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WHEELED BIPED ROBOT FOR RECONNAISSANCE AND TACTICAL SUPPORT: A BATTLEFIELD-ORIENTED ADVANCED PROTOTYPE

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Abstract—**This paper describes the design and development of a physical and geometrical prototype of a Wheeled Biped Robot (WBR) for battlefield assistance. This model has been developed for research and educational purposes only.**
The robot has been scaled to a maximum length of 0.6 meters and a minimum length of 0.45 meters. It is an optimized version of a 2 wheel self-balancing and a bipedal robot. It combines the best features of both models. The system is powered by low voltage electronics. The project incorporates concepts of additive manufacturing, embedded systems, control systems, and the Internet of Things (IoT). The prototype consists of four modular parts. They are the body, payload, and two legs for locomotion. The mechanical structures have been designed using Computer aided Design (CAD) and physically printed using 3D printers.

Keywords: **Wheeled Biped Robot, 3D printing, embedded systems, control systems, additive manufacturing**

I. INTRODUCTION

Over the years, Unmanned Ground Vehicles (UGVs) have evolved as combat multipliers in modern-day military and operations requiring immediate response. This enhancement eliminates the need for human intervention in operations that take place in dangerous environments while maintaining situational awareness. [1]. Among the UGV types, the two-wheel self-balancing variant offers a captivating trade-off: a compactly designed robot navigates its path through narrow passages, while dynamically balancing itself. This maintains agility in response to movement on uneven terrain and rapid directional changes [2].
This paper extends the classical inverted-pendulum self balancing robot to a composite bipedal variant of itself. Key contributions are:
i. a double PID loop.
ii. Integration of a night vision camera on a single 0.6-meter chassis.
iii. LiDAR-SLAM and visual-odometry fusion for GPS-denied localization.
iv. an encrypted Wi-Fi communication architecture.
v. a modular payload bay supporting 1kg of medical supply delivery and humanitarian aid.

The remainder of this paper is structured as follows. Section II surveys related work. Section III details system architecture. Section IV presents design specifications. Section V describes the sensor suite. Section VI covers control and autonomy algorithms. Section VII outlines the 16-week execution plan. Section VIII reports testing and results. Section IX explains results and further discussion. Section X discusses future work.

II. RELATED WORK

The inverted-pendulum two-wheel robot has been extensively studied since the development of the Segway platform. Grasser et al. [3] demonstrated a PID-controlled JOE robot achieving stable balance on flat ground; following the work by Yap and Hoon [4] applied LQR state feedback for improved obstacle rejection. Terrain-adaptive variants using IMU-based tilt estimation over inclined surfaces have been reported in [5].
For autonomous navigation, LiDAR based Simultaneous Localization and Mapping (SLAM) frameworks such as Cartographer and LOAM have been used in small UGV platforms on embedded Jetson hardware, achieving room wide mapping with sub-10cm accuracy [6]. Vision-based threat detection using YOLOv5 on Jetson Nano has been performed at 15–25fps with 91% mean average precision on person-class detection [7].
Dual-link communication combining short-range Wi-Fi with long-range LoRa has been validated for small UGVs operating in urban canyon environments, achieving connectivity beyond 500 m with sub-100ms command

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latency [8]. The present design builds upon these foundations, integrating them into a cohesive tactically oriented platform.

III. SYSTEM ARCHITECTURE

The robot is divided into five subsystems: (1) mechanical chassis and protection, (2) propulsion and balancing, (3) sensor suite, (4) compute and communication, and (5) mission payload. Fig. 2 shows the assembled platform, and Fig. 3 shows the CAD exploded-view render.

A. Mechanical Chassis

The frame and legs are constructed from Acrylonitrile Butadiene Styrene (ABS) 3D printing filament. It is an extremely sturdy and shock absorbing material which allows decoupling the electronics bay from the load impact. The camera is mounted on the front wall of the robot while the IMU is mounted on the floor of the electronics bay. This position of the IMU is the closest to the wheels, hence giving accurate measurements. High Torque Geared DC motors are embedded in 100mm diameter rugged-tread wheels, eliminating external drive shafts. It consists of two legs for different terrains. The leg has 2 joints – the hip and the knee, each containing a servo motor in it of torques 35kgfcm and 10kgfcm respectively.

B. Propulsion and Balancing

Two 12V high-torque geared DC motors provide differential drive. The stability loop runs at 500Hz on the Raspberry Pi5, reading the IMU whose outputs are fused via a discrete Kalman filter to produce a tilt angle estimate with $< 0.3°$ RMS noise. A PID outer loop commands the overall tilt angle from the IMU and a PID inner loop is used in the wheels. Fig 1 shows the block diagram of the robot.

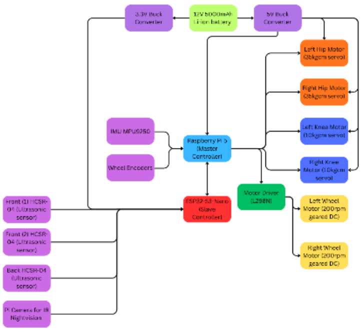

Fig. 1. Block diagram of the robot

C. Compute and Communication

The Raspberry Pi 5 handles the double PID loop for the movement of the robot and collects live data feed from the Raspberry Pi Night Vision IR Camera Module. The ESP32 collects data from the ultrasonic sensors and sends it to the Raspberry Pi5 via a UART bus for obstacle avoidance. A Wi-Fi dashboard provides a website for controlling the robot's movements. It also displays the distance measured by the ultrasonic sensors between the robot and an obstacle.

D. Mission Payload

A weatherproof payload bay (1kg capacity) accepts modular inserts. These include medical supply containers, sensor drop modules (RF beacons, seismic sensors, chemical detectors), or a small drone launcher.

Fig. 2. Final assembled prototype of the Wheeled Biped robot.

IV. DESIGN SPECIFICATIONS

Table I compares the baseline project specification against the modified parameters chosen for this implementation. All 'Modified Value' cells are to be completed by the authors following final hardware build and measurement.

TABLE I. Platform Design Parameters

Parameter	**Measurement**
Robot height (m)	0.6
Wheel diameter (mm)	100
Frame material	ABS
Operating speed (m/s)	1m/s
Payload capacity (kg)	1
Battery voltage (V)	12 V Li-ion
Battery runtime (min)	30-40 min
Main processor	Raspberry Pi 5

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Secondary MCU	ESP32
Stability controller	Double PID loop
Camera(s)	IR camera
Communication links	Wi-Fi

V. TACTICAL SENSOR SUITE

Table II lists the sensors integrated on the platform, with model/type fields left for the editor to populate once procurement is finalised.

TABLE II. Sensor Suite — Function and Model

Sensor	Model / Type	Purpose
IMU (primary)	MPU9250	Balancing / attitude
IR camera	5MP OV5647	Night vision
Ultrasonic sensor	HC-SR04	Motion detection
Wheel encoders	OE-775	Odometry

VI. CONTROL AND AUTONOMY ALGORITHMS

A. Kalman Filter Imu Fusion

Let x = $[\theta, \dot{\theta}, bg]^T$ denote the state vector of tilt angle θ, tilt rate $\dot{\theta}$, and gyroscope bias bg. The discrete-time prediction and update steps follow the standard Kalman recursion with process noise Q and measurement noise R tuned empirically on the physical platform.

B. Inner and Outer PID loops

The outer PID loop generates a body-tilt setpoint correction based on wheel position error (to prevent drift). The LQR minimises the quadratic cost:

$$J = \Sigma (x^T Q x + u^T R u)$$

where state vector x = $[\theta, \dot{\theta}, vw, sw]^T$ and u is the differential torque command. Q and R weight matrices are tuned offline
via MATLAB LQR solver and validated in simulation before deployment. The inner PID loop follows the following equation:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$

VII. 16-WEEK EXECUTION PLAN

The development of the WBR took place in a 16-week timeline. The below table describes the steps achieved in the respective week.

TABLE III. 16-week execution plan

Week	Tasks
1-2	Requirements analysis, component procurement, simulation environment setup.
3-4	Chassis and armour shell fabrication; DC motor bench tests.
5-6	IMU and electrical circuit wiring; Kalman filter implementation and tuning on bench.
7-8	PID+LQR controller deployment; first self balancing demonstration.
9-10	Working on ultrasonic sensor mechanism using ESP32.
11-12	Camera and thermal IR integration
13-14	Wi-Fi dashboard development; encrypted telemetry validation.
15-16	Movement testing of the robot.

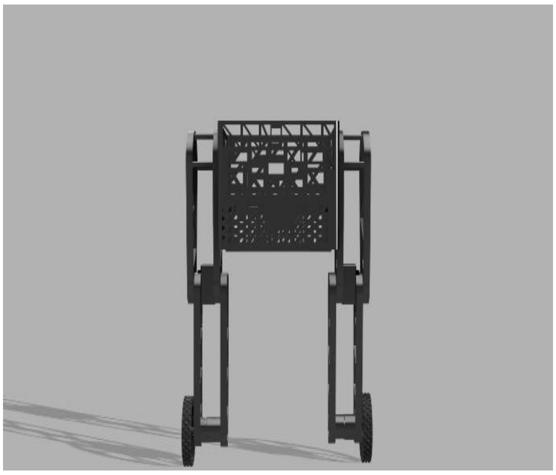

Fig. 2. CAD view render showing chassis, and payload bay.

VIII. TESTING AND VALIDATION

Table IV summarizes the validation test matrix. Achieving proper balance and movement is still in progress.

TABLE IV. Validation Test Matrix

Test	Method	Result
Object detection	Person at 5 m; measure hit rate	95% accuracy
Comms range	Wifi link; walk to max range	> 200 m LOS
Battery runtime	Continuous patrol cycle	~ 30min
Payload delivery	Carry 1 kg; navigate 10 m	Delivered

IX. RESULTS AND DISCUSSION

The Wheeled Bipedal Robot (WBR) is extremely useful in research and educational purposes. It integrates concepts of mechanics and control systems into a tangible, interactive prototype. Students can understand the following concepts through hands-on experience:
1. The Inverted Pendulum principle.
2. Control systems
3. Electrical circuitry and power distribution.
4. Mechanics, Embedded systems and IoT.

This prototype also teaches about the processes of ideation, prototyping, testing and iteration. This makes it ideal for multidisciplinary fields like robotics, mechanical, electrical etc.

X. FUTURE WORK

The current model of the WBR is still quite unstable and a very basic prototype focusing on the mechanical section. We wish to add the following upgrades to it:
1. Achieve better stability during movement.
2. Integrate mmWave motion detection sensors to add to the Wi-Fi dashboard for more accurate detection.
3. Creation of a 2D LiDAR SLAM using VL53L1X and a micro servo at the top of the bot.
4. Using YOLOV5 ML algorithm for a better, more industry-focused prototype.
5. Further upgrades on the Wi-Fi dashboard to provide a live feed by improving communication between the master and slave microcontrollers.

XI. CONCLUSION

This paper presented a battlefield-oriented wheeled bipedal robot combining IMU Kalman fusion, double PID loops, multi-spectral object detection, and a Wi-Fi based encrypted communication system on a 0.6-meter-class chassis. The modular payload architecture supports diverse mission roles from ammunition delivery to supply delivery without structural modification.

The robot demonstrates that embedded hardware, when carefully integrated with robust control algorithms like the PID algorithm, can replicate many capabilities of industry focused military UGVs at a fraction of the cost, making it a valuable research and educational tool for academic institutions and defence research groups.

XII. ACKNOWLEDGEMENTS

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