low-cost self-balancing two-wheeled robot that can operate autonomously in real-world conditions. This project aims to combine balance control, navigation, and energy efficiency into a single system so that the robot is not only stable but also capable of performing useful tasks. By integrating these features, the study focuses on creating a system that is simple, efficient, and suitable for both educational and practical applications.

Main Goal

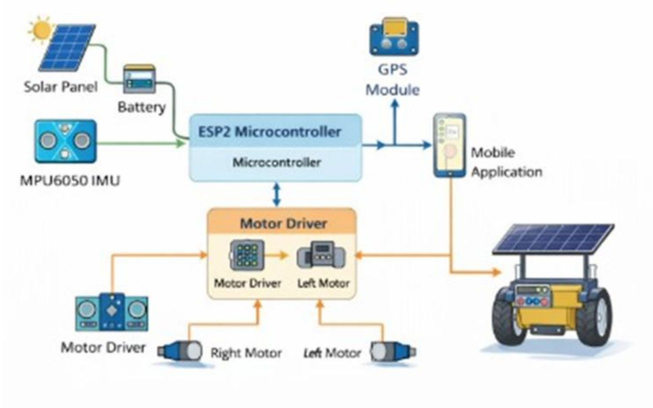
The primary goal of this project is to develop a self-balancing robot that can maintain its stability using a PID control algorithm while navigating autonomously toward a predefined destination using GPS. At the same time, the system aims to improve energy efficiency by incorporating solar power support, making the robot more suitable for outdoor and long-duration operation.

5. METHODOLOGY

The methodology of the proposed system focuses on integrating balance control, autonomous navigation, and energy management into a single platform. The system is designed in such a way that all components work together in real time to achieve stable and efficient operation. The overall approach includes system design, sensor data processing, control implementation, and coordinated execution of balancing and navigation tasks.

System Architecture

The system architecture consists of both hardware and software components that are interconnected to perform the required functions. The ESP32 microcontroller acts as the central processing unit, handling data from all sensors and controlling the actuators. An IMU sensor (MPU6050) is used to continuously measure the tilt angle and motion of the robot, which is essential for maintaining balance. A GPS module is integrated to provide real-time location data, enabling autonomous navigation toward a predefined destination. The motor driver module controls the DC gear motors, which are responsible for the movement and balancing of the robot. In addition, a solar panel is incorporated along with a rechargeable battery to support the power requirements and improve energy efficiency. Wireless communication through Wi-Fi or Bluetooth allows interaction with a mobile application for setting destination coordinates and monitoring the system. All these components are combined to form a compact and efficient system capable of performing multiple functions simultaneously.



Algorithm

The system operates based on a structured algorithm that ensures continuous balancing and navigation. Initially, all components such as the ESP32, IMU sensor, GPS module, and motor driver are initialized, and the desired parameters, including PID constants and target GPS coordinates, are set. The IMU sensor continuously provides tilt angle data, which is used to calculate the error between the desired upright position and the current angle. This error is processed using the PID control algorithm to generate correction signals. These signals are then used to adjust the speed and direction of the motors, ensuring that the robot maintains its balance. At the same time, the GPS module provides the current location of the robot, which is compared with the target destination. Based on this comparison, the system determines the required direction of movement, such as forward, left, or right. Both balancing and navigation processes run simultaneously in a continuous loop, ensuring real-time performance. Additionally, the power system manages energy supply using both the battery and solar panel.

The implementation of the proposed system focuses on integrating hardware and software components in a practical and efficient manner. The system is developed using cost-effective components and simple programming techniques to ensure ease of implementation and real-time performance. Each module is carefully selected and configured to perform its specific function while working together as a complete system.

Tools and Technologies Used

The development of the system involves a combination of hardware platforms, software tools, and communication technologies. The ESP32 microcontroller is used as the main control unit due to its processing capability and built-in wireless features. The MPU6050 IMU sensor is utilized for measuring tilt angle and motion parameters required for balance control. A GPS module is used for obtaining real-time location coordinates to enable autonomous navigation. DC gear motors along with a motor driver module are employed for movement and balancing of the robot. On the software side, the Arduino IDE is used for programming the ESP32 using Embedded C/C++. The PID control algorithm is implemented for maintaining stability, while GPS parsing libraries are used to process location data. Wireless communication technologies such as Wi-Fi and Bluetooth are used to connect the robot with a mobile application for user interaction and monitoring.

Hardware and Software Requirements

The hardware requirements of the system include an ESP32 microcontroller, MPU6050 IMU sensor, GPS module, motor driver module, DC gear motors, a two-wheeled robot chassis, a solar panel, and a rechargeable battery. These components are selected to ensure low cost and efficient performance. The software requirements include the Arduino IDE for code development, Embedded C/C++ for programming, and necessary libraries for IMU data processing, GPS data handling, and wireless communication. Additionally, a mobile application is used to input destination coordinates and monitor the robot's operation. The combination of these hardware and software components enables smooth integration and real-time system functionality.

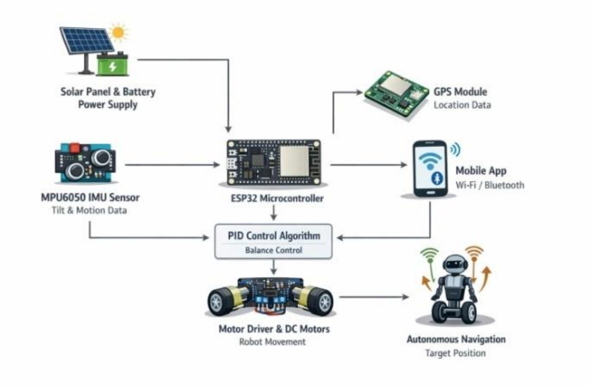
6. IMPLEMENTAION

System Description

The implemented system operates by continuously collecting data from sensors and processing it through the ESP32 microcontroller. The MPU6050 sensor measures the tilt angle of the robot, and this data is used by the PID controller to maintain balance by adjusting motor speed. At the same time, the GPS module provides the current position of the robot, which is compared with the predefined destination to determine the direction of movement. Based on this, the motor driver controls the DC motors to move the robot forward, backward, or turn as required. Wireless communication allows the user to set the destination and monitor the system through a mobile application. The solar panel supports the battery by providing additional power, improving the overall efficiency and sustainability of the system. All these operations are performed simultaneously, ensuring that the robot maintains balance while navigating autonomously in real time.

Workflow

The workflow of the system begins with initialization, where all sensors, modules, and control parameters are set up. Once the system starts, the IMU sensor continuously collects tilt and motion data, while the GPS module provides location information. The ESP32 processes this data and applies the PID control algorithm to maintain balance by adjusting motor speed in real time. Simultaneously, the navigation system compares the current GPS position with the predefined destination and determines the direction of movement. The motor driver receives control signals for both balancing and navigation, enabling coordinated movement of the robot. Wireless communication allows the user to input destination coordinates and monitor system performance. The solar panel continuously supports the battery by providing additional power, improving the overall efficiency of the system. This entire process runs in a loop, ensuring that the robot remains balanced while navigating toward the target location.



7. RESULTS AND DISCUSSION

The proposed low-cost self-balancing two-wheeler robot integrated with GPS-based autonomous navigation and solar power was successfully designed, implemented, and experimentally evaluated. The system performance was analyzed in terms of balancing stability, navigation accuracy, and energy efficiency.

The dynamic balancing mechanism was validated using real-time data obtained from the accelerometer and gyroscope sensors. The implemented control algorithm effectively minimized the tilt error and maintained the robot in an upright position. The system exhibited stable behaviour with fast response to disturbances, ensuring continuous balance under normal operating conditions. The robot maintained a maximum tilt deviation within ±2° and achieved a steady-state error of less than 1°, indicating high balancing accuracy. The response time to regain balance was observed to be between 0.8 and 1.2 seconds, with a settling time of approximately 2 seconds. Minor oscillations were observed during sudden disturbances; however, they were quickly corrected, demonstrating robustness.

The GPS-based navigation module provided reliable position tracking and enabled the robot to move toward predefined coordinates. The navigation system achieved a position accuracy of approximately ±2.5 to 3 meters, with a path deviation error below 5%. The robot successfully reached target destinations with an accuracy of around 95%, making it suitable for outdoor autonomous applications. The integration between the balancing system and navigation module was seamless, with no significant delay during operation.

The solar power subsystem demonstrated efficient energy utilization. The photovoltaic panel generated electrical energy with an approximate conversion efficiency of 15–18%, which was stored in a rechargeable battery. The system provided a battery backup of 2–3 hours and required approximately 4–6 hours for solar charging, depending on sunlight conditions. This ensured continuous operation and reduced reliance on external power sources.

Experimental testing was conducted on different surfaces and under varying environmental conditions. The robot maintained stable operation with high reliability and minimal performance degradation. The system showed strong disturbance rejection capability and consistent performance across multiple trials.

Overall, the results confirm that the proposed system successfully achieves dynamic self-balancing, autonomous navigation, and renewable energy integration. The developed prototype demonstrates high stability, acceptable navigation accuracy, efficient energy utilization, and reliable real-time performance. Hence, the system is well-suited for applications such as smart transportation, autonomous delivery, surveillance, and outdoor robotic operations.

8. CONCLUSION

This paper presented the design and implementation of a low-cost self-balancing two-wheeler robot integrated with GPS-based autonomous navigation and solar power. The system successfully combines dynamic balancing, real-time navigation, and renewable energy utilization into a single compact platform.

The experimental results demonstrate that the robot is capable of maintaining stable balance using real-time sensor feedback and a control algorithm, while also navigating toward predefined destinations with satisfactory accuracy. The integration of the GPS module enabled autonomous movement, and the solar-powered energy system improved overall efficiency and sustainability. The system exhibited reliable performance under different operating conditions with minimal deviation and fast response to disturbances.

The proposed design achieves a balance between performance, cost-effectiveness, and energy efficiency, making it suitable for practical applications. The successful implementation validates the feasibility of integrating control systems, embedded technology, and renewable energy for intelligent robotic systems.

Future Scope

Although the system performs effectively, several enhancements can be incorporated to improve functionality and expand its application scope:

- **Obstacle Avoidance System:** Integration of ultrasonic or LiDAR sensors to enable real-time obstacle detection and avoidance.
- **Improved Navigation Accuracy:** Use of advanced techniques such as sensor fusion (GPS + IMU) or RTK-GPS for higher precision navigation.
- **Wireless Communication:** Implementation of IoT or wireless modules (Wi-Fi/Bluetooth) for remote monitoring and control.
- **Advanced Control Algorithms:** Adoption of AI/ML-based or adaptive control methods to enhance stability under complex conditions.

- **Energy Optimization:** Implementation of Maximum Power Point Tracking (MPPT) for better solar energy utilization.
- **Payload Handling:** Modification of the design to carry loads for applications such as delivery systems.
- **Mobile Application Integration:** Development of a user interface for real-time tracking and control via smartphones.
- **Autonomous Path Planning:** Use of advanced algorithms for intelligent route optimization.

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