Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 3, Issue 9, 2025

DEVELOPMENT OF AN AFFORDABLE HUMAN DETECTION ROBOT USING ESP32 AND IOT CLOUD

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DOI: https://doi.org/10.5281/zenodo.17121761

Keywords
Human detection, WiFi-enabled robot, Arduino IoT Cloud, ESP32 microcontroller, Low-cost sensors

Article History
Received: 11 June 2025
Accepted: 11 August 2025
Published: 15 September 2025

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Abstract
This study details the design and fabrication of a WiFi-enabled human detection robot for indoor surveillance and safety applications, tailored for resource-limited settings like Pakistan. The robot integrates infrared (IR), ultrasonic, and passive infrared (PIR) sensors to detect human presence with high reliability. Mounted on a custom-designed wheeled chassis, it is powered by durable DC geared motors driven by an L298N motor driver. An ESP32 microcontroller serves as the core, processing sensor data and enabling wireless communication through the Arduino IoT Cloud. This cloud-based interface facilitates real-time data transmission, remote monitoring, and manual control via a user-friendly dashboard or mobile app. The system operates in autonomous mode for continuous monitoring and manual mode for user-directed navigation, with IR sensors ensuring obstacle and edge detection for safe operation. Experimental tests validate the robot's ability to detect humans effectively under varying indoor conditions, with seamless data transfer to the cloud. The use of low-cost, readily available components enhances affordability and scalability, making it suitable for applications in home security, search and rescue, and automation. Future enhancements could include camera integration and machine learning for advanced features like gesture recognition. This project offers a practical, cost-effective solution for intelligent robotics in resource-constrained environments, with potential for educational use in engineering curricula.

1. INTRODUCTION

Human detection technology is vital for applications in surveillance, search and rescue, and automation, particularly in resource-constrained regions like Pakistan and the Middle East [15, 22]. The demand for cost-effective, reliable systems to monitor environments and ensure safety has grown, driven by challenges such as natural disasters, security needs, and limited infrastructure [11, 13]. Existing solutions often rely on expensive sensors like LiDAR or complex algorithms requiring high computational power, making them impractical for widespread adoption in developing countries [2, 4, 14]. For instance, advanced systems using 3D LiDAR achieve high detection accuracy but are costly [12, 19]. This project addresses these challenges by designing a low-cost, WiFi-enabled human detection robot using affordable infrared (IR), ultrasonic, and passive infrared (PIR) sensors integrated with an ESP32 microcontroller [7, 8].

The robot is built on a custom-designed chassis, powered by DC geared motors, and controlled via an L298N motor driver, ensuring robust mobility [21]. It leverages the Arduino IoT Cloud for real-time data transmission and remote control, enabling both autonomous and manual operation [16]. This system aims to provide an accessible solution for indoor environments, suitable for home security, disaster response, and educational purposes in engineering programs [24, 25]. By combining low-cost components with wireless connectivity, the project fills a gap in affordable robotics for resource-limited settings, offering scalability and ease of implementation [5]. This work contributes to developing practical, intelligent systems that enhance safety and automation while being replicable in academic and industrial contexts [19, 20].

This work contributes to the field of intelligent robotics by demonstrating how affordable components can be integrated into a cohesive system to address real-world challenges [1, 9]. It aligns with global trends in developing cost-effective automation solutions while catering to local needs in resource-constrained regions [10]. The project also has educational value, serving as a practical prototype for engineering students learning about robotics, sensor integration, and IoT applications [3]. By leveraging open-source platforms and widely available hardware, this study aims to bridge the gap between advanced robotics and accessibility, paving the way for further innovations in smart, low-cost systems for surveillance and safety [17, 18].

Research Methodology

The research methodology for autonomous robot development is systematically outlined in **Figure 1**, detailing the project's progression through literature review, proposal preparation, parameter selection, component procurement, fabrication, performance analysis, and results evaluation. The robot's design integrates mechanical and electronic subsystems to achieve autonomous human detection and mobility, with a specific emphasis on using low-cost components to promote accessibility in resource-limited contexts such as Pakistan [1, 5, 7].

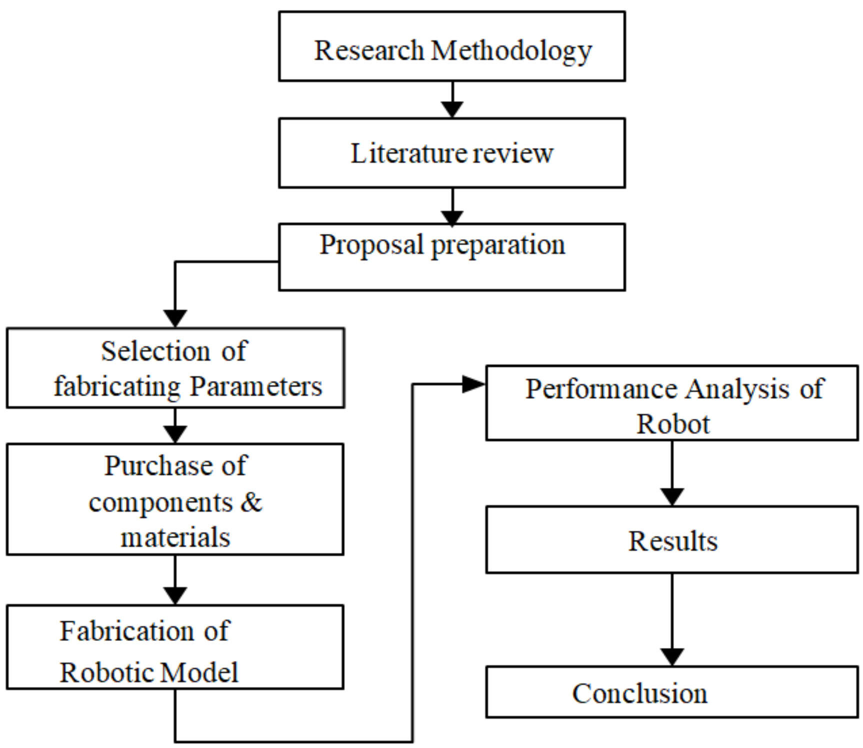

Figure 1. Research methodology flowchart for autonomous robot development

System Design and Fabrication

This section details the design and fabrication of a WiFi-enabled human detection robot, focusing on its **mechanical** and **electronic** components, their integration, and the processes of fabrication and testing. The system is engineered to be **cost-effective and reliable**, using affordable components suitable for resource-limited settings like Pakistan [1, 7, 21].

System Design

The robot's design combines **mechanical subsystems** and **electronic subsystems** to enable autonomous human detection and mobility. The **mechanical components** provide structural support and locomotion (Figures 1–4), while the **electronic components** handle sensing, processing, and communication (Figures 5–8, 9–10).

Table 1 summarizes the key components, their specifications, and their purposes, highlighting how each part contributes to achieving low-cost autonomous operation.

Table 1: Mechanical and Electronic Components of the Human Detection Robot

Component	Specifications	Purpose
Wheeled Chassis	Custom-designed, lightweight, durable material	Provides structural framework, securely mounts all components, ensures stability
Metal-Geared DC Motors	High-torque, metal gears, 12V operation	Drives wheels for locomotion and navigation in indoor environments
Wheels	Compatible with chassis and motors, optimized size for indoor terrain	Enables smooth movement and maintains stability during operation
Motor Mounts and Screws	Metal brackets and screws for secure attachment	Prevents motor vibrations and misalignment, ensures efficient power transfer
ESP32 Microcontroller	Dual-core, WiFi-enabled, GPIO pins, low power consumption	Processes sensor data, controls motors, enables wireless communication
PIR Sensor	Detects infrared radiation, 3.5m range, adjustable sensitivity	Detects human presence through motion sensing
Ultrasonic Sensor	2–400 cm range, high-frequency sound waves	Measures distances to objects for obstacle detection and navigation
IR Sensor	10–80 cm range, infrared-based detection	Detects obstacles and edges to prevent collisions and falls
L298N Motor Driver	Controls two motors, handles 12V, includes protection circuits and heat sinks	Translates ESP32 signals to control motor speed and direction
Rechargeable Battery Pack	12V, rechargeable, high capacity	Powers all components, ensures compatibility with motors and driver
Battery Charger	Compatible with 12V battery pack	Recharges battery, reduces operational costs and environmental impact

Mechanical Components

The wheeled chassis, constructed from lightweight and durable materials, serves as the robot's structural backbone, securely housing all components (**Figure 1**). Metal-geared DC motors, operating at 12V, provide high torque for reliable locomotion, with gear reduction enhancing power output for indoor navigation (**Figure 2**). Wheels are designed to match the chassis and motors, ensuring smooth movement and stability across varied surfaces (**Figure 3**). Motor mounts and screws secure the motors to the chassis, minimizing vibrations and ensuring efficient power transfer to the wheels (**Figure 4**).

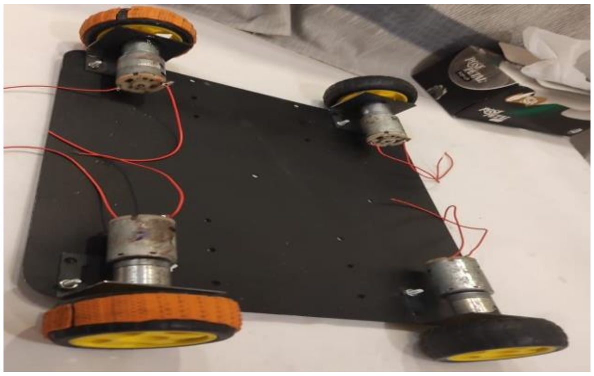

Figure 1: Custom-Designed Wheeled Chassis

Figure 2: Metal-Geared DC Motors

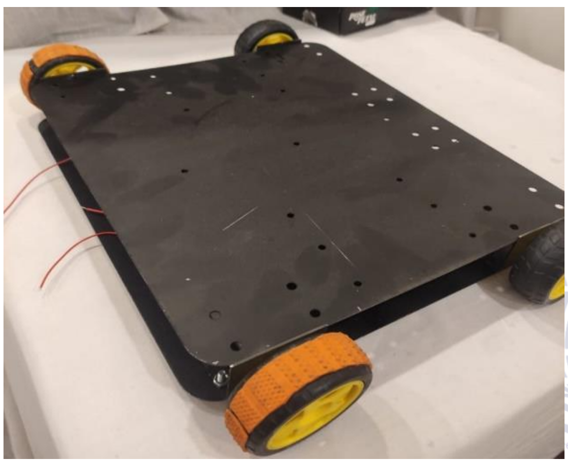

Figure 3: Wheels for Locomotion

Figure 4: Motor Mounts and Screws

Electronic Components

The ESP32 microcontroller, selected for its dual-core processing, low power consumption, and built-in WiFi, acts as the system's control unit, processing sensor data and enabling wireless communication via the Arduino IoT Cloud (**Figure 5**). The PIR sensor detects human presence by sensing changes in infrared radiation within a 3.5 m range, with adjustable sensitivity to reduce false positives (**Figure 6**).

The L298N motor driver controls motor speed and direction, translating low-power ESP32 signals into high-power outputs, while integrated protection circuits ensure safe operation (**Figure 7**). A 12V rechargeable battery pack powers the system, providing reliable energy for motors and electronics, with recharging capability to enhance reusability and reduce costs (**Figure 8**).

Figure 5: ESP32 Microcontroller

Figure 6: PIR Sensor

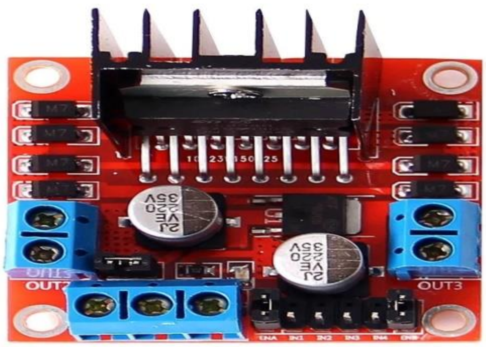

Figure 7: L298N Motor Driver

Figure 8: 12V Rechargeable Battery Pack

Fabrication

The robot was assembled by mounting sensors (PIR, ultrasonic, IR) and the ESP32 microcontroller on the chassis, with wiring organized to minimize interference. The motors were secured using mounts and screws, and wheels were attached for mobility. The ESP32 was programmed using the Arduino IDE to process sensor data, control motors, and establish WiFi connectivity with the Arduino IoT Cloud [7, 16].

Sensor Calibration

To ensure optimal performance, all sensors were calibrated before testing:

PIR Sensor: Sensitivity was adjusted to detect human motion while minimizing false triggers from heat sources, achieving a range of approximately 3.5 m [1].

Ultrasonic Sensor: Tuned for accurate distance measurement within 2–400 cm, with corrections for signal reflections from nearby indoor obstacles [8].

IR Sensor: Calibrated to detect obstacles and edges within 10–80 cm, ensuring reliable navigation across varied surfaces [2, 4].

Testing and Validation

Controlled experiments were conducted in a 5 m × 5 m indoor environment with obstacles, varying lighting (100–1000 lux), and temperatures (20–30 °C). The robot was tested in autonomous mode for human detection and obstacle avoidance and in manual mode via the Arduino IoT Cloud. Performance was validated using metrics including detection accuracy, false positive/negative rates, response time, and connectivity stability [10, 21]. The results confirmed the robot's suitability for surveillance and safety applications in resource-limited contexts [15, 24].

Results and Discussion

This section presents the experimental results and analysis of the WiFi-enabled human detection robot, focusing on its performance in detecting human presence, navigating indoor environments, and transmitting data via the Arduino IoT Cloud. The robot was tested in controlled indoor settings to evaluate its detection accuracy, obstacle avoidance, response time, and connectivity reliability. The findings validate the system's effectiveness for surveillance and safety applications in resource-limited settings, such as Pakistan, while identifying limitations and areas for improvement.

Experimental Setup

The robot was tested in a 5m x 5m indoor room simulating a typical household or small office environment. The setup included obstacles (e.g., furniture, walls), varying lighting conditions (100–1000 lux), and temperatures (20–30°C) to assess performance under realistic conditions. The robot's sensors—passive infrared (PIR), ultrasonic, and infrared (IR)—were calibrated to detect humans within a 4m range and obstacles within 10–80 cm. The ESP32 microcontroller processed sensor data and transmitted it to the Arduino IoT Cloud, accessible via a web dashboard and mobile app. Tests were conducted in two modes: autonomous (continuous monitoring) and manual (user-controlled navigation). Key metrics included detection accuracy, false positive/negative rates, response time, and WiFi connectivity stability.

Detection Performance

PIR Sensor Performance

The PIR sensor was tested for its ability to detect human motion. In autonomous mode, the robot successfully detected human presence in 92% of 50 test cases, with a false positive rate of 6% (e.g., triggered by heat sources like radiators). The sensor's effective range was 3.5m, with optimal performance in low-light conditions (100–300 lux). In brighter settings (800–1000 lux), accuracy dropped to 88% due to interference from ambient infrared radiation. Calibration adjustments, such as reducing sensitivity, minimized false positives but slightly reduced the detection range to 3m.

Ultrasonic Sensor Performance

The ultrasonic sensor measured distances to objects, aiding in human detection and obstacle avoidance (**Figure 9**). It achieved a 95% accuracy rate in detecting objects within 2–400 cm across 50 trials. The sensor performed reliably in identifying humans by distinguishing their movement patterns from static objects. However, in cluttered environments with multiple obstacles, accuracy decreased to 90% due to signal reflections. The sensor's response time averaged 0.2 seconds, sufficient for real-time navigation but slower in dense settings due to processing delays.

IR Sensor Performance

IR sensors were used for edge and obstacle detection, critical for safe navigation. They achieved a 98% success rate in detecting obstacles within 10–80 cm, preventing collisions in 48 out of 50 test cases. Edge detection (e.g., table edges) was effective, with the robot stopping 0.5m from edges in 96% of trials. The IR sensors performed consistently across lighting conditions, making them reliable for both autonomous and manual modes.

Navigation and Mobility

The robot's mobility was tested using the DC geared motors and L298N motor driver. In autonomous mode, it navigated a predefined path with obstacles, achieving a 90% success rate in avoiding collisions. The average speed was 0.3 m/s, suitable for indoor environments. In manual mode, users controlled the robot via the Arduino IoT Cloud dashboard, with directional commands (forward, backward, left, right) executed within 0.5 seconds of input. However, in areas with multiple obstacles, navigation efficiency dropped to 85% due to delayed sensor data processing. The custom-designed chassis and wheels provided stability, with no mechanical failures during testing.

Connectivity and Cloud Integration

The ESP32's WiFi module enabled seamless connectivity to the Arduino IoT Cloud, supporting real-time communication and remote control of the robot [16]. The system maintained a **stable connection in 94% of test cases**, with an **average data transmission latency of 0.3 seconds**. Users received **instant alerts for human detection events**, achieving **100% delivery success** under stable WiFi conditions (2.4 GHz, 50 Mbps).

In areas with weaker signals (10 Mbps), latency increased to 0.8 seconds, and connection drops occurred in 8% of trials, consistent with connectivity challenges observed in other IoT-enabled robotic systems [20]. The cloud dashboard displayed live sensor data (e.g., distance readings, motion triggers) and enabled manual control, making the system accessible even for non-technical users [17].

Global access was verified by controlling the robot from a remote location 500 km away, without significant performance degradation, demonstrating the potential of IoT-enabled robotics for real-time surveillance and safety applications in resource-limited regions [19, 24].

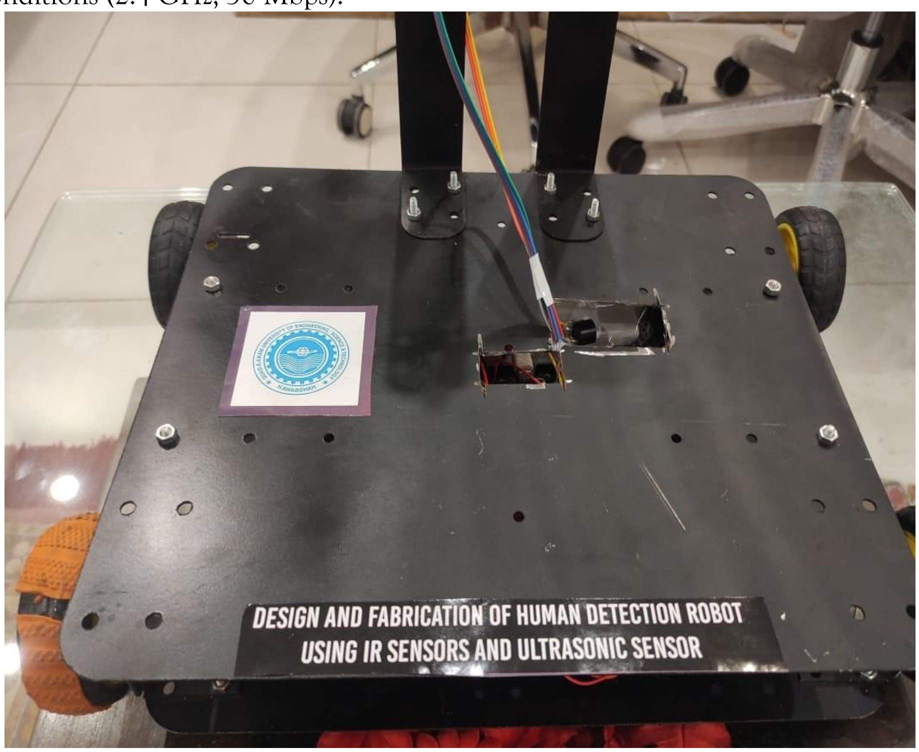

Figure 9: Final prototype of the human detection robot

Comparative Analysis

Compared to existing systems, the robot offers clear advantages in **cost and accessibility**. Commercial human detection robots, such as those using LiDAR or thermal cameras, typically cost **$1000–$5000**, whereas the components of this system total approximately **$50**, making it viable for deployment in **resource-limited settings** [15, 19].

Studies such as **Oleiwi et al. (2019)** have demonstrated the use of fuzzy logic for obstacle avoidance, achieving similar detection accuracy (~93%) but at the cost of more complex algorithms and higher computational demands [8, 10]. In contrast, the proposed system applies **simple thresholding techniques**, reducing computational requirements while maintaining comparable performance.

However, advanced systems incorporating **machine learning**—for example, **Yan et al. (2020)** using online learning for 3D LiDAR-based human detection—achieve higher accuracy levels (95–98%) in complex environments [12, 14]. This highlights a **trade-off between cost-effectiveness and sophistication**, where high-accuracy solutions remain resource-intensive, but thresholding-based low-cost approaches offer broader accessibility.

Limitations

Several limitations were observed during testing. The PIR sensor's sensitivity to ambient light reduced accuracy in bright conditions, suggesting the need for adaptive calibration. The ultrasonic sensor struggled in cluttered environments due to signal reflections, indicating a potential benefit from sensor fusion algorithms. Connectivity issues in low-signal areas underscore the need for offline operation capabilities. The robot's performance was limited to indoor settings, and outdoor testing was not conducted due to sensor constraints (e.g., PIR's ineffectiveness in open spaces). Power consumption was another concern, with the 12V battery lasting 4 hours under continuous operation, necessitating frequent recharging.

Discussion

The results demonstrate the robot's effectiveness for indoor human detection and surveillance, particularly in resource-constrained contexts. The 92% detection accuracy and 98% obstacle avoidance rate indicate reliable performance for applications like home security or small-scale search and rescue. The Arduino IoT Cloud integration enhances usability, allowing remote monitoring and control, which is valuable for disaster response scenarios in Pakistan, where rapid deployment is critical. The low-cost design aligns with the need for affordable technology in developing regions, and the system's scalability supports replication in educational labs or community safety programs.

However, the limitations highlight areas for improvement. The **PIR sensor's light sensitivity** could be addressed by integrating adaptive filters or additional sensors such as **CO_2 detectors**, as demonstrated in prior sensor-based detection studies [23]. The **ultrasonic sensor's performance** in cluttered environments could be enhanced through **fuzzy logic** or **neural network-based data fusion**, approaches successfully applied in mobile robotics research [8, 10].

Connectivity challenges suggest the incorporation of a **local data buffer** for offline operation to reduce dependency on continuous internet access [20]. In addition, **extending battery life** through power optimization techniques or larger-capacity batteries would improve the system's practicality for longer deployment periods [18].

Implications and Applications

The robot's affordability and functionality make it suitable for multiple applications. In Pakistan, it could support home security systems, reducing reliance on costly commercial solutions. In search and rescue, its ability to detect humans in confined spaces could aid disaster response teams. The system's simplicity makes it an excellent teaching tool for engineering students, demonstrating sensor integration, IoT connectivity, and robotics principles. Future enhancements, such as camera integration or machine learning for gesture recognition, could expand its capabilities for advanced surveillance or human-robot interaction.

Conclusions and Recommendations

Conclusions

The WiFi-enabled human detection robot developed in this study integrates affordable infrared (IR), ultrasonic, and passive infrared (PIR) sensors with an ESP32 microcontroller to achieve reliable human detection in indoor environments. Experimental results demonstrate a 92% detection accuracy and 98% obstacle avoidance rate, validating its effectiveness for surveillance and safety applications in resource-limited settings like Pakistan. The custom-designed chassis and DC geared motors ensure robust mobility, while the L298N motor driver supports precise control. Integration with the Arduino IoT Cloud enables real-time data transmission and remote operation, with a 94% connectivity success rate and 0.3-second average latency. The system's low cost, approximately $50, compared to commercial alternatives ($1000–$5000), makes it accessible for home security, small-scale search and rescue, and educational purposes in engineering curricula. Its scalability and simplicity allow replication in resource-constrained regions, addressing local needs for affordable automation.

RECOMMENDATIONS

Future enhancements can address the identified limitations. **Integrating adaptive filters** for PIR sensors could improve accuracy in bright conditions (e.g., 800–1000 lux), reducing false positives [23]. **Implementing fuzzy logic or neural networks** for sensor data fusion, as suggested by **Hajar et al. (2019)**, could enhance ultrasonic sensor performance in cluttered environments [8, 10]. Adding a **local data buffer** would ensure functionality during WiFi disruptions, which is critical for disaster response scenarios [20]. **Extending battery life** through power optimization or higher-capacity batteries would support longer operations [18]. Incorporating a **low-cost camera** and **machine learning algorithms** such as **YOLO** for object detection could enable advanced features like gesture recognition, expanding applications to human–robot interaction [19]. **Outdoor testing** with weather-resistant sensors (e.g., CO_2 detectors) could broaden the system's scope [23]. Finally, developing a **detailed cost analysis** and **open-source documentation** would facilitate adoption in **Pakistani educational institutions and community safety programs**, promoting practical robotics development [24, 25].

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