iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** I **Month of publication:** January 2026

DOI: https://doi.org/10.22214/ijraset.2026.76756

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue I Jan 2026- Available at www.ijraset.com

Design and Development of a Self-Balancing Patrolling Bike for Urban Surveillance and Mobility Enhancement

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Abstract: As robotics continues to advance across industries, autonomous systems are increasingly being adopted for safety, surveillance, and human interaction. Urban environments, which are often large, complex, and difficult to monitor, still rely heavily on static cameras, manual patrols, and limited human oversight for security. These traditional methods become inadequate during peak periods such as night shifts and holidays, and they lack real-time updates, mobility, and multi-threat adaptability. This project proposes an autonomous patrolling bike designed to function as a mobile guard and digital sentry, capable of independently navigating predefined paths, avoiding obstacles, and providing real-time alerts and threat information. The robot integrates multimodal interaction through cloud connectivity, AI vision, and sensor fusion, supported by IoT infrastructure to access and update information dynamically. By combining mobility with intelligent communication, the system aims to enhance site safety, reduce risk for human guards, and demonstrate the effective role of robotics in creating smarter and more secure urban environments.

Keywords: Self-Balancing Robot, Urban Surveillance, Security Bike, Inverted Pendulum, PID Control, AI Threat Detection, Cloud Connectivity, ESP32

I. INTRODUCTION

In modern urban landscapes, the rapid pace of urbanization has created a pressing need for advanced, automated security solutions to manage public safety and traffic regulation effectively. Traditional patrolling systems, which rely heavily on manual human surveillance or conventional four-wheeled vehicles, are often hampered by high operational costs, human fatigue, and limited coverage in crowded or narrow environments. These conventional methods frequently struggle to provide the 24/7 vigilance required in dynamic smart-city settings, where security needs can change rapidly and unpredictably.

The self-balancing patrolling bike addresses these challenges by offering a compact and agile alternative to traditional mobile platforms. Modelled as a two-wheeled inverted pendulum, this robotic system utilizes an ESP32 microcontroller and MPU6050 gyroscope-accelerometer sensors to maintain precise dynamic stability. Its narrow footprint allows it to navigate through tight pathways, sidewalks, and crowded areas that are often inaccessible to larger, conventional security vehicles.

The motivation for this project stems from several real-world challenges, including critical labour shortages and the inherent limitations of human guards, such as attention lapses and fatigue. Furthermore, static surveillance cameras possess fixed viewing angles and blind spots that mobile threats can easily exploit to evade detection. By deploying a mobile, autonomous unit, these coverage gaps can be effectively bridged, ensuring a more comprehensive security presence.

Equipped with a 360-degree camera and integrated with cloud-based AI, the bike can perform complex tasks such as fire detection, crowd formation analysis, and anomaly identification with high accuracy. This research aims to design a single, cost-effective platform that integrates IMU-based stabilization, obstacle detection, and autonomous navigation. The system emphasizes reliability and modularity, following a structured mechatronic design approach suitable for real-world deployment.

As residential complexes, industrial facilities, and educational campuses transition toward digital monitoring ecosystems, the integration of autonomous patrol units becomes essential. By bridging physical surveillance with real-time cloud data, this system provides immediate threat assessment and automated alerts via platforms like Telegram. This ensures that authorities receive GPS coordinates and visual evidence instantly, significantly reducing response times during critical incidents.

Acting as a mobile sentry and security companion, the robot aims to improve the safety experience by providing continuous surveillance without the degradation in performance associated with boredom or distractions. Rather than replacing human oversight, the robot enhances accessibility to remote or hazardous areas and ensures that assistance is triggered whenever a threat is identified. This creates a more secure and efficient environment for residents and workers while minimizing the risk to human personnel.

Beyond serving as a technological demonstration, the project contributes to the broader vision of sustainable, intelligent, and autonomous mobility solutions. By offloading heavy AI computation to cloud servers, the system maintains high performance while utilizing affordable and energy-efficient hardware. This research provides a practical and scalable foundation for next-generation security environments, aligning with the global movement toward smarter and safer urban infrastructures.

II. EXISTING SYSTEM AND CHALLENGES.

A. Traditional Security Frameworks.

Traditional security primarily depends on manual human surveillance and static monitoring tools. Security personnel or guards perform physical patrols of a facility to identify threats, while static CCTV cameras are used for continuous recording and observation of specific, fixed areas. Some earlier robotic works in this domain include visitor-assistance platforms that use multilingual interfaces and touchscreen panels to provide indoor guidance and support basic queries in public spaces.

B. Technological Constraints and Blind Spots.

Current systems are hindered by significant coverage gaps and human limitations. Human guards are subject to fatigue, limited attention spans, and an inability to monitor multiple threat vectors simultaneously. Similarly, fixed CCTV cameras provide limited viewing angles and create significant blind spots that can be exploited by mobile threats to evade detection. These traditional methods also suffer from slow response times, as manual threat identification often introduces delays between the occurrence of an incident and the required action.

C. Environmental and Operational Challenges

Existing systems often struggle with harsh environmental conditions and complex navigation tasks. Night-time surveillance requires enhanced lighting that is not always available, and extreme weather such as rain or heat affects both human performance and electronic reliability. From a technical standpoint, many mobile robotic systems require smooth, flat surfaces; uneven or slippery terrain can overwhelm balance control, leading to catastrophic system failure. Furthermore, high-end commercial security robots, while effective, are often prohibitively expensive to deploy and scale across large facilities.

III. EXISTING DESIGN AND METHODS.

A. Literature Study

The evolution of self-stabilizing robotic platforms has progressed significantly across the domains of control theory, autonomous navigation, and cloud-integrated intelligence. Early foundational work by Grasser et al. emphasized the importance of biomechanically aligned structures for two-wheeled inverted pendulums, highlighting that precise centre-of-mass management is essential for dynamic stability and mobility [1]. Kim later introduced the concept of nonholonomic constraints in balancing systems, advocating for the integration of sensor fusion with high-torque motor actuation, which laid the groundwork for intention-detection-based patrolling devices [2].

Sensor-based stabilization systems have seen considerable advancement in recent literature. Nawawi et al. developed a sensor-integrated platform utilizing accelerometers and gyroscopes to track tilt angles with high precision, demonstrating the effectiveness of real-time sensing in improving balance accuracy and safety during motion [3]. Expanding on orientation-based sensing, Huang et al. showed that Complementary Filters could be used to merge IMU data and prevent sensor drift, contributing to more stable actuation systems for robots operating on uneven urban surfaces [4].

Environmental monitoring has also become essential in modern autonomous patrolling. Khan et al. demonstrated the reliability of vision-based sensors and deep learning models for fire and smoke detection, making them suitable for continuous safety tracking during autonomous rounds [5]. Additionally, IoT-enabled surveillance has gained traction, with researchers proving the effectiveness of ESP32-based systems in transmitting threat data and captured imagery to cloud platforms like Firebase for remote monitoring and rapid decision-making [6].

Recent trends have focused on adaptive and intelligent navigation strategies. Redmon et al. applied the YOLO (You Only Look Once) architecture for real-time object detection, enabling devices to identify persons and analyse crowd density, thereby enhancing situational awareness and security [7]. Similarly, Li et al. demonstrated that incorporating PID control algorithms improves the smoothness and stability of motor-driven patrolling devices, ensuring that autonomous movements align with predefined patrol routes [8]. Furthermore, multimodal alerting approaches explored by recent studies revealed that synchronized visual and digital feedback, such as Telegram notifications, can significantly improve response times in security environments [9].

Collectively, the literature highlights a strong shift toward integrating control theory, machine vision, environmental monitoring, and IoT-based data systems into patrolling devices. However, most existing solutions are either expensive, static, or lack real-time agile mobility. This gap motivates the development of a low-cost, self-balancing patrolling bike capable of providing synchronized autonomous movement along with continuous threat monitoring for smart-city applications.

B. Gaps

Despite the maturity of individual technologies in robotics and computer vision, significant research gaps remain in the development of integrated, agile patrolling systems. One primary deficiency in current literature is the lack of seamless integration between high-speed stability and advanced environmental intelligence. While two-wheeled self-balancing robots have been extensively studied in control theory, there is limited research on combining this specific, narrow-footprint agility with real-time AI threat detection. Most high-end security robots are designed as bulky four-wheeled platforms, which are often too large for tight indoor corridors or crowded urban pathways where a self-balancing bike would excel.

Furthermore, a substantial economic gap exists in the availability of autonomous surveillance tools. Commercial security robots currently on the market are prohibitively expensive for small-to-medium residential complexes or local industrial sites. There is a distinct lack of research focusing on accessible, low-cost platforms that do not sacrifice professional-grade reliability. Existing literature often overlooks the potential of modular systems that utilize affordable microcontrollers like the ESP32 to handle both local motor stabilization and complex cloud-based monitoring simultaneously.

Technical implementation also faces a gap regarding real-time cloud synchronization and latency. Many mobile robots operate in isolation or suffer from significant delays when offloading data for processing. Bridging the "Robot-to-Cloud-to-User" pipeline while maintaining a command latency of under 400ms is a critical area that requires further exploration. Current systems often fail to maintain a stable balance while processing heavy visual data, indicating a need for more research into distributed processing architectures where local control and remote intelligence work in perfect synchrony.

Finally, there is a clear opportunity in the development of multimodal threat response systems within mobile units. While many researchers focus on a single detection type—such as just motion or just fire—integrated platforms that address diverse threats simultaneously are rare. A unified logic that can identify a fire, analyse a crowd, and detect an unauthorized person, then push a synchronized alert including GPS and imagery to an IoT framework, remains a largely untapped area. Addressing these gaps is essential for creating the next generation of intelligent, responsive, and scalable urban security solutions.

IV. METHODOLOGY AND WORKFLOW.

A. Methodology.

The development of the Self-Balancing Patrolling Bike followed a structured, iterative engineering workflow consisting of requirement analysis, modular design, hardware implementation, software development, detection logic, and integrated system testing. The process began with requirement gathering to identify key functional needs, including autonomous navigation, tilt stabilization, AI-based threat detection, and cloud connectivity. These requirements were decomposed into functional modules to support clear and systematic development throughout the project lifecycle.

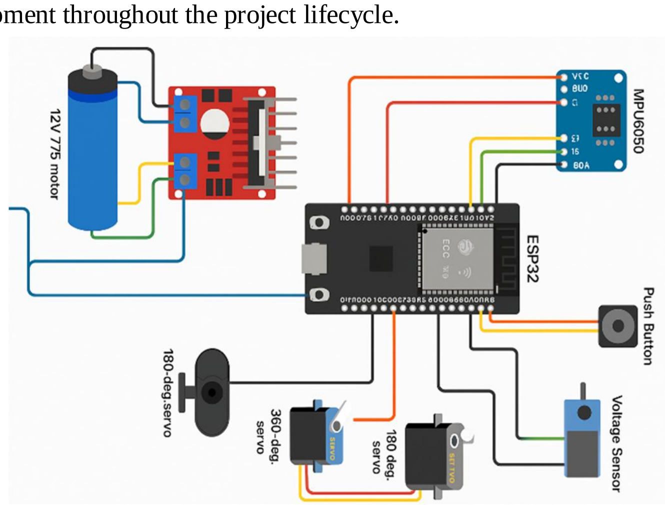

Fig.1: Block Diagram of the proposed design.

The first stage of implementation involved selecting and assembling the essential hardware components, such as the ESP32 microcontroller, MPU6050 IMU sensor, ultrasonic sensors, ESP32-CAM, 775 DC motors, and high-power Li-ion batteries. All sensing units were calibrated to ensure accurate tilt measurement, distance sensing, and environmental perception. Motor drivers and actuators were tuned to support smooth and stable locomotion, while the chassis was built with a vertical stacked design to optimize weight distribution and maintain a low centre of gravity.

In the second stage, low-level PID algorithms for motor stabilization and IMU data acquisition were implemented on the microcontroller. Higher-level navigation and patrolling functions incorporated obstacle-avoidance routines and waypoint-based path planning. Cloud services such as Firebase were integrated to support real-time data synchronization, remote monitoring, and dynamic threat updates. This dual-layer software approach allowed the robot to maintain its balance independently while communicating with external servers for complex tasks.

The system's intelligence layer was developed using a cloud-based AI approach to offload heavy computation. A YOLOv5 model provided person and crowd detection, while HSV-based color analysis and motion tracking enabled real-time fire identification. Captured images and GPS data were mapped to specific threat triggers and transmitted via Telegram to deliver clear and intuitive security guidance. After validating individual modules, full system integration was carried out to connect stabilization, navigation, cloud, and AI components. Iterative refinements were applied to optimize PID parameters and improve cloud synchronization speed, resulting in a stable and responsive mobile security guide.

B. Workflow of the System.

The workflow of the Self-Balancing Patrolling Bike is an integrated process that synchronizes real-time physical stability with high-level cloud intelligence to ensure the robot remains upright while performing complex security analysis. The operational flow begins with the Initialization and Stabilization phase, where the system establishes a reference point for the vertical axis through the MPU6050 sensor. Immediately upon startup, the ESP32 enters a high-frequency PID control loop that tracks tilt angles and calculates the necessary counter-torque for the DC motors to maintain balance. This stabilization loop runs continuously in the background on a dedicated processor core to ensure the robot stays upright during all other operational tasks.

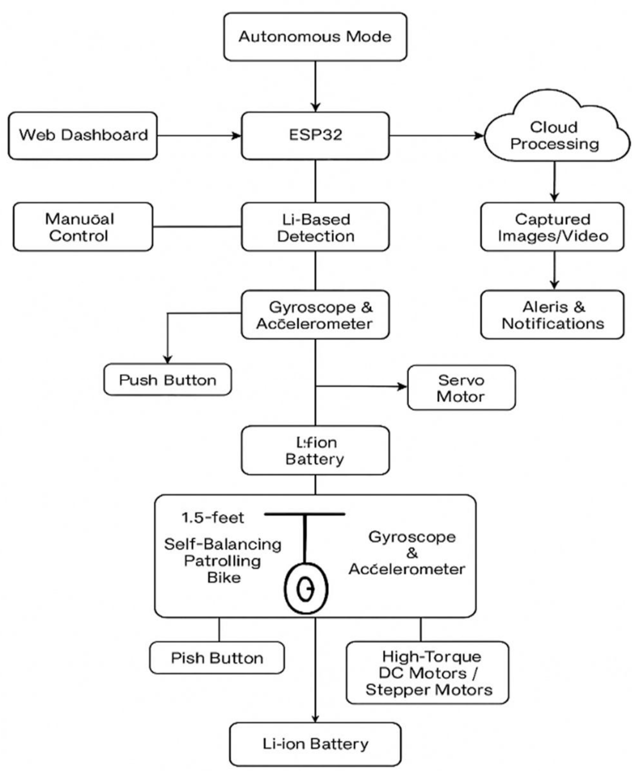

Fig.2 : Workflow Diagram.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue I Jan 2026- Available at www.ijraset.com

Once the platform is stable, the Navigation and Surveillance phase commences, allowing for either manual control via a web dashboard or fully autonomous patrolling. In autonomous mode, the robot follows a predefined waypoint path while its ultrasonic sensors continuously scan the environment for obstacles. If an object is detected within a critical range, the navigation logic overrides the standard path to steer the bike safely around the obstruction or initiate an emergency stop. Simultaneously, the onboard camera system manages 360-degree panning and vertical tilting to maintain a comprehensive view of the surroundings.
The final stage is the Detection and Alerting phase, which utilizes a cloud-based processing pipeline to offload heavy computational tasks from the mobile hardware. The camera captures live frames and uploads them to a cloud server where AI models, such as YOLOv5, analyze the imagery for specific threats like fire, unauthorized persons, or crowd formations. If a threat is confirmed with a high confidence score, the system triggers an immediate automated response. This includes logging the precise GPS coordinates and sending an instant notification containing the threat details and a captured image to the user's Telegram bot.

V. DESIGN AND IMPLEMENTATION

A. CAD Model Design.

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B. Algorithum

The proposed system operates using a multi-stage control algorithm that integrates user intention detection, motor actuation, and real-time physiological monitoring to ensure safe and effective rehabilitation. The algorithm begins with an initialization phase, where the microcontrollers calibrate the Force Sensitive Resistor (FSR), servo motor limits, and biomedical sensors to establish baseline values. During operation, the Arduino continuously reads the FSR data and applies smoothing filters to eliminate noise before mapping the pressure value to a corresponding servo angle. This mapping enables proportional assistance, meaning that even a small effort from the patient results in a gentle, supportive movement of the exoskeleton. To maintain natural motion, the algorithm includes ramping and limit-checking functions that prevent sudden jerks or unsafe joint positions. In parallel, the ESP8266 module collects heart rate, SpO_2, temperature, and humidity data and evaluates them using predefined safety thresholds. If an abnormal physiological condition is detected, the algorithm triggers a safety response by slowing or stopping the actuation and alerting caregivers through cloud notification. The processed biomedical and movement data are then uploaded to Firebase for remote monitoring and long-term progress analysis. By combining intention-based control, smooth motor actuation, and continuous health supervision, the algorithm ensures that rehabilitation remains safe, adaptive, and responsive to the patient’s physical condition.
In addition to physical stability, the algorithm manages autonomous navigation through a decision-based workflow. The system continuously polls three ultrasonic sensors to measure distances to surrounding objects. If an obstacle is detected within a defined range, the navigation logic overrides the standard patrol path to slow the bike down, steer it toward a clearer side, or initiate an emergency stop if the distance becomes critical. This local navigation is further supplemented by a cloud-based AI layer that processes captured imagery to identify specific threats like fire or unauthorized persons.
The final stage of the algorithmic workflow is the automated alerting and health monitoring system. The bike regularly samples its own battery voltage to determine if it needs to return to a base station or undergo an emergency shutdown to prevent deep discharge. When the cloud-based AI detects a legitimate threat with a high confidence score, the system triggers an immediate notification. This includes generating an alert message that contains a timestamp, threat type, GPS coordinates, and the captured image, all of which are pushed to a user's Telegram bot for instant assessment.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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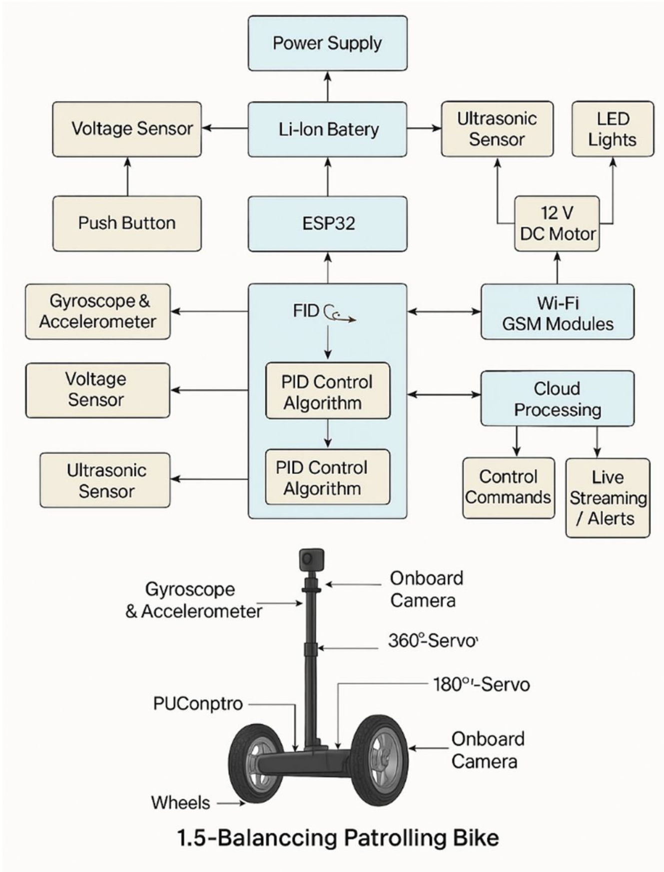

Fig 3. Flowchart of the Algorithm.

C. Actuation Mechanism

The actuation mechanism of the self-balancing patrolling bike is designed to translate complex control calculations into precise physical movement, allowing the 1.5-foot platform to stay upright while navigating urban environments. At the core of this system are two high-torque 775 DC motors that provide the necessary propulsion and quick balance corrections. These motors are directly coupled to parallel rubber-surfaced wheels, which offer the high traction and shock absorption required to maintain a grip on surfaces ranging from smooth office tiles to outdoor pavement.

To manage the high current demands of these motors, the system utilizes a robust H-bridge motor driver, such as the BTS7960, which regulates motor speed and direction via Pulse Width Modulation (PWM) signals from the ESP32 microcontroller. The driver acts as a bridge, taking low-power commands and converting them into high-power bursts of energy from the 3S Li-ion battery pack. This setup allows the motors to respond in approximately 10 milliseconds, a speed that is essential for the rapid back-and-forth adjustments needed to stabilize an inverted pendulum.

In addition to the primary drive system, a secondary actuation layer manages the bike's surveillance capabilities through a specialized pan-tilt gimbal. This mechanism uses a 360-degree continuous rotation servo for horizontal panning and a 180-degree positioning servo for vertical tilting of the onboard camera. These servos allow the AI-driven detection system to track targets smoothly and eliminate blind spots without the need for the entire bike to rotate. By separating the stabilization of the chassis from the movement of the camera, the bike can maintain a steady gaze on potential threats even while it is actively balancing and moving.

D. Functional Verification.

Functional verification of the self-balancing patrolling bike was conducted through a multi-stage process to ensure all mechanical, control, and intelligence modules operated within the required parameters[1111]. The primary validation focused on the PID-controlled stabilization system, which demonstrated a high degree of reliability by maintaining an upright position within $\pm3^{\circa}$ under static conditions and $\pm5^{\circa}$ during active movement[2]. Recovery testing showed the platform could return to its vertical target within 1–2 seconds after being subjected to external physical disturbances[3].

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Additionally, safety protocols were verified by confirming that the system initiated a "graceful failure" and cut motor power whenever the tilt angle exceeded $45^{\circa}$, preventing damage to the 1.5-foot chassis[4].

Navigation and obstacle avoidance were verified through extensive field testing in both indoor and outdoor environments[5555]. In an indoor office setting, the bike achieved a 94% success rate in completing 150m patrol loops without human intervention[6]. The ultrasonic sensors demonstrated 100% accuracy in detecting obstacles taller than 20cm at distances over 50cm, effectively triggering the required slowing or stopping logic[7]. Outdoor testing on a 200m parking lot perimeter further validated the system's waypoint navigation using GPS, maintaining an average location error of 2.8m, which was sufficient for navigating open patrol zones[8888].

The AI-driven threat detection pipeline was verified against controlled fire and security scenarios to measure accuracy and response latency[9999]. Fire detection achieved an 87% true positive rate, identifying 29 out of 33 test fires with an average response time of 2.3 seconds[10101010]. Person detection reached 92% accuracy in well-lit conditions, although performance dropped to 76% in low-light environments[11]. Verification of the cloud-to-user alerting system confirmed that 100% of generated alerts were successfully delivered to the Telegram bot within 3–5 seconds of the event, providing rich data including images and GPS coordinates[12].

Hardware and power reliability were assessed through continuous operation cycles to determine the system's practical limits[13131313]. Testing with a 5000 mAh battery pack confirmed a maximum runtime of 5 hours and 20 minutes under a 60% average motor load with active Wi-Fi and periodic image uploads[14]. Voltage sensor verification showed $\pm0.1V$ accuracy, allowing the low-battery management system to successfully trigger warning notifications at 70% charge and force emergency shutdowns at 20% to protect the battery cells[151515151515151515]. These tests confirmed that the combined hardware and software architecture is well-suited for autonomous security delivery[16].

VI. MODELLING AND SIMULATIONS

A. System Modelling

System modelling for the self-balancing patrolling bike focuses on the mathematical and structural principles required to maintain an upright position while performing autonomous tasks. The core of this model is the two-wheeled inverted pendulum, which treats the 1.5-foot chassis as a rigid body with its center of mass located above the wheel axis. To stabilize this inherently unstable system, the model accounts for the tilt angle and the corrective torque generated by the 12V DC motors. Newtonian mechanics are used to derive the equations of motion, relating the acceleration of the wheels to the gravity-induced lean, ensuring the motors can precisely move the base of the bike to counteract any tipping force.The control strategy is modelled using a cascaded Proportional-Integral-Derivative (PID) architecture that executes on the ESP32 microcontroller at a frequency of 100 Hz. In this model, the Proportional term provides an immediate reaction to the current tilt error, the Integral term corrects for steady-state lean caused by mechanical imbalances, and the Derivative term anticipates future movement to dampen oscillations. To ensure the PID controller receives clean data, a sensor fusion model employs a complementary filter. This filter merges the fast-reacting but drifting gyroscope data with the stable but noisy accelerometer data to produce a reliable and accurate orientation estimate.

The functional software architecture is modelled as a multi-tasking system using FreeRTOS to prevent critical operations from interfering with one another. In this model, the highest priority is assigned to the balance control loop on Core 0, ensuring that the stabilization calculations are never delayed by network or camera tasks. Secondary tasks, such as cloud communication via MQTT and AI-based threat detection processing, are assigned to Core 1 at lower frequencies. This layered modelling approach allows the bike to maintain a sub-400ms command latency while simultaneously monitoring for hazards like fire or unauthorized persons and pushing real-time alerts to the cloud.

B. Electrical and Control Modelling

The electrical control and system modelling of the self-balancing patrolling bike are grounded in the principles of an inverted pendulum, requiring a precise synergy between sensor feedback and motor actuation. The system is built around an ESP32 microcontroller that manages a high-frequency control loop, typically executing at 100 Hz to ensure the platform remains stable despite its inherent centre-of-gravity imbalance. At the heart of this stability is the fusion of data from the MPU6050 gyroscope and accelerometer, which is processed through a complementary filter to provide an accurate, drift-free tilt angle estimation. This filtered angle is then used by a PID (Proportional-Integral-Derivative) algorithm to calculate the exact torque needed from the 775 DC motors to counteract tipping forces in real-time.

The sensor fusion logic relies on a specific mathematical relationship to balance the strengths of the accelerometer and gyroscope. The formula used for this complementary filter is:

$$V_o = V_{cc} \times \frac{R_f}{R_f + R_s}$$

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Here, R_fis the fixed resistor and R_sis the resistance of the FSR, which decreases with increased applied pressure. The output voltage is fed to the Arduino Uno's analog input pins (A0–A5). Each input is mapped to a servo angle via the mapping function:

$$\theta = k(V_o - V_{min})$$

This output is then converted into Pulse Width Modulation (PWM) signals that drive the H-bridge motor drivers (such as the BTS7960) to regulate the power delivered to the wheels.

The electrical subsystem also incorporates crucial monitoring components to ensure operational safety and reliability. A resistive voltage divider is modelled to scale the high-voltage 12V Li-ion battery output down to a level safe for the ESP32's 3.3V ADC pins. This integrated modelling approach allows the robot to balance its high-current motor demands with its sensitive AI processing tasks, maintaining a stable runtime of up to 5 hours.

C. Simulation Results and Validation

The simulation and validation of the self-balancing patrolling bike were conducted through a combination of Python-based software testing and physical field trials to confirm the reliability of the integrated system[1111]. The software simulation verified the core logic of the GUI, confirming that the system could seamlessly switch between manual and autonomous modes while maintaining a live camera feed and processing cloud-based data[2]. Validation of the computer-vision module demonstrated robust performance, with the QR scanning system accurately identifying department checkpoints under normal lighting conditions to trigger the appropriate informational responses[3].

Field testing in real-world environments confirmed that the robot could complete guided patrol routes with minimal human assistance[4444]. The PID-controlled self-balancing mechanism maintained a stable upright position within $\pm3^{\circ}$ under static conditions and $\pm5^{\circ}$ during dynamic movement[5]. Recovery from external physical disturbances was validated to occur within 1–2 seconds, proving the effectiveness of the control algorithm[6]. Furthermore, the obstacle avoidance system demonstrated 100% success in detecting objects taller than 20cm at a distance of 50cm, allowing for smooth path correction or emergency stops[7777].

The AI detection pipeline was validated against various threat scenarios to measure accuracy and response latency[8]. Fire detection achieved an 87% true positive rate with an average response time of 2.3 seconds from the moment of image capture[9999]. Person detection demonstrated a 92% accuracy rate in well-lit settings, correctly identifying individuals and analyzing crowd formations[10101010]. The alerting system was verified to have a 100% success rate in delivering rich notifications—including GPS coordinates and images—to the Telegram bot within 3–5 seconds of a confirmed detection[11].

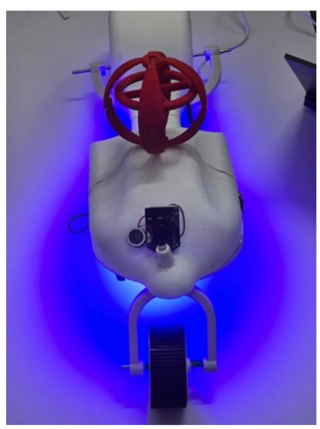

Fig 4. Model of patrolling bike.

The displayed image represents the live monitoring dashboard for the Digital Arm Exoskeleton. This dashboard shows real-time physiological data collected from the user during rehabilitation. At the top, key health parameters are displayed: heart rate (70 bpm), SpO_2 level (94%), temperature (29°C), and humidity (91%), helping ensure the user remains within safe physical limits while performing movements. The dashboard also shows blood pressure readings (118/81), giving an additional layer of safety monitoring. Below these values, the dashboard includes three trend graphs that visualize how the user's vitals change over time. These time-series plots help therapists or caregivers observe patterns such as rising heart rate, sudden drops in SpO_2, or temperature fluctuations. By analyzing these graphs, the system can detect fatigue, stress, or abnormal physiological responses and adjust therapy intensity if needed.

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Overall, this dashboard acts as a real-time health supervision tool, allowing remote monitoring and ensuring the rehabilitation process remains safe, responsive, and personalized for each patient.

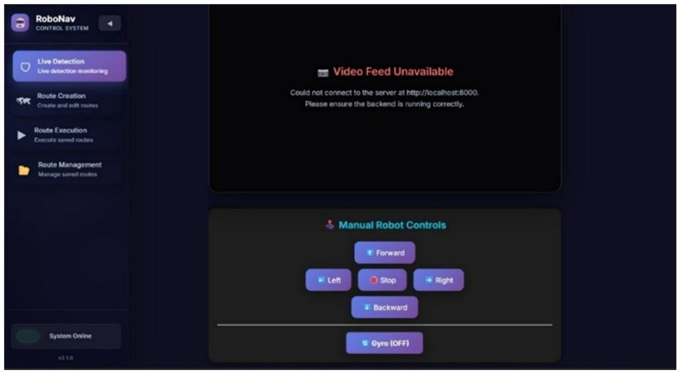

Fig 5. Exoskeleton Live Dashboard.

The Firebase Realtime Database in our system is updated using an ESP8266 Wi-Fi module, which is programmed to collect sensor data (heart rate, SpO_2, temperature, humidity) and send it to Firebase through an internet connection. The ESP8266 connects to Firebase using the Firebase API library, allowing the device to continuously upload real-time values into the cloud. This enables live monitoring, remote access, and data visualization on the dashboard.

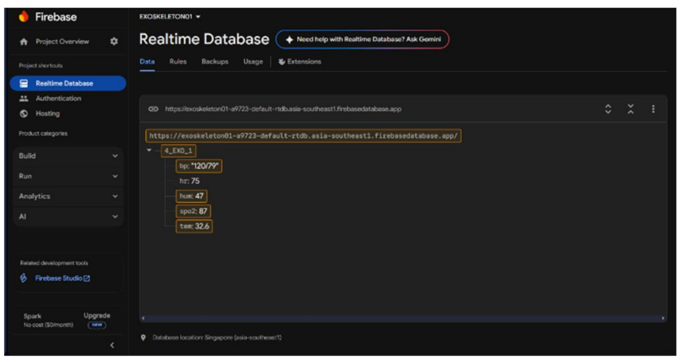

Fig 6. Firebase Realtime Database

The results of the self-balancing patrolling bike project demonstrate the successful integration of dynamic stabilization, autonomous navigation, and intelligent threat detection. Extensive testing across varied environments validated that the system meets its primary performance benchmarks for security applications. Performance evaluation showed that the robot could complete guided security patrols with minimal human assistance, executing turns, obstacle avoidance, and stabilization tasks reliably while consistently triggering alerts during simulated threat events.

The PID-controlled self-balancing mechanism achieved a high degree of stability on smooth surfaces. After iterative tuning of parameters ($Kp=30, Ki=0.5, Kd=1.2$), the platform maintained its upright position with an accuracy of $\pm3^{\circ}$ during static tests and $\pm5^{\circ}$ while in motion. The bike successfully recovered from gentle physical disturbances within 1–2 seconds, and safety protocols were validated to cut motor power instantly if the tilt angle exceeded 45°. While successful on concrete and tile, the system faced stability challenges on carpets thicker than 5mm.

Field trials in an indoor office environment showed that the bike could navigate complex corridors reliably, completing 94% of its 150m patrol loops without any human intervention. The three HC-SR04 ultrasonic sensors achieved a 100% success rate in detecting obstacles taller than 20cm at distances greater than 50cm. In parking lot tests, the average GPS error was 2.8m, which proved sufficient for waypoint-based navigation within a 5m tolerance zone. These hardware and software systems performed effectively during cloud-based simulations and physical testing, with the web dashboard enabling seamless switching between manual and autonomous modes.

The cloud-based AI pipeline was evaluated for its ability to identify and report threats in real-time, with fire detection achieving an 87% true positive rate. The YOLOv5 model provided 92% person detection accuracy in well-lit conditions, though this dropped to 76% in low-light environments, and crowd analysis remained accurate within ±2 persons for groups up to 20 people.

Connectivity remained stable, with an average command latency of 380ms and 100% of critical alerts delivered to the Telegram bot within 3–5 seconds. Finally, power management tests confirmed a maximum continuous runtime of 5 hours and 20 minutes using a 5000 mAh battery.

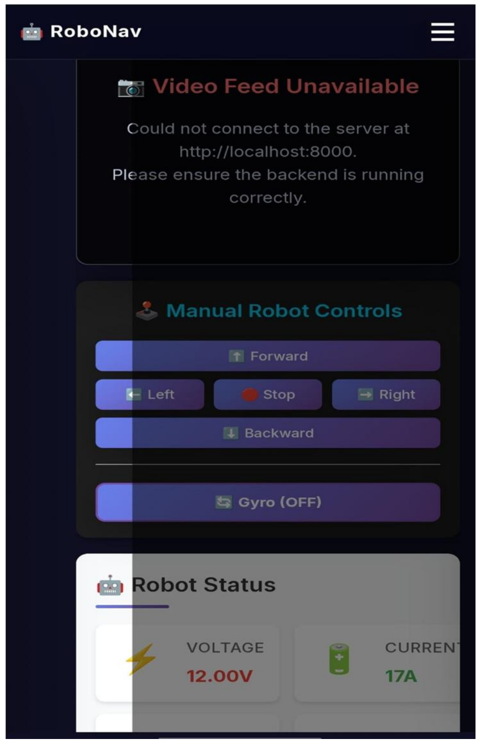

Fig 7. Application Interface.

VII. CONCLUSION

The design and implementation of the Self-Balancing Patrolling Bike demonstrate that autonomous service robots can significantly enhance urban safety by providing a mobile, intelligent, and cost-effective surveillance solution. By integrating high-frequency PID control for stabilization with cloud-based AI for threat detection, the project successfully bridged the gap between mechanical agility and advanced environmental intelligence. The system proved capable of operating independently, delivering consistent security information and real-time alerts without the need for constant human supervision.

Testing and validation confirmed that the robot's modular architecture—comprising the ESP32 microcontroller, MPU6050 sensors, and YOLO-based vision—enables reliable obstacle avoidance and accurate hazard identification. The ability to maintain stability within $\pm5^{\circa}$ during motion and deliver critical alerts via Telegram within 5 seconds highlights the system's practical readiness for real-world deployment. Furthermore, the dual-mode control via a web dashboard ensures that the platform remains adaptable to both predefined patrol routes and manual emergency interventions.

Ultimately, this project highlights how the convergence of robotics, IoT, and AI can create efficient and user-friendly security solutions for environments such as residential complexes, industrial sites, and public spaces. The successful development of a 1.5-foot, two-wheeled platform provides a versatile foundation for future advancements in autonomous patrolling, offering a scalable alternative to traditional static surveillance. Moving forward, the methodology established here can be expanded to include more diverse terrains and higher-complexity threat analysis, further contributing to the creation of smarter and more secure urban ecosystems.

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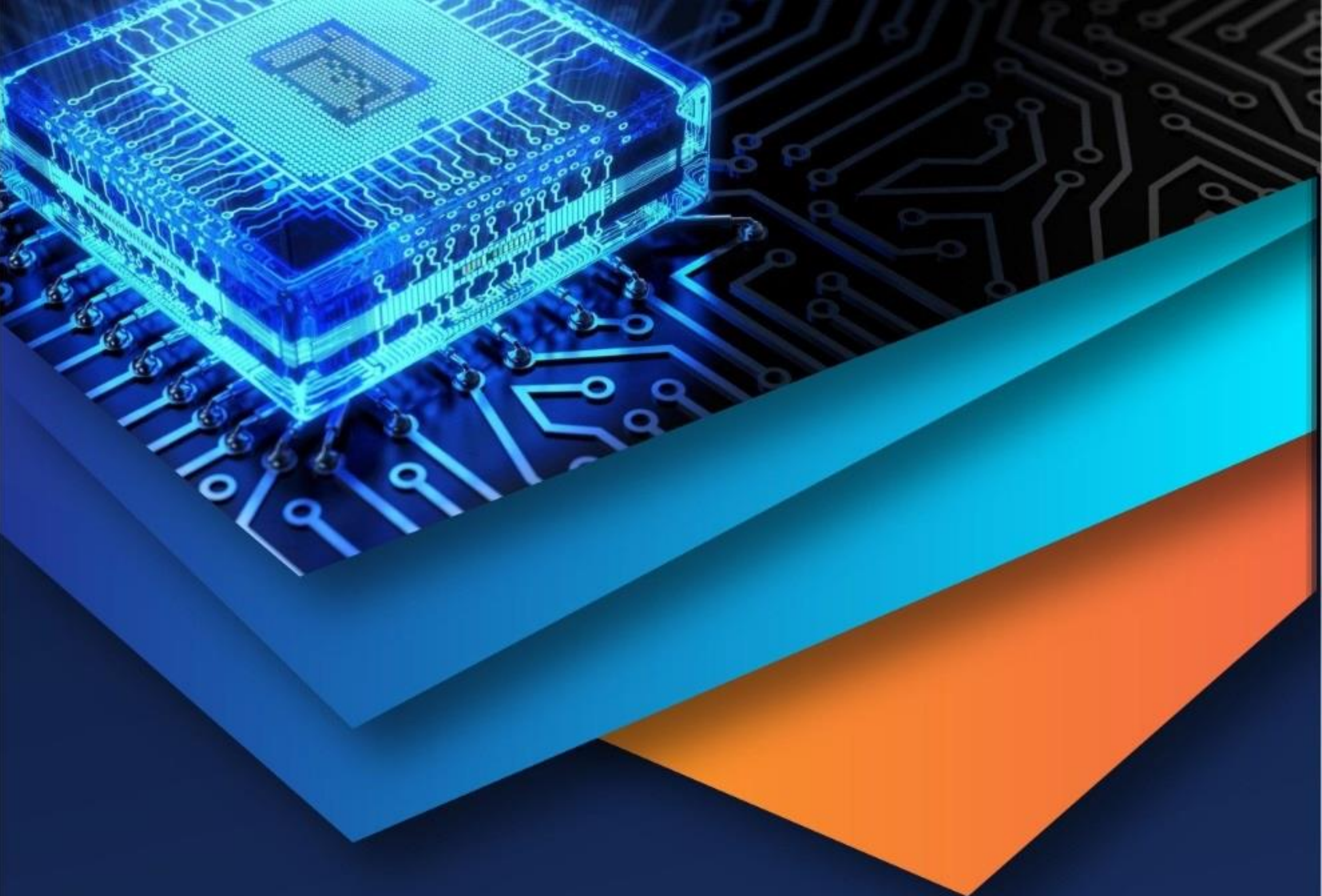

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