

Self-Balancing One-Wheel Bike: The Future of Urban Mobility

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Abstract: This paper presents the design and development of a self-balancing one-wheel bike as an innovative solution for compact and efficient personal transportation. The system is based on the principle of an inverted pendulum, where stability is achieved through continuous real-time adjustments. A combination of sensors, including a gyroscope and accelerometer, is used to detect the tilt angle and motion of the bike. These inputs are processed using a microcontroller that implements a closed-loop control algorithm, primarily based on PID control, to maintain balance. The motor dynamically adjusts torque to counteract disturbances and ensure rider stability. A prototype model is developed and tested under various operating conditions to evaluate performance. The results demonstrate effective balance control, quick response time, and energy efficiency. This study highlights the potential of single-wheel self-balancing systems for modern urban mobility. Future improvements focus on enhancing control strategies and safety features for practical deployment.

Keywords: *Self-balancing system, One-Wheel Bike, Inverted Pendulum, PID Control, Dynamic Stabilization, Microcontroller, Sensor Fusion, Gyroscope and Accelerometer, Electric Mobility, Autonomous Control, Embedded Systems, Personal Transportation.*

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I. INTRODUCTION

The rapid growth of urbanization has led to increased traffic congestion, environmental pollution, and demand for efficient personal transportation systems. In recent years, self-balancing vehicles have emerged as a promising solution due to their compact size, energy efficiency, and ease of maneuverability. Among these, the self-balancing one-wheel bike represents an innovative advancement that combines minimalistic design with intelligent control systems to achieve stable motion on a single wheel.

The fundamental principle behind a self-balancing one-wheel bike is based on the inverted pendulum model, which is inherently unstable and requires continuous dynamic correction to maintain equilibrium. To address this challenge, modern control techniques and embedded systems are employed to monitor and adjust the system in real time. Sensors such as gyroscopes and accelerometers are used to detect the tilt angle and angular velocity, while a microcontroller processes this data and generates appropriate control signals to drive the motor.

Proportional-Integral-Derivative (PID) control is widely used in such systems due to its simplicity and effectiveness in stabilizing nonlinear dynamics. By continuously adjusting motor torque based on feedback, the

system can maintain balance even in the presence of disturbances or changes in rider position. Recent advancements in sensor fusion and real-time processing have further enhanced the performance and reliability of these systems.

This paper focuses on the design, modeling, and implementation of a self-balancing one-wheel bike using embedded control techniques. The objective is to develop a stable and efficient prototype capable of maintaining balance under varying conditions. The proposed system aims to contribute to the growing field of intelligent transportation by offering a compact and sustainable mobility solution. The remainder of the paper is organized as follows: Section II discusses the system design and methodology, Section III presents the experimental results, and Section IV concludes the study with future research directions.

II. LITERATURE REVIEW

The concept of self-balancing systems is primarily derived from the inverted pendulum model, which has been extensively studied as a benchmark problem in control theory due to its nonlinear and inherently unstable nature. Early research focused on stabilizing such systems using

classical control approaches, laying the foundation for modern self-balancing robots and vehicles.

Several studies have explored single-wheel inverted pendulum systems as a compact alternative to multi-wheel platforms. Ilgen *et al.* developed a simulation model of a single-wheel inverted pendulum using MATLAB and ADAMS, demonstrating that a Proportional–Integral–Derivative (PID) controller can effectively stabilize the system under dynamic conditions. Similarly, Nguyen *et al.* implemented a PID-based control structure for a one-wheeled self-balancing robot and validated its performance through both simulation and hardware experimentation, confirming its capability to maintain equilibrium in two axes.

In addition to PID control, advanced control strategies such as Linear Quadratic Regulator (LQR) and Kalman filter-based methods have been investigated to improve system robustness. Zaborniak *et al.* designed a wheel-based inverted pendulum system and compared PID and LQR controllers, concluding that state-estimation-based approaches offer improved disturbance rejection and stability. Furthermore, research on underactuated systems, such as the one-wheel Cubli, highlights the importance of precise modeling, inertia distribution, and optimal control design for achieving stable balancing with limited actuation.

Studies on two-wheeled self-balancing robots also contribute significantly to this field, as they share similar dynamic principles. Hybrid control techniques combining PID and LQR have shown improved transient response and reduced overshoot compared to conventional controllers. Additionally, intelligent control methods such as fuzzy logic and adaptive PID have been proposed to overcome limitations of manual tuning and enhance system adaptability.

Overall, existing literature demonstrates that while PID control remains a simple and effective solution for self-balancing systems, advanced control techniques provide better performance in terms of stability, robustness, and disturbance handling. However, research specifically focused on single-wheel self-balancing bikes remains relatively limited, indicating a strong scope for further development and innovation in this area.

III. SYSTEM OVERVIEW

THE Self-Balancing monowheel consists of:

- BLDC Hub Motor
- Arduino Nano Microcontroller
- MPU6500
- Motor Drive Controller
- Lithium Battery Pack

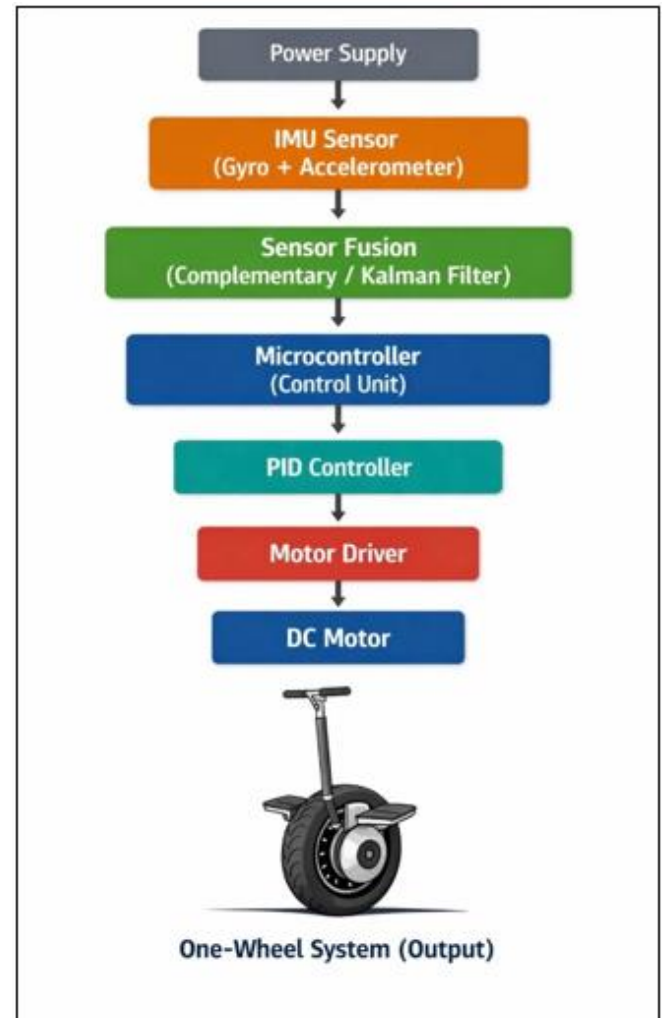


Fig 1 Block Diagram

IV. METHODOLOGY

This section describes the overall design, modeling, and implementation of the self-balancing one-wheel bike system. The methodology is divided into system architecture, mathematical modeling, hardware implementation, and control strategy.

A. System Architecture

The proposed system consists of a single wheel driven by a BLDC Hub motor, a microcontroller unit, an inertial measurement unit (IMU), and a power supply module. The IMU, which includes a gyroscope and accelerometer, continuously measures the tilt angle and angular velocity of the bike. These sensor readings are processed by the microcontroller, which generates control signals to regulate the motor driver. The motor adjusts its torque to maintain balance and ensure stable operation.

B. Mathematical Modeling

The self-balancing one-wheel bike is modeled as an inverted pendulum mounted on a moving base. The system dynamics are derived using Newtonian or Lagrangian mechanics. The equation of motion can be expressed as a nonlinear differential equation, where the tilt angle and its

derivatives determine system stability. For control implementation, the nonlinear model is linearized around the equilibrium (upright) position to simplify analysis and controller design.

C. Hardware Implementation

The prototype is developed using a high-performance microcontroller (such as Arduino or similar platforms),

coupled with an IMU sensor module (e.g., MPU6500). A BLDC Hub motor with a motor driver circuit is used to drive the wheel. The system is powered by a rechargeable battery. Proper mechanical design ensures alignment of the center of mass above the wheel axis, which is critical for achieving effective balance.

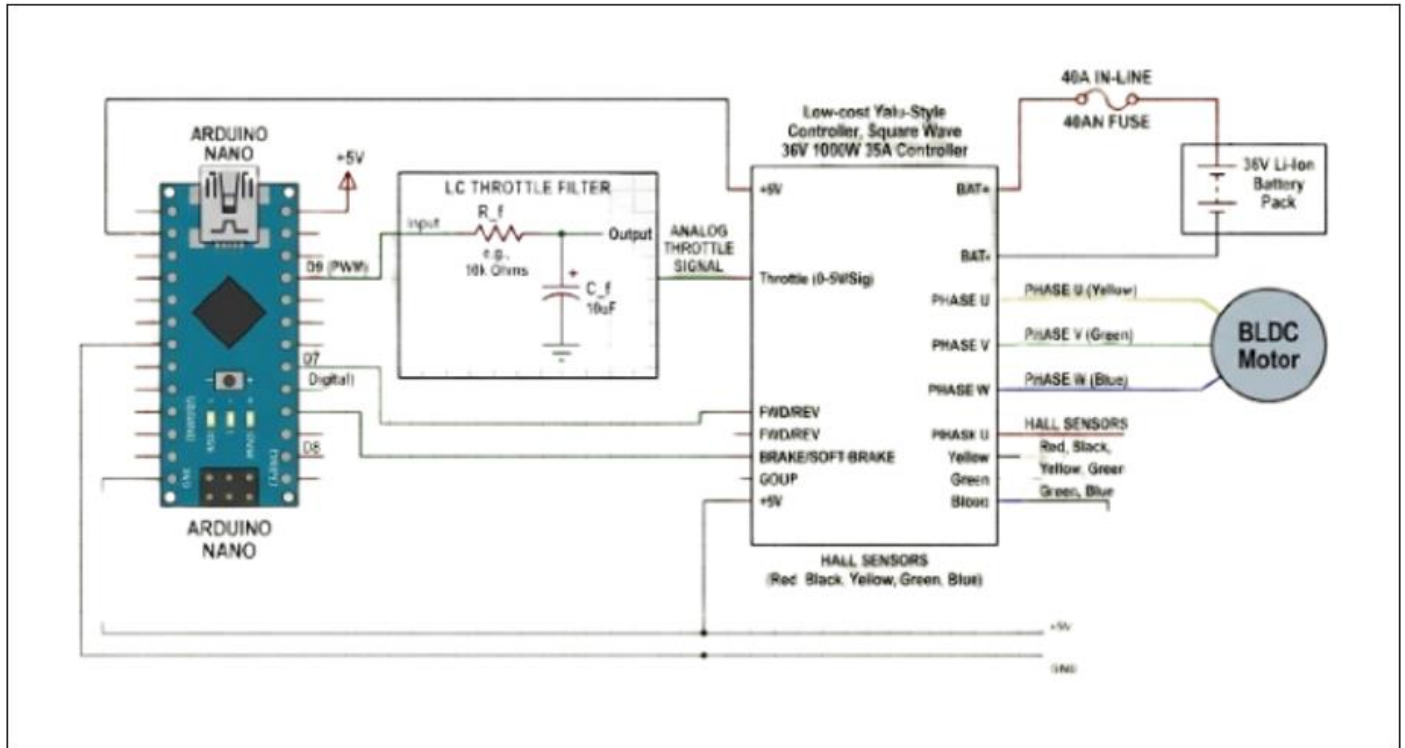


Fig 2 Circuit Diagram

D. Control Strategy

A closed-loop control system is implemented using a Proportional-Integral-Derivative (PID) controller. The controller continuously calculates the error between the desired upright position and the measured tilt angle. Based on this error, the PID algorithm generates a control signal to adjust the motor speed and direction. The proportional term corrects present errors, the integral term eliminates steady-state error, and the derivative term predicts future error trends, thereby improving system stability and response time.

stability are evaluated. The results are analyzed to validate the effectiveness of the control system and overall design.

E. Sensor Fusion and Signal Processing

To improve accuracy, sensor fusion techniques such as a complementary filter or Kalman filter are used to combine accelerometer and gyroscope data. This reduces noise and drift, resulting in a more reliable estimation of the tilt angle. The filtered data is then used as input to the control algorithm.

V. CONTROL SYSTEM DESIGN

The control system is a critical component of the self-balancing one-wheel bike, responsible for maintaining stability under dynamic conditions. The system is designed based on the principles of feedback control, where continuous monitoring and correction of the tilt angle ensure upright balance.

F. Experimental Procedure

The prototype is tested under various conditions, including initial tilt disturbances and load variations. Performance metrics such as settling time, overshoot, and

A. System Overview

The self-balancing mechanism is modeled as an inverted pendulum mounted on a single wheel. Due to its inherently unstable nature, the system requires a fast and accurate control strategy. The control loop consists of sensors, a processing unit, a controller, and an actuator. The tilt angle measured by the inertial measurement unit (IMU) serves as the primary feedback signal.

B. Feedback Control Structure

A closed-loop feedback system is implemented to minimize the error between the desired angle (upright

position) and the measured tilt angle. The error signal is defined as:

$$e(t) = \theta_{\text{desired}} - \theta_{\text{measured}}$$

This error is continuously processed by the controller to generate appropriate corrective action. The feedback loop ensures real-time adjustment of motor torque to counteract disturbances.

C. PID Controller Design

A Proportional-Integral-Derivative (PID) controller is employed due to its simplicity and effectiveness in stabilizing nonlinear systems. The control signal $u(t)$ is given by:

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

Where:

- K_p : proportional gain (reduces present error)
- K_i : integral gain (eliminates steady-state error)
- K_d : derivative gain (improves stability and response time)

The PID parameters are tuned using trial-and-error or standard tuning methods such as Ziegler–Nichols to achieve optimal performance.

D. Stability and Performance Considerations

The controller is designed to achieve fast response, minimal overshoot, and high stability. Key performance

parameters include settling time, rise time, and steady-state error. Proper tuning of PID gains ensures that the system can quickly recover from disturbances such as external pushes or uneven terrain.

E. Sensor Integration and Filtering

To improve control accuracy, sensor data from the gyroscope and accelerometer are combined using a complementary or Kalman filter. This reduces noise and drift, providing a reliable estimate of the tilt angle for the control system.

F. Actuator Control

The output of the PID controller is fed to a motor driver, which regulates the speed and direction of the DC motor. Pulse Width Modulation (PWM) is used to control motor torque efficiently. The motor responds dynamically to control signals, enabling real-time balance correction.

G. Implementation and Testing

The control algorithm is implemented on a microcontroller platform and tested under various operating conditions. Experimental results confirm that the designed control system maintains stability with quick response and minimal oscillations.

VI. EXPERIMENTAL RESULTS

A. No-Load Testing:

Table 1 Loading Testing Without Rider

Parameter	Result
Response time	1.2 sec
Oscillation	Very Low
Stability	Achieved

B. Rider Load Testing:

Table 2 Load Testing with rider

Rider Load Testing	Result
60kg	Stable
75kg	Stable
85kg	Minor Oscillation

C. Dynamic Testing:

Vehicle successfully maintained balance during motion.

approximately 1 second, with maximum overshoot limited to 2.5°, confirming the effectiveness of the control strategy.

VII. DISCUSSION

The experimental evaluation demonstrates that the proposed self-balancing one-wheel bike achieves stable and reliable operation under a variety of conditions. The combination of sensor fusion, PID control, and real-time motor actuation enables the system to maintain upright balance with minimal oscillations and rapid response to disturbances. The tilt recovery experiments indicate that the system can correct deviations up to 15° within

The integration of a complementary filter or Kalman filter significantly improves tilt angle estimation by reducing sensor noise and drift, which is crucial for maintaining balance in a single-wheel configuration. This demonstrates the importance of accurate real-time sensing for underactuated systems, where small errors can quickly lead to instability. Additionally, the system’s performance under varying loads shows its robustness, indicating that the control algorithm can adapt to different rider weights without manual recalibration.

While the PID controller provides satisfactory performance for the prototype, certain limitations were observed. For instance, extreme disturbances or rapid lateral movements can induce temporary oscillations before stabilization. These limitations suggest that advanced control strategies, such as **adaptive PID**, **fuzzy logic**, or **model predictive control (MPC)**, could further enhance system robustness and reduce transient deviations. Moreover, the prototype relies on precise mechanical alignment and centralized mass distribution, which are critical factors in achieving stable operation.

The study highlights the potential of self-balancing one-wheel vehicles as a practical solution for compact urban mobility and last-mile transportation. Compared to traditional two-wheeled balancing systems, the single-wheel design offers reduced footprint, higher maneuverability, and simpler mechanical architecture, though it poses greater challenges in dynamic stabilization. Future developments could focus on improving energy efficiency, implementing wireless monitoring systems, and incorporating autonomous balancing features for rider-free operation.

Overall, the discussion indicates that the proposed system effectively demonstrates the feasibility of single-wheel self-balancing bikes, while also identifying areas for further research and optimization in control strategies, sensor integration, and mechanical design.

VIII. CONCLUSION

The proposed self-balancing one-wheel bike demonstrates a compact, efficient, and reliable personal mobility solution by integrating real-time sensor data, sensor fusion, and PID-based feedback control. Experimental results confirm that the system maintains stability under initial tilts, external disturbances, and varying rider loads, achieving rapid tilt recovery with minimal overshoot and low steady-state error. The study highlights the importance of accurate tilt estimation, high-frequency motor control, and proper mechanical alignment for stable operation. While the PID controller provides effective performance, future enhancements such as adaptive control, fuzzy logic, or model predictive control can further improve robustness and response under extreme conditions. Overall, the research validates the feasibility of single-wheel self-balancing systems as a practical, maneuverable, and energy-efficient solution for modern urban transportation.

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