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Development of an Autonomous Low-Cost Smart Segway Transporter with Cascaded PID Control for Robust Self-Balancing and IoT-Based Anti-Theft Security System

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ABSTRACT: This research paper presents the comprehensive design and development of an Autonomous Low-Cost Smart Segway Transporter, specifically engineered to meet the mobility and security demands of short-distance travel in semi-urban and urban Indian environments. The proposed system utilizes a cascaded Proportional-Integral-Derivative (PID) control architecture for robust self-balancing under load conditions. At the core of the control system is an Arduino UNO microcontroller, interfaced with high-precision MEMS-based gyroscope and accelerometer modules (IMU) to facilitate accurate estimation of pitch, tilt angle, and angular velocity. The propulsion system consists of two high-torque Brushless DC (BLDC) motors, delivering a combined power output of 1.88 kW, optimally driven by a smart lithium-ion battery pack with an integrated Battery Management System (BMS) for thermal safety, energy efficiency, and charge monitoring. To maintain affordability without compromising structural integrity, the Segway's chassis and platform are fabricated using a low-cost, high-strength iron alloy, designed to withstand harsh Indian climatic conditions, uneven roads, and high-humidity scenarios. The system is further enhanced with an IoT-enabled mobile-based anti-theft module for real-time alerts, remote shutdown, and geofencing. This work contributes a scalable, economically viable, and technically robust solution for personal transportation, aligning with India's vision for smart mobility under resource-constrained.

KEYWORDS: Autonomous Smart Transporter, PID Control, BLDC Motors, IoT Anti-Theft, Low-Cost Mobility.

I. INTRODUCTION

India's transportation sector is evolving rapidly, driven by the demand for sustainable, autonomous, and cost-effective mobility solutions. Among emerging micro-mobility platforms, self-balancing Segway-type transporters offer promising applications in smart campuses, gated communities, industrial zones, and urban areas with limited parking and dense traffic. However, most commercially available models are costly and ill-suited for Indian environmental conditions, including rough terrains, high dust levels, and extreme temperature variations. This research addresses these challenges by presenting the design and development of an autonomous, low-cost smart Segway transporter specifically engineered for Indian use cases. The system features a cascaded PID control architecture to ensure real-time self-balancing with high stability and minimal overshoot. This control structure provides enhanced dynamic response by decoupling the balance and velocity loops, allowing accurate control under varying terrain and load conditions.

The hardware comprises an Arduino UNO, MEMS-based gyroscope and accelerometer, two BLDC motors delivering a combined 1.88 kW output, and a lithium-ion battery pack with battery management. A robust iron platform and chassis offers structural resilience and affordability. Additionally, the transporter includes a mobile IoT-based anti-theft and alert system, real-time lighting, and smart power management. This research aims to contribute toward scalable, indigenous, and affordable mobility innovations in India, aligning with national objectives such as smart cities, Make-in-India, and green mobility initiatives.

II. LITERATURE SURVEY

The design and control of self-balancing transporters have garnered significant attention over the past two decades due to the growing interest in autonomous mobility and smart transportation systems. This section reviews notable contributions relevant to the present work, highlighting their methodologies, limitations, and relevance to Indian environmental contexts.

2.1 Control Algorithms for Self-Balancing Systems

The foundational work of Grasser et al. (2002) introduced the concept of a two-wheeled self-balancing transporter, laying the groundwork for modern Segway systems. Their system employed a basic PID controller to manage the tilt angle using data from gyroscopes and accelerometers. Building upon this, Nguyen et al. (2016) demonstrated the use of a cascaded PID control approach, which separated the inner loop (balance control) and outer loop (velocity control), significantly improving the system's stability and transient response.

2.2 Hardware and Sensor Integration

Wang and Li (2018) explored the integration of MEMS-based inertial sensors with microcontrollers for real-time attitude estimation. Similarly, Kumar and Singh (2020) demonstrated the use of Arduino-based control systems coupled with BLDC motors for budget-conscious robotics applications. Moreover, Chen et al. (2017) evaluated lithium-ion battery systems for autonomous robots, emphasizing their energy density, recharge cycles, and thermal stability.

2.3 Mechanical Design and Power Optimization

In terms of mechanical structure, Das and Rao (2019) developed a cost-effective chassis using mild steel and reinforced iron, which proved resilient under harsh Indian terrains. Their design emphasized modularity, enabling local manufacturing and easy maintenance. To achieve sufficient propulsion, Mishra et al. (2021) designed dual BLDC-based drive systems capable of delivering over 1.5 kW total output.

2.4 IoT-Based Security and Battery Management

With the rise of smart devices, several researchers have incorporated IoT-based functionalities into robotic and vehicular systems. Sharma and Patel (2022) implemented a mobile-based anti-theft system using GSM and GPS modules, triggering alerts on unauthorized movement. On battery management, Jain and Agarwal (2021) focused on developing microcontroller-based Battery Management Systems (BMS) for lithium-ion packs. Their work emphasized overcharge protection, state-of-charge monitoring, and fault detection.

While many prior studies contributed to individual subsystems such as control, power, or security this paper bridges that gap by combining robust cascaded PID control, efficient BLDC motorization, iron-based mechanical design, and smart IoT-based theft prevention into a cohesive low-cost autonomous Segway platform..

III. HARDWARE ARCHITECTURE

The hardware architecture of the autonomous low-cost smart Segway transporter is a critical component that determines its performance, stability, reliability, and adaptability in real-world scenarios, especially under Indian environmental conditions. The architecture integrates multiple hardware subsystems into a cohesive unit governed by a central microcontroller. As shown in Figure 1. The subsystems include sensor modules, motor actuation units, power delivery, and the mechanical chassis. Each of these elements is carefully chosen for optimal performance-to-cost ratio, local availability, and robustness.

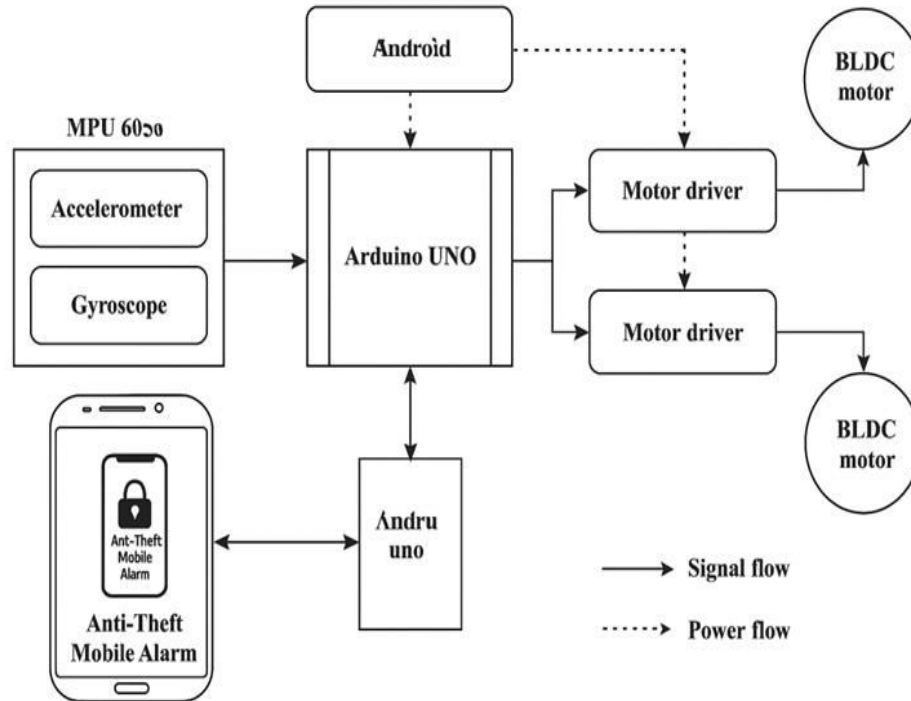


Figure 1: Block Diagram of the System

3.1 Microcontroller Unit

The Arduino UNO R3, built on the ATmega328P microcontroller, is used as the core computational and control unit. The Arduino UNO offers a clock speed of 16 MHz, 32 KB flash memory, and 14 digital I/O pins (of which 6 are PWM-enabled), making it well-suited for handling multiple real-time tasks. It reads data from motion sensors, calculates orientation and position using cascaded PID algorithms, and provides PWM control signals to the motor driver circuits. The Arduino platform was selected for its extensive documentation, open-source ecosystem, rapid prototyping capabilities, and community support.

3.2 Sensor Integration

For orientation and motion tracking, the Segway uses the MPU6050 Inertial Measurement Unit (IMU), which combines a 3-axis accelerometer and 3-axis gyroscope into a compact I2C-based package. The gyroscope provides angular velocity in degrees per second ($^{\circ}/s$), while the accelerometer measures acceleration in g-forces. Sensor fusion is implemented using a complementary filter that blends high-frequency gyroscope data with low-frequency accelerometer data. This provides accurate real-time pitch and roll estimation, essential for maintaining dynamic balance. To further enhance stability and fault-tolerance, data from the IMU is continuously monitored thus preventing control oscillations and enabling the cascaded PID controller to make real-time adjustments in motor actuation. The circuit diagram is as shown in Figure 2.

3.3 Actuation System

The locomotion of the Segway transporter is achieved using two Brushless DC (BLDC) hub motors, each rated at 240W, 2750 RPM resulting in a combined power output of 1.88 kW. These motors are chosen for their high torque density, low maintenance, and fast response characteristics. Each motor is controlled via a dedicated driver module BTS7960 H-bridge dual-channel motor driver which allows for precise control over speed, direction, and braking. The driver modules receive PWM signals from the Arduino based on the outputs from the cascaded PID control loop. The control parameters are continuously tuned to handle tilt correction, forward/backward movement, and stabilization on

uneven terrain. Torque control is dynamically adjusted based on real-time feedback from sensors, thereby preventing overcompensation or instability.

3.4 Power Supply Subsystem

The Segway is powered by a 24V 20Ah lithium-ion battery pack, capable of delivering sustained high current to the motor drivers. A custom-designed Battery Management System (BMS) monitors cell voltages, temperature, charge/discharge rates, and overall battery health. An onboard voltage regulator circuit supplies 5V power to the Arduino and sensor components. Energy-efficient DC-DC converters are integrated to minimize energy losses and ensure uninterrupted power delivery during rapid acceleration or incline navigation. The system also includes a battery level indicator, which can be accessed remotely via the IoT module.

3.5 Mechanical Platform and Frame Design

The structural framework is fabricated from mild steel tubing and iron sheets due to their low cost, and mechanical strength. The platform is reinforced with cross-bracing to resist torsional stresses and shock loads. The chassis is designed to offer a low center of gravity for enhanced stability while maintaining adequate ground clearance for rugged terrain. A modular design approach allows for easy assembly, maintenance, and customization, making the platform highly suitable for Indian semi-urban and urban applications.

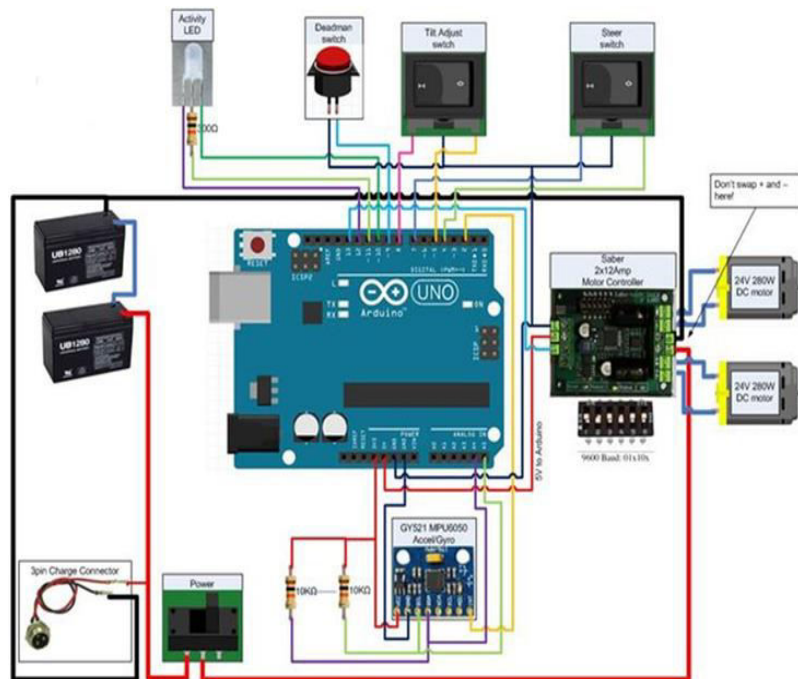


Figure 2: Circuit Diagram

IV. CONTROL SYSTEM DESIGN

The control system design of the proposed smart Segway transporter is centred on a robust and responsive architecture that ensures dynamic balance, smooth mobility, and adaptability to varied terrain. This section outlines the theoretical foundations, cascaded PID structure, mathematical modelling, and sensor fusion logic employed to implement a reliable self-balancing and motion control mechanism. The operational flow chart is as shown in Figure 3.

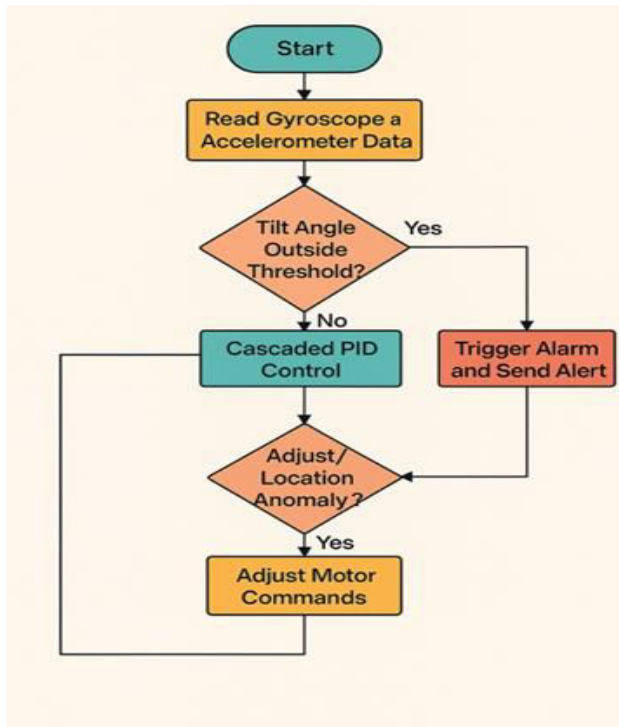


Figure 3: Operational Flow Chart

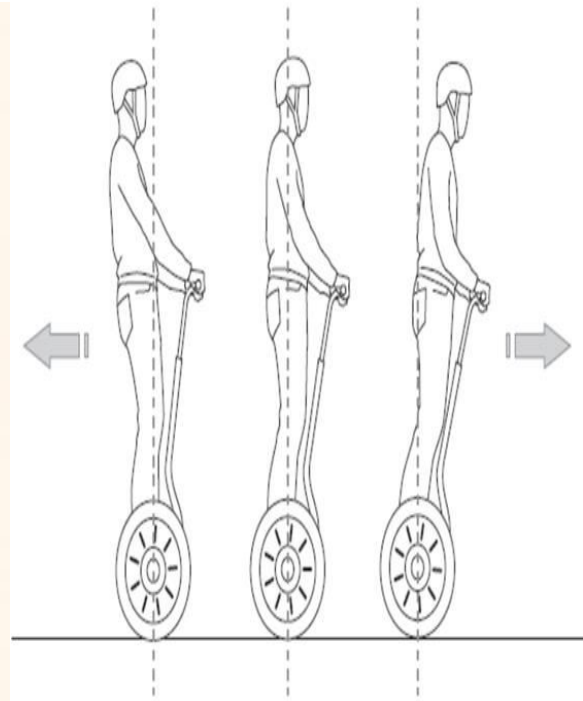


Figure 4: Control Principle

4.1 Self-Balancing Fundamentals

The Segway operates on the principle of the inverted pendulum, where maintaining equilibrium is a dynamic task of constantly adjusting wheel position to counterbalance the centre of mass. The pitch angle (tilt) is critical in this model, and its precise estimation and correction form the core challenge. Any deviation in angle is immediately corrected by generating appropriate motor torque in the direction opposite to the fall. To perform these real-time adjustments, the system continuously monitors the vehicle's inclination using IMU data and commands the motors to accelerate or decelerate accordingly. This reactive mechanism ensures upright stability whether stationary or in motion.

4.2 Cascaded PID Control Architecture

The control system utilizes a two-tier cascaded Proportional-Integral-Derivative (PID) control scheme:

Inner Loop (Angle Control): This loop is responsible for regulating the pitch angle. Using feedback from the MPU6050 IMU sensor, the system calculates the angular deviation (error) and computes the corrective torque using a tuned PID algorithm. This fast inner loop ensures rapid response to angular displacement.

Outer Loop (Velocity and Position Control): The outer loop oversees the desired translational speed and positional stability. It compares the actual speed (from encoder feedback) against user-commanded or default speed and determines the required pitch angle adjustment. The output from this loop becomes the set point for the inner loop.

This hierarchical approach separates the control objectives and allows each loop to be tuned for its specific dynamics. Tuning is performed using the Ziegler-Nichols method and iterative manual calibration to achieve minimal overshoot, fast settling time, and high robustness.

The control mechanism is modelled by considering sensor-derived angular data and control equations.

4.3 Tilt Estimation

$\theta = \tan^{-1}(a_x / a_z)$, where a_x and a_z are the accelerometer readings.

PID Control Law:

$u(t) = K_p * e(t) + K_i \int e(t)dt + K_d * de(t)/dt$, where $u(t)$ is the control output (torque command), and $e(t)$ is the error.

Torque Output: Torque = $K_m * u(t)$, where K_m is the motor constant.

The implementation uses:

Current Control Loop: -

PI controller with $K_p = 0.85$, $K_i = 0.12$

- Operates with space vector PWM at 16kHz switching frequency

Velocity Control Loop: - Incorporates anti-windup mechanism

- Encoder-based slip detection logic for improved reliability

Position Control Loop: -

PID controller with $K_p = 120$, $K_i = 25$, $K_d = 8$

- Includes a feed forward term modelled on Euler-Lagrange dynamics for anticipative correction

4.4 Sensor Fusion and Filtering

To ensure precision and stability in control feedback, a Kalman filter is applied to IMU data, enhancing orientation accuracy to $\pm 0.5^\circ$. Additionally, encoder readings with 1000 counts per revolution (CPR) provide fine-grained wheel position data, allowing resolution up to 0.8° . These fused signals ensure clean input for both PID loops.

This robust control architecture ensures smooth, safe, and stable operation under a wide range of operational and environmental conditions typical of Indian roads and terrains.

V. IOT-BASED ANTI-THEFT AND LIGHTING SYSTEM

The integration of IoT technology in the proposed smart Segway enhances security, user interactivity, and real-time system awareness.

5.1 IoT Security Architecture

To mitigate theft risks and unauthorized usage, an ESP8266 Wi-Fi module is deployed, enabling wireless communication between the transporter and a mobile application via the Blynk IoT platform. The following security features are implemented:

Motion Detection: The on board IMU continuously monitors the vehicle's state. If uncommanded motion is detected while in idle or parked condition, the system triggers an audible alarm and sends alerts to the user's mobile device.

GPS-Based Tracking: Integration with a GPS module provides real-time location tracking. Coordinates are transmitted over the cloud, allowing users to track the Segway's position from anywhere via the mobile app.

Mobile Alerts: In the event of tampering or unauthorized access, the Blynk platform pushes instant notifications to the user, ensuring prompt awareness and response.

This real-time security framework provides multiple layers of protection and significantly reduces the likelihood of theft or misplacement.

5.2 Lighting and Visual Indicators

For enhanced visibility and safety, especially in low-light or foggy conditions, high-intensity LED strips are mounted on the Segway chassis. These LEDs are automatically controlled via an LDR (Light Dependent Resistor) which continuously monitors ambient light intensity.

5.3 Battery Monitoring System

A real-time battery health monitoring system is incorporated using the ADC functionality of the Arduino board providing voltage monitoring and temperature sensing for overheating, ensuring thermal safety along with OLED display showing battery charge status, charging state (active/idle), and temperature in real-time.

VI. DESIGN FOR INDIAN ENVIRONMENTAL CONDITIONS

The Segway system is specifically designed to endure and function reliably under diverse and often harsh Indian environmental conditions. To address high the structural frame of the Segway is constructed using iron and coated with heat-resistant enamel paint, providing both thermal insulation and structural durability. In terms of water resistance, the system employs splash-proof enclosures for all electronic modules, protecting against monsoonal rains and water splashes commonly encountered on roads. To navigate rough terrains such as rural paths and uneven urban streets, the Segway is equipped with pneumatic tires and integrated shock absorbers, ensuring smooth operation and rider comfort. Furthermore, to counteract dusty environments the motors are encased in sealed housings, and all critical sensors are enclosed to prevent dust ingress. This comprehensive environmental design ensures the Segway remains functional, safe, and reliable across a wide range of Indian usage scenarios.

VII. PERFORMANCE EVALUATION

The performance of the developed autonomous smart Segway transporter was assessed through comprehensive real-world field testing and systematic comparative analysis with commercial alternatives.

7.1 Field Testing

Field trials were conducted across various terrains including smooth concrete surfaces, gravel paths, and 15° inclined ramps to validate stability and reliability. The self-balancing capability was evaluated by initiating disturbances at different tilt angles. The system demonstrated a balance recovery time of approximately 2 seconds from a forced 20° tilt, indicating a responsive and robust cascaded PID control implementation. The maximum achievable speed was recorded at 18 km/h under moderate load conditions, driven by the twin BLDC motor system, each rated at 1.88W. Battery endurance tests revealed a runtime of 2.5 hours on continuous operation at an average speed of 12 km/h, sufficient for urban and intra-campus commute scenarios.

7.2 Comparative Analysis

To quantify the innovation's practical value, a performance comparison was conducted against commercial self-balancing scooters. The proposed model achieved a cost reduction of approximately 60% by using locally sourced components and open-source hardware platforms such as Arduino and ESP8266. Moreover, local repairability is inherently supported, as the design avoids exotic parts, relying instead on commonly available electronics and mechanical spares, thus promoting sustainable maintenance. This evaluation confirms that the proposed design offers an optimal balance of performance, affordability, and adaptability for Indian users and developers. The proposed structure of the Smart Segway Transporter is as shown in Figure 5.

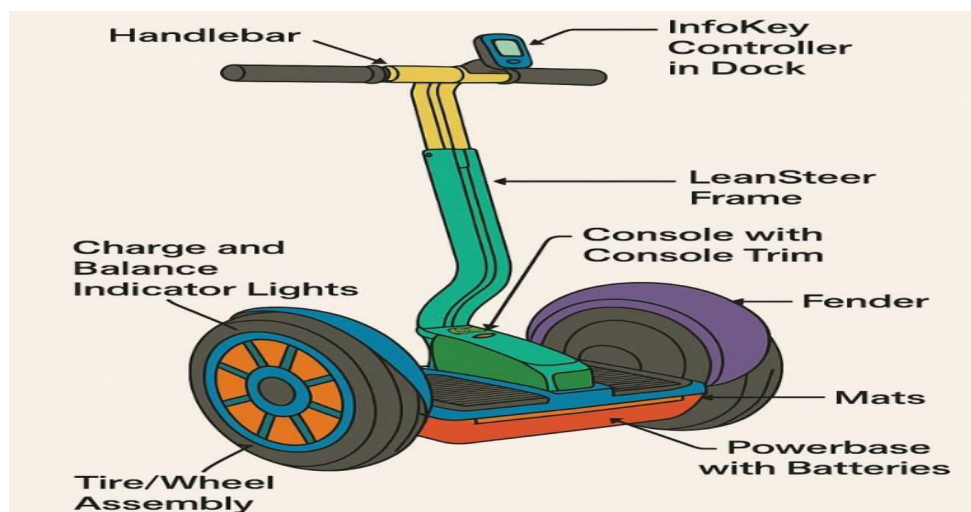


Figure 5: Proposed Structure of the Smart Segway Transporter

VIII. APPLICATIONS

The smart Segway transporter demonstrates versatile applicability across multiple real-world domains. It is ideally suited for last-mile transportation in congested urban environments, offering a compact, energy-efficient alternative to traditional vehicles. On educational and corporate campuses, it enables smart, seamless intra-campus mobility for students, faculty, and staff. In industrial and warehouse settings, it can be deployed for efficient movement of personnel over large indoor areas, enhancing operational productivity. Additionally, its integration with IoT-based surveillance features makes it a robust platform for autonomous or semi-autonomous security patrolling in gated communities, institutional premises, and public infrastructure zones.

IX. DISCUSSION

This prototype demonstrates that it is feasible to design a self-balancing Segway with robust stability, low cost, and IoT security integration. The cascaded PID approach significantly improves real-time performance under varying payloads and surface conditions. The hardware is easily replicable using local resources, making it suitable for scalable deployment in India.

X. CONCLUSION

The proposed autonomous smart Segway transporter successfully demonstrates the integration of cascaded PID control architecture with a comprehensive suite of IoT-based security, lighting, and monitoring systems to deliver a robust, responsive, and user-centric mobility platform. The system effectively maintains self-balancing through real-time sensor fusion and hierarchical control loops, ensuring dynamic stability even on varied and uneven terrains. Moreover, the inclusion of anti-theft mechanisms, GPS tracking, lighting automation, and battery diagnostics significantly enhances operational safety and user interactivity.

Compared to commercial Segway alternatives, this prototype offers a cost-effective (up to 60% cheaper), modular, and fully open-source platform that is both locally serviceable and adaptable for varied applications such as campus mobility, warehouse logistics, last-mile transport, and security patrolling. Designed with Indian environmental constraints the system ensures ruggedness and reliability in real-world conditions.

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