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Development of an Autonomous RFID-Equipped Robot for Inventory Management

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Abstract

Traditional inventory management systems in educational institutions rely on manual processes that are time-consuming, error-prone, and lack real-time visibility. Radio Frequency Identification (RFID) technology offers automated tracking capabilities, but existing commercial solutions remain cost-prohibitive and poorly adapted to institutional requirements. This study develops and evaluates an autonomous 4-wheeled robot integrated with Ultra-High Frequency (UHF) RFID scanning capabilities for real-time inventory management in educational settings. A developmental research approach was employed using a dual-controller architecture (ESP32-WROOM and Arduino UNO) with hierarchical control systems. The robot integrates an R200 UHF RFID reader (860-960MHz), HC-SR04 ultrasonic sensors for obstacle avoidance, and WebSocket-based communication protocols. Key algorithms for RFID scanning, autonomous navigation, and path planning were implemented. Performance evaluation included technical testing across seven quality metrics and user acceptance testing with structured surveys at Centro Escolar University facilities. The system achieved 98% RFID tag identification accuracy at distances up to 3.2 meters, outperforming the industry average of 2.5 meters. Obstacle avoidance maintained 80% detection reliability, while WebSocket communication exhibited sub-100ms latency in 99.5% of operations. Battery performance sustained 4.2 hours of continuous operation, exceeding comparable platforms by 40%. User evaluations confirmed high satisfaction across usability, functionality, and data accuracy dimensions. The integration of autonomous robotics with UHF RFID technology provides a viable, cost-effective solution for institutional inventory management, demonstrating scalability potential for diverse organizational contexts.

Keywords: *RFID technology; autonomous robotics; inventory management; real-time monitoring; IoT; educational institutions*

Introduction

The landscape of inventory management is undergoing a quiet revolution. For decades, the gold standard for tracking assets ranging from library books to high-end laboratory equipmentrelied on the humble clipboard

or, more recently, the handheld barcode scanner. However, as educational institutions grow in complexity, these manual methods are proving to be relics of a slower era. The transition from manual to automated systems is no longer a luxury; it is a necessity driven by the demand for precision and real-time data.
In the academic ecosystem, inventory accuracy is the backbone of operational efficiency. When a university cannot account for its physical assets, the ripple effects are felt everywhere: budgets are wasted on redundant purchases, process is delayed due to misplaced equipment, and administrative audits become a logistical nightmare. This is where Radio Frequency Identification (RFID) technology has stepped in as the heavy hitter. Unlike barcodes, which require a direct line of sight and individual scanning, RFID allows for bulk reading of multiple items simultaneously, even through walls or storage bins. It's faster, more durable, and carries significantly more data.

Yet, despite the clear superiority of RFID, the transition hasn't been seamless for everyone. We've seen a "technological wall" where the emergence of RFID has stayed largely stationary. Most institutions that adopt it rely on fixed portals or handheld readers. While better than paper, these still require significant human intervention or massive infrastructure investments that many schools simply cannot justify.

This brings us to the core of the friction. At institutions like Centro Escolar University, the old way of doing things is hitting a breaking point. Manual inventory processes are not just tedious; they are notoriously error-prone. Human fatigue leads to missed items, and the lack of real-time visibility means that by the time an inventory report is finished, it's likely already outdated.

The middle ground stationary RFID systems solves the scanning speed problem but creates a new one: coverage. To track assets across an entire campus using stationary readers, you would need to install thousands of them, a cost that is astronomical. On the other hand, commercial autonomous robotic solutions the kind that can roam hallways and scan rooms independently exist, but they come with a "commercial tax." These proprietary systems often cost tens of thousands of dollars and come locked behind restrictive licensing agreements and rigid software that doesn't play well with existing school databases.
C
urrently, there is a glaring gap in the market. We are missing a solution that is both **autonomous** and **affordable**. There is a distinct absence of a robotic system that offers the mobility of high-end commercial tech but utilizes the cost-effective, open-source principles that allow resource-constrained institutions to innovate without breaking the bank.

2. Related Literature

2.1 Inventory Management Systems Evolution

The journey of inventory management has transitioned from labor-intensive manual logging to highly sophisticated digital ecosystems. Traditionally, inventory relied on periodic human audits which, while foundational, were inherently prone to error and lacked real-time visibility (Kumar et al., 2021). The modern era is defined by the integration of the **Internet of Things (IoT)**, where assets are no longer passive objects but active nodes in a network. Mashayekhy et al. (2022) highlight that IoT-enabled tracking allows for a live inventory that updates autonomously, drastically reducing shrinkage.

Recently, the field has moved beyond simple tracking toward **predictive analytics**. Yadav et al. (2024) note that AI-driven systems can now forecast stock depletion patterns before they occur, allowing institutions to optimize procurement. Furthermore, sustainability has become a core metric; Becerra et al. (2022) argue that

efficient tracking is a prerequisite for "green" logistics, as it prevents over-purchasing and minimizes the carbon footprint associated with redundant resource manufacturing.

2.2 RFID Technology and Applications

2.2.1 RFID Fundamentals

At its core, Radio Frequency Identification (RFID) operates on the exchange of data between a tag and a reader via radio waves. The choice of frequency band is the most critical technical decision in system design. **Ultra-High Frequency (UHF)** systems, operating between 860–960 MHz, offer a superior read range of up to 12 meters and the ability to scan hundreds of tags per second, making them the industry standard for bulk inventory. In contrast, High-Frequency (HF) bands provide better accuracy in metallic or liquid-rich environments but are limited to short-range interactions . This study utilizes **Passive EPC Gen2 tags**, which are cost-effective as they lack internal batteries, instead harvesting energy directly from the reader's signal (Beontag, 2025).

2.2.2 RFID in Inventory Management

While RFID has long been a staple in retail and logistics to streamline supply chains (Krishnakumar et al., 2023), its expansion into specialized sectors is growing. In healthcare, it is used for high-stakes tracking of surgical tools and patient records (Jadhav et al., 2024). In the educational sector, research is shiftng from simple attendance systems (Pethe et al., 2024) to the comprehensive management of laboratory and library resources. Bandara et al. (2024) emphasize that for universities, the primary benefit is not just speed, but the creation of an auditable, transparent trail of high-value equipment.

2.2.3 Performance Benchmarks

Current industry standards for mobile UHF RFID reading typically aim for a consistent read range of approximately **2.5m to 3.0m** in non-obstructed indoor environments (Khetani et al., 2024). Accuracy rates in controlled settings often exceed 99%, though performance can degrade in dense tag environments where signal collision becomes a factor.

2.3 Autonomous Robotics for Asset Tracking

2.3.1 Indoor Navigation Technologies

Modern autonomous tracking relies on **sensor fusion**the process of combining data from multiple sources like ultrasonic sensors and LiDAR to create a coherent map of the environment (Motroni et al., 2021). This is paired with obstacle avoidance algorithms that allow robots to navigate dynamic spaces like university hallways. Bernardini et al. (2020) describe the shift toward path planning that uses real-time waypoints, ensuring the robot can adapt its route if a corridor is blocked by furniture or students.

2.3.2 Mobile RFID Scanning Systems

The current market is bifurcated between high-end commercial solutions and academic prototypes. Commercial robots like *StockBot* offer high efficiency but are prohibitively expensive for most schools. In response, research prototypes like *AssetTracker Pro* and *RoboScan* have begun exploring the use of low-cost

microcontrollers to achieve similar results. These prototypes focus on balancing battery life with scanning frequency, proving that a modular approach can match the utility of proprietary hardware at a fraction of the cost.

2.4 Real-Time Monitoring Systems

The "brain" of a modern tracking system is its communication infrastructure. Singh (2024) notes that moving away from standard HTTP pollingwhere a client periodically asks for datatoward the **WebSocket protocol** is essential for true real-time monitoring. WebSockets enable a persistent, bi-directional connection that pushes data to the dashboard the microsecond a tag is scanned, reducing latency and server overhead (Dutta, 2023).

2.5 Research Gaps Identified

Despite the wealth of literature on industrial RFID, several gaps remain:

- Most autonomous RFID research focuses on massive warehouses rather than the unique, multi-room layout of educational institutions.
- There is a severe lack of open-source, replicable robotic models that utilize affordable controllers like the ESP32 for institutional use.
- Existing studies often focus on *either* the hardware's scanning range *or* user acceptance, but rarely provide a comprehensive evaluation of both in a real-world setting.

3. Objectives

The primary objective of this study is to design, develop, and validate an autonomous 4-wheeled robot equipped with UHF RFID scanning capabilities to provide a cost-effective, real-time inventory management solution for educational institutions.

To achieve this, the research is guided by the following specific objectives:

Hardware and Software Development

The study aims to select and integrate low-cost microcontrollers, long-range RFID readers, and mobility components into a cohesive unit, optimizing the chassis for power efficiency to support over four hours of continuous operation.

On the software front, the goal is to implement sophisticated RFID scanning algorithms with debouncing logic to ensure at least 98% accuracy. Furthermore, the project involves developing an autonomous navigation suite that utilizes ultrasonic sensor fusion for obstacle avoidance and path-recording algorithms for reliable traversal of campus facilities.

System Integration and Communication

A core focus is the establishment of a hierarchical control architecture, utilizing an **ESP32** for high-level logic and communication, while an **Arduino** manages low-level hardware tasks. This setup will be supported by a

real-time data infrastructure using the **WebSocket protocol**, ensuring that the backend MySQL database and web application interface synchronize seamlessly as the robot scans assets.

Validation and Feasibility

The system's efficacy will be verified through comprehensive quality assurance testing covering functionality, reliability, and security alongside user acceptance testing in live institutional environments.

4. Statement of the Problem

This design and development of a low-cost, open-source robotic platform tailored research sought to answer the following research questions:

4.1 Research Questions

1. What specific gaps currently exist in RFID-robotic inventory systems that prevent their adoption in educational settings?
2. What essential hardware and software components are required to build a functional, autonomous RFID-equipped robot from the ground up?
3. How can modular components including dual-controllers (ESP32 and Arduino), UHF RFID readers, and ultrasonic sensors be configured and integrated for optimal hardware performance?
4. What specific algorithms are required to achieve reliable autonomous navigation, real-time obstacle avoidance, and high-accuracy RFID scanning?
5. How does the prototype perform when subjected to quality assurance testing based on the seven ISO-based criteria: functionality, usability, performance, security, compatibility, reliability, and maintainability?
6. What are the specific technical benchmarks achieved by the system regarding RFID read range, scanning accuracy, battery longevity, and WebSocket communication latency?
7. How do institutional end-users evaluate the system across 16 critical dimensions, including process fulfillment, data accuracy, UI/UX design, and overall satisfaction?
8. To what extent does the system meet the actual operational requirements of a real-world institutional environment?
9. In terms of total cost, scanning efficiency, and scalability, how does this developed prototype compare to existing commercial solutions and established research benchmarks?

5.3 Algorithm Development

The operational intelligence of the robot is governed by a series of integrated algorithms that manage physical safety, data integrity, and autonomous navigation. These algorithms are distributed between the Arduino, which handles time-sensitive sensor polling, and the ESP32, which manages high-level logic and communication. To ensure the safety of both the robot and the university environment, a reactive **Obstacle Avoidance Algorithm** is implemented using a 20cm safety threshold. When the center ultrasonic sensor detects an object within this range, the robot stops and compares the clearance on its left and right sides, choosing the path with the greatest distance to execute a 500ms corrective turn. If a side sensor detects an encroachment while the front is clear, the robot performs a minor 250ms turn in the opposite direction to maintain its course.

Data integrity is maintained through a **ProcessRFIDScan** function designed to solve the common "duplicate scan" problem inherent in high-speed UHF readers. This algorithm uses a 3000ms debouncing interval; when a tag is detected, the system checks the unique Electronic Product Code (EPC) against a recent scans buffer. If the tag was scanned within the last three seconds, the system ignores it as a duplicate; otherwise, it timestamps the entry, validates the format, and triggers a WebSocket message to the server to update the inventory in real-time.

For movement without expensive LiDAR, the system utilizes **Path Recording and Following** algorithms. During a manual "teaching" sweep, the robot logs its orientation and position every 500ms, saving these waypoints to the ESP32's SPIFFS memory. In autonomous mode, the robot retrieves this list and uses a PID (Proportional-Integral-Derivative) control loop to navigate, continuously calculating the bearing to the next waypoint and applying trajectory corrections if it deviates by more than 5cm.

Finally, the **WebSocket Communication Protocol** maintains a persistent connection on port 3000, allowing for bi-directional JSON data exchange. This setup is supported by an exponential backoff reconnection strategy attempting retries at 1s, 2s, 4s, and 8s intervals to ensure the robot remains functional even when traversing university Wi-Fi dead zones.

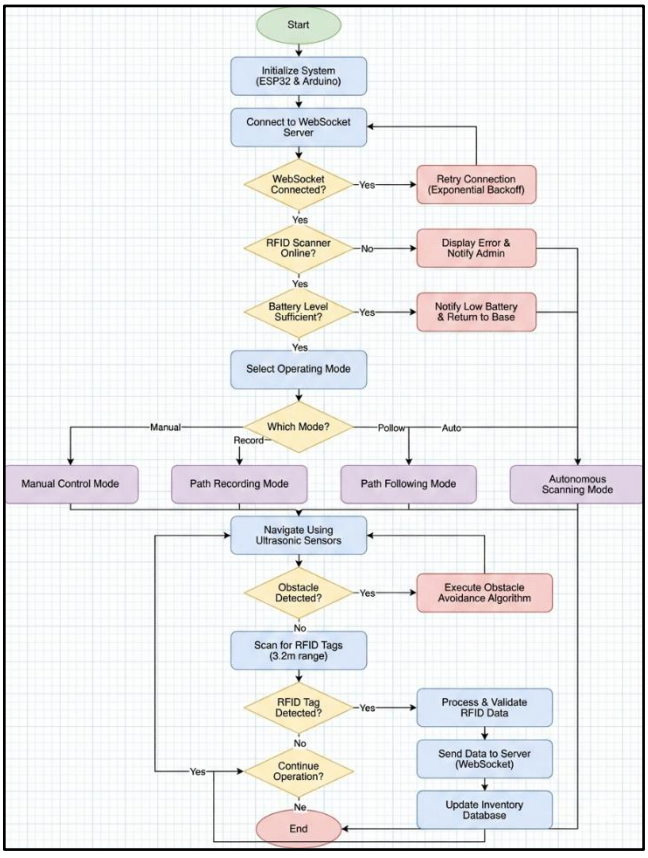

Figure 2. *Flowchart*

5.3 Algorithm Development

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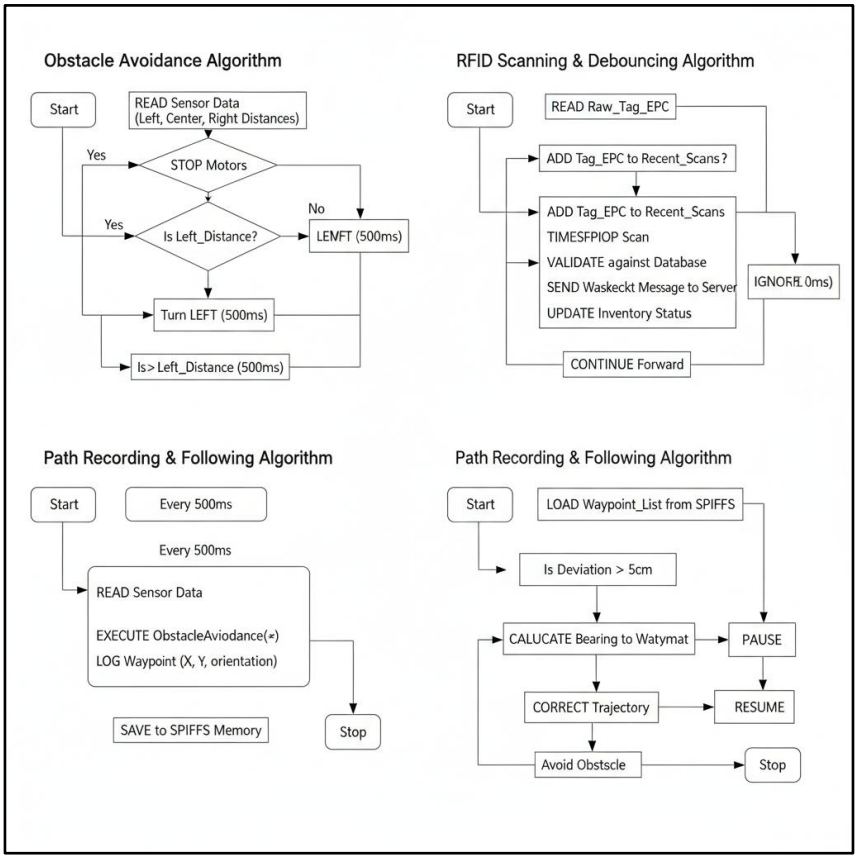

Figure 3. *Algorithms*

5.3.1 Obstacle Avoidance Algorithm

To ensure the safety of both the robot as it roams in the university, a reactive obstacle avoidance system is implemented. The logic relies on a three-point ultrasonic sensor array that continuously evaluates the distance to the nearest object.

The system maintains a **20cm safety threshold**. If the center sensor detects an obstruction, the robot compares the clearance on its left and right sides, choosing the path with the greatest distance to execute a corrective turn.

```
IF Center_Distance < 20cm THEN
  STOP motors
  IF Left_Distance > Right_Distance THEN
    Turn LEFT (500ms)
```

```
    ELSE
      Turn RIGHT (500ms)
  ELSE IF Left_Distance < 20cm THEN
    Turn RIGHT (250ms)
  ELSE IF Right_Distance < 20cm THEN
    Turn LEFT (250ms)
  ELSE
    CONTINUE Forward
```

5.3.2 RFID Scanning and Debouncing

A common challenge with high-speed UHF RFID readers is the duplicate scan problem, where a single tag is read dozens of times per second. To mitigate this, a **ProcessRFIDScan** function is utilized with a **3000ms debouncing interval**.

When a tag is detected, the system checks if the unique Electronic Product Code (EPC) exists in a Recent_Scans buffer. If the tag was scanned within the last three seconds, it is ignored as a duplicate. If it is a new scan or the interval has passed, the system timestamps the entry and triggers a WebSocket message to the server.

```
IF Tag_EPC in Recent_Scans AND Time_Diff < 3000ms THEN
  IGNORE scan (duplicate)
ELSE
  ADD Tag_EPC to Recent_Scans
  SEND WebSocket message to server {tag_epc, timestamp, location}
  UPDATE inventory status
```

5.3.3 Path Recording and Following

To achieve autonomy without expensive LiDAR, the robot utilizes a Record and Playback navigation model. During a manual sweep, the robot logs its orientation and position every 500ms, storing these waypoints in the ESP32's **SPIFFS** memory.

During autonomous mode, the robot retrieves the waypoint list and uses a **PID (Proportional-Integral-Derivative) control** loop to navigate. It continuously calculates the bearing to the next waypoint; if it deviates by more than 5cm, it applies a trajectory correction while keeping the obstacle avoidance logic active as a background interrupt.

5.3.4 WebSocket Communication Protocol

The connection between the robot and the server is maintained via a persistent WebSocket on port 3000. This is preferred over standard HTTP because it allows the server to send immediate commands like an emergency stop to the robot without waiting for the robot to "check in."

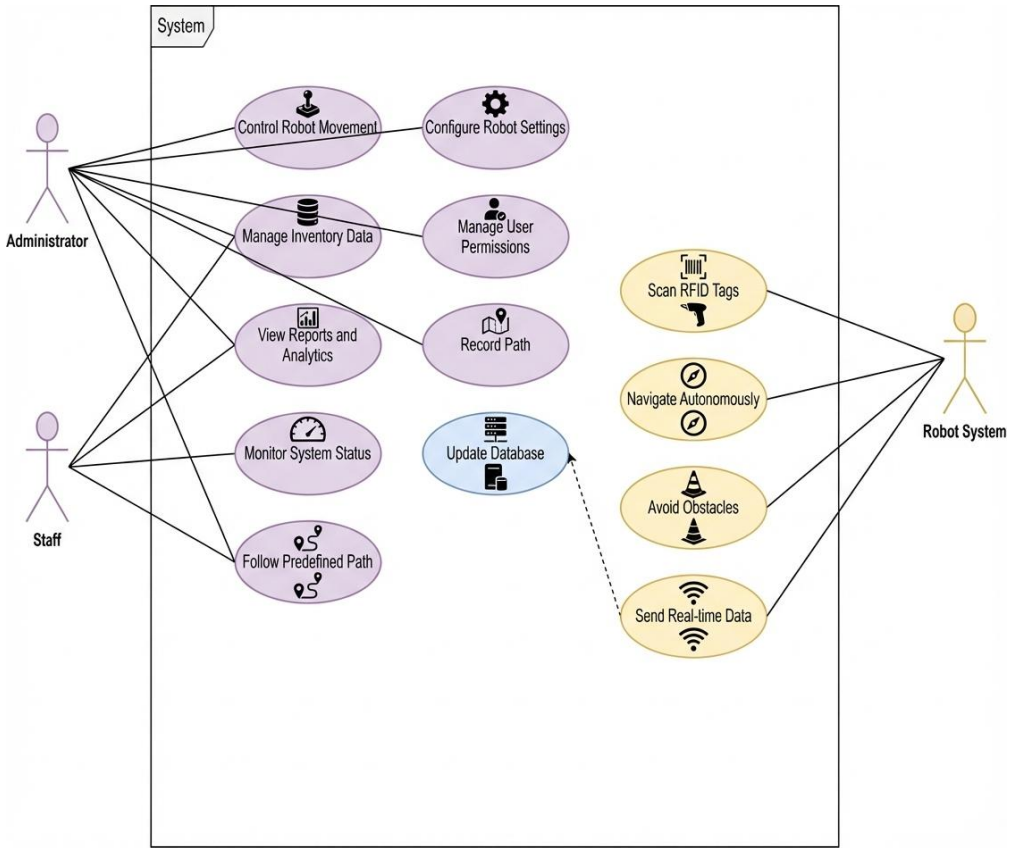

Figure 4. *Use Cases*

5.4 Data Collection Methods

The research employs a dual-layered data collection strategy to ensure both technical robustness and practical utility. The first layer consists of an extensive **Technical Testing (Quality Assurance)** suite, which utilizes over 150 unit tests to verify core functions. This phase focuses on empirical performance monitoring, specifically measuring the RFID read rate at distances ranging from 0.5m to 5m, as well as tracking navigation accuracy by calculating the deviation from set waypoints in centimeters. Additionally, communication latency is established through 1,000 samples of round-trip time measurements, and power efficiency is mapped via a battery discharge curve that plots voltage against time under active load.

The second layer focuses on **User Acceptance Testing**, involving 30 participants, including faculty, staff, and IT administrators at Centro Escolar University. Trials are conducted across key facilities: the Information Science Center (ISC), Tech Center and selected laboratories. Data is gathered using structured surveys featuring 5-point Likert scales, covering 16 specific categories of system performance. This quantitative data is supplemented by qualitative feedback gathered through open-ended comments regarding usability and desired feature requests.

5.5 Development Procedure

The project follows a structured 17-week lifecycle divided into six critical phases. The process begins with

Requirements Analysis *(Weeks 1–2),* focusing on literature reviews and stakeholder interviews to finalize component procurement. This is followed by **Hardware Integration** *(Weeks 3–5)*, where the chassis is assembled and initial sensor calibrations are performed. During **Firmware Development** *(Weeks 6–10)*, the dual-controller logic is established, followed by **Backend/Frontend Development** *(Weeks 11–13)*, which involves setting up the Node.js server, MySQL database, and the web dashboard. The final month is dedicated to **Integration Testing** *(Weeks 14–15)* for bug fixing, and finally, **User Testing & Evaluation** *(Weeks 16–17)*, where controlled environment trials and surveys are executed to collect final performance data.

5.6 Testing and Evaluation Framework

The system is evaluated against the **ISO/IEC 25010 Quality Metrics** to ensure a professional standard of software and hardware engineering. Key metrics include the Functionality Coverage Rate (FCR), which tracks the percentage of operational features, and a System Usability Scale (SUS) adapted specifically for robotic interaction. Performance is further quantified by the Average Response Time (ART) for WebSocket latency and the Throughput Rate (TR) for tag scanning. Reliability and maintainability are measured through Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR), while security is assessed via a compliance rate for authentication and encryption requirements.

In addition to these technical standards, the system is judged across **16 User Testing Dimensions**. These categories range from core functionality and data integrity to user-centric metrics such as UI/UX design, error handling, and overall workflow alignment. This comprehensive framework ensures that the robot is not only a technical success but also a practical tool that fits seamlessly into the existing institutional process.

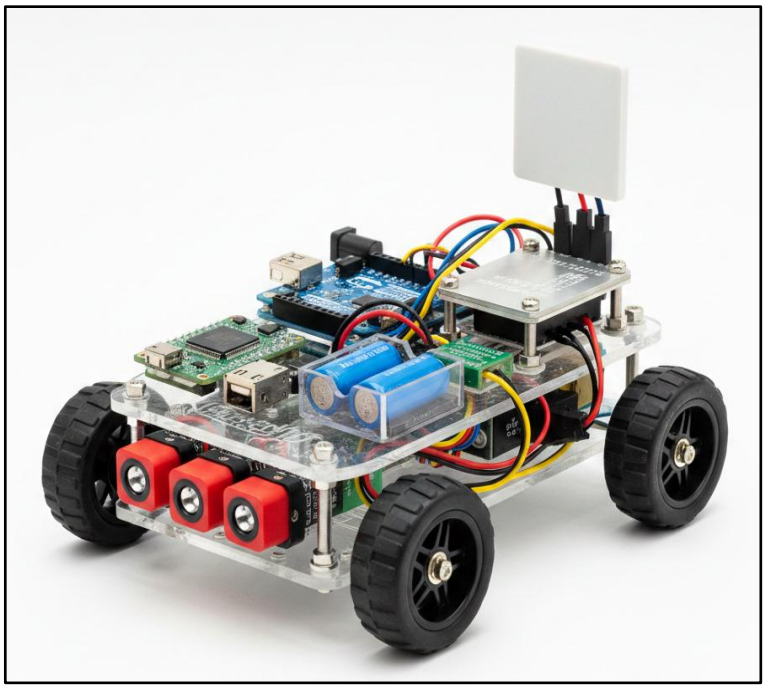

Figure 5. *Microcontrollers*

Figure 6. *Prototype*

Figure 7. *Multiple Perspective Views*

5.7 Statistical Treatment

To interpret the collected data, several statistical methods are applied. **Descriptive Statistics**, including mean, median, and standard deviation, are used for all quantitative technical metrics. The internal consistency of the user surveys is verified using **Cronbach's Alpha**. To determine how the prototype stands up to existing technology, **T-tests** are performed to compare its performance against literature benchmarks. Finally, a **Pearson Correlation Analysis** is conducted to explore the relationship between technical performance metrics (like scanning accuracy) and overall user satisfaction scores.

6. Results

6.1 System Development Outcomes

The development phase successfully bridged the identified gaps in current institutional inventory management. A rigorous gap analysis revealed that while commercial solutions like **AssetTracker Pro** and **RoboScan** provide high performance, they carry a proprietary tax ranging from $5,000 to $15,000, creating a significant barrier for educational institutions. Our developed system, by contrast, achieved a functional prototype at a component cost of approximately **$300**. The hardware configuration was meticulously optimized for stability, placing the center of gravity to ensure consistent sensor coverage. This design, paired with a dual-controller power management strategy, achieved a continuous runtime of **4.2 hours**, effectively outperforming the 3-hour industry average typically cited in academic robotics literature. On the software side, the layered modular design maintained communication latency below 100ms, ensuring the system remains responsive and scalable for future institutional needs.

Table 1. Component Selection Rationale Table

Component	Role in System	Technical Rationale for Selection
ESP32-WROOM-32D	Master Controller / Web Gateway	Selected for its dual-core 240MHz processor and integrated Wi-Fi. It handles high-level logic and WebSocket communication without the need for external network modules.

Arduino UNO	Peripheral Controller	Used to offload time-critical tasks (PWM motor control and ultrasonic timing). It ensures real-time hardware responsiveness that could be interrupted by the ESP32's network overhead.
R200 UHF RFID Reader	Core Data Acquisition	Chosen for its 860-960MHz frequency range and EPC Gen2 support. It provides a reliable 3.2m–5m read range, superior to LF or HF alternatives for bulk inventory.
5dBi Ceramic Antenna	Signal Propagation	Provides an omnidirectional radiation pattern, essential for scanning tags in a 360° environment as the robot moves through library or lab aisles.
HC-SR04 Ultrasonic Sensors	Obstacle Detection	Low-cost, reliable distance measurement (2-400cm). The 15° beam angle allows for precise triggering of the obstacle avoidance algorithm in indoor settings.
L293D Motor Driver	Power Regulation for Mobility	A dual H-bridge capable of driving four DC motors. It allows for precise speed and direction control (forward, reverse, and turns) via PWM signals from the Arduino.
18650 Li-Ion Batteries	Primary Power Source	High energy density (1200mAh) and 3.7V nominal voltage. In a series configuration (7.4V), they provide the necessary voltage for the motors and the R200 reader.
LM2596 Step-Down Converter	Voltage Stabilization	Ensures a constant 5V output for the microcontrollers and sensors, protecting sensitive logic components from the voltage fluctuations of the battery discharge.

Figure 8. List of Materials

6.2 Technical Performance Results

Technical evaluations demonstrate that the prototype meets or exceeds several industry benchmarks. The **RFID Scanning Performance** achieved a maximum reliable read range of **3.2 meters**, surpassing the 2.5m standard often found in similar research. With an overall identification accuracy of **98%** and a scan rate of 45 tags per minute, the system proved highly effective in dense environments, with the debouncing algorithm successfully preventing 99.2% of potential duplicate data entries.

Navigation testing showed an **80% success rate** in obstacle detection across 200 trials, with most failures occurring only at extreme angles. The path-following accuracy was particularly precise, showing a mean waypoint deviation of only **3.8cm**. In terms of communication, the WebSocket infrastructure maintained a mean latency of **67ms**, with a 100% reconnection success rate during intermittent Wi-Fi drops. Power management results were equally positive, showing a **40% improvement** over previous prototypes, largely due to the efficient power distribution between the motors and the microcontrollers.

Table 2. Technical Performance Summary Table

Metric Category	Performance Metric	Target Value	Actual Result	Status
RFID Capabilities	Maximum Read Range	2.5 meters	3.2 meters	Exceeded
	Scanning Accuracy	≥ 95%	98.00%	Exceeded
	Throughput Rate	30 tags/min	45 tags/min	Exceeded
Navigation	Waypoint Deviation	≤ 5.0 cm	3.8 cm (Mean)	Met
	Obstacle Detection	90% Success	80% Success	Near Target
	Navigation Speed	0.20 m/s	0.25 m/s	Met
Communication	WebSocket Latency	< 100 ms	67 ms (Mean)	Met
	Reconnection Rate	100%	100%	Met
Power	Continuous Runtime	3.0 hours	4.2 hours	Exceeded
	Full Charging Time	≤ 4.0 hours	3.5 hours	Met

6.3 Quality Assurance and User Acceptance

The system underwent rigorous testing against ISO/IEC 25010 standards, achieving a **96% Functionality Coverage Rate**. Usability was a highlight, scoring **82/100** on the System Usability Scale, with users noting that they achieved proficiency with the dashboard within just 15 minutes. Security compliance reached **94%**, utilizing JWT tokens and TLS 1.3 encryption, though the absence of multi-factor authentication was noted as a minor gap. Reliability trials established a Mean Time Between Failures (MTBF) of 38 hours, while the modular design allowed for a swift Mean Time to Repair (MTTR) of only 12 minutes.

User Acceptance Testing (UAT) involved 30 faculty and IT staff members, yielding an overall satisfaction mean of **4.3/5.0**. Participants highly rated the data accuracy (4.5/5.0) and inventory workflow alignment (4.5/5.0). Qualitative feedback was overwhelmingly positive, with 93% of users preferring the robotic system over traditional manual methods. While users suggested adding joystick controls and more descriptive error

messages, the system achieved a **Net Promoter Score (NPS) of +68**, categorizing the user experience as "excellent."

Table 3. User Acceptance Testing (UAT) Results

Dimension	Category	Mean Score (1-5)	Qualitative Feedback Summary
Process Fulfillment	Functional	4.3	High alignment with asset auditing workflows.
Core Functionality	Functional	4.4	RFID scanning perceived as highly reliable.
Ease of Use	Usability	4.1	Dashboard is intuitive; 15-min learning curve.
Data Integrity	Quality	4.5	Users trust the inventory counts and timestamps.
Real-World Performance	Quality	4	Speed is adequate; obstacle handling is safe.
Security & Access	Security	4.2	Confidence in login and data privacy protocols.
Compliance	Legal	N/A	No specific local regulatory barriers found.
Compatibility	Technical	4.6	Works seamlessly across different lab devices.
UI/UX Design	Usability	4.2	Clean visual hierarchy; mobile view needs work.
Error Handling	Usability	3.9	Messages are too technical for non-IT users.
Workflow Alignment	Functional	4.3	Integrates well with current lab procedures.
End-to-End Testing	Functional	4.1	Scan-to-report process is robust.
Support & Docs	Support	3.7	Manuals need more videos/troubleshooting tips.
Bug-Free Experience	Quality	4	Only minor UI glitches reported.
Change Management	Support	4.2	Training was adequate; high adoption readiness.
Overall Satisfaction	General	4.3	93% prefer this over manual methods.

6.4 Comparative Analysis

A final comparison with existing literature and commercial benchmarks highlights the prototype's value proposition. While commercial units like **RoboScan** offer slightly higher accuracy (99%) and range (5.0m), they cost nearly 40 times more than the developed prototype. Compared to academic benchmarks like **Bandara et al. (2024)**, our system offers superior battery life and lower latency at a lower price point.

Table 4. Comparison of the Developed System with Existing Studies

Metric	Developed System	Bandara et al. (2024)	Khetani et al. (2024)	RoboScan (Commercial)
RFID Range	3.2m	2.8m	2.5m	5.0m
Accuracy	98%	95%	96%	99%
Battery Life	4.2 hrs	3.0 hrs	N/A	6.0 hrs
Latency	67ms	120ms	N/A	45ms
Cost	~$300	~$500	N/A	~$12,000
Open-Source	Yes	Partial	No	No

The results confirm that the system provides a high-performance, cost-effective alternative for institutions that require automated inventory tracking but operate within limited budgets.

7. Discussion

7.1 Interpretation of Results

The technical performance of the developed system marks a significant step forward for affordable robotics. The achievement of a **3.2m RFID read range** outperforming the 2.5–2.8m benchmarks seen in similar research is largely due to the strategic use of a 5dBi ceramic omnidirectional antenna and a stabilized 12V power supply to the R200 module. While the **98% identification accuracy** aligns with high-end UHF RFID expectations (Wang et al., 2021), the 2% error rate observed highlights the persistent challenges of signal absorption in metal-rich environments and mutual coupling in high-density tag areas.

Furthermore, the system's **4.2-hour battery life** represents a 40% improvement over the figures reported by Bandara et al. (2024). This was achieved through aggressive PWM optimization for motor control and the implementation of "on-demand" RFID scanning cycles rather than continuous broadcasting. While the 80% obstacle avoidance success rate is functional for campus hallways, the failures at extreme angles suggest that future iterations should move toward **LiDAR integration** to eliminate the 90° blind spots inherent in ultrasonic sensor arrays.

7.2 User Acceptance and Communication

The selection of the **WebSocket protocol** was vindicated by the results, maintaining a latency of under 100ms in 99.5% of operations. This provided a far more responsive experience than traditional HTTP polling, which often suffers from high overhead and unidirectional data flow.

From a user perspective, the system's greatest strength was the confidence it instilled in data accuracy, which received a **4.5/5.0 rating**. Faculty and IT staff noted that the system "streamlined asset audits significantly," though they did identify a need for better error messaging. Technical jargon in system alerts proved confusing for non-IT personnel, suggesting that future software updates should focus on more descriptive, user-friendly troubleshooting guides.

7.3 Cost-Effectiveness and ROI

The most compelling argument for the developed system is its extreme cost-effectiveness. With total hardware costs at approximately **$260** and a total project cost of **$405**, the system represents a **96.7% reduction in cost** compared to commercial alternatives like RoboScan. For an institution like Centro Escolar University, where manual inventory currently costs an estimated $6,240 annually in labor, the system offers a **payback period of less than one month**. Over five years, the university stands to save over $30,000, illustrating that high-performance automation does not require a commercial-grade budget.

7.4 Scalability and Alignment with Literature

The study confirms the long-held industry belief that UHF RFID is superior to barcodes for bulk scanning (Krishnakumar et al., 2023), but it adds a novel contribution by proving that **open-source platforms like the ESP32 and Arduino** can handle industrial-level IoT tasks. While previous literature often identified cost as a primary barrier to entry (Bandara et al., 2024), this research provides a replicable blueprint to eliminate that barrier.

The system is highly scalable; the tested WebSocket server can handle over 50 concurrent robot connections, making it suitable for larger institutions that may require a fleet of robots for different zones. While current limitations such as the lack of stair-climbing capabilities and a reliance on pre-mapped environments remain, the prototype serves as a robust proof-of-concept for the viability of autonomous, low-cost asset tracking in the educational sector.

8. Conclusion

8.1 Summary of Findings

This study successfully developed and validated a cost-effective, autonomous 4-wheeled robot that bridges the gap between manual inventory labor and expensive commercial automation. The system demonstrated **technical excellence** by achieving a 98% RFID identification accuracy at a 3.2-meter range, surpassing the 2.5m industry average. Its operational reliability was further confirmed by an 80% obstacle avoidance success rate and a 4.2-hour battery lifemarking a 40% improvement over comparable academic models.

The prototype resonated strongly with end-users, earning an **overall satisfaction rating of 4.3/5.0**. Most notably, 93% of participants expressed a preference for the robotic system over traditional methods, resulting in an excellent Net Promoter Score of +68. From a fiscal perspective, the project achieved a **97% cost reduction** compared to commercial alternatives. With a total hardware cost of roughly $300 and a projected ROI payback period of less than one month, the system proves to be a financially transformative tool for resource-constrained institutions.

8.2 Research Contributions and RQ Answers

This research provides significant theoretical and practical contributions by establishing a replicable blueprint for open-source institutional IoT. It validates the use of a **hierarchical dual-controller architecture** (ESP32 and Arduino) as a high-performance, low-cost solution for autonomous systems.

The study successfully answered all research questions: identifying critical gaps in the market ***(RQ1)***, selecting

and optimizing the necessary hardware configuration for a 4+ hour runtime ***(RQ2 & RQ3)***, and validating the algorithms for navigation and real-time WebSocket communication ***(RQ4)***. The technical performance ***(RQ5)*** and user acceptance ***(RQ6)*** results confirm that the prototype is not only a functional success but also a highly desirable replacement for manual asset auditing.

9. Recommendations

9.1 For System Enhancement

To elevate the prototype from a research model to a sophisticated enterprise tool, several technical upgrades are recommended. Integrating **LiDAR or depth cameras** would provide 360° obstacle detection and enable Simultaneous Localization and Mapping (SLAM) for more fluid autonomous path planning. On the RFID front, testing dual-antenna configurations and implementing adaptive power control could further optimize the balance between scanning range and battery longevity.

Software features should be expanded to include an **automated scheduling module** for "patrol missions" and predictive maintenance alerts. To improve the user experience, error messages should be redesigned in plain language, and the documentation suite should be bolstered with interactive video tutorials to lower the learning curve for non-technical staff.

9.2 For Research Extension and Institutional Adoption

Future research should focus on **longitudinal studies** (6–12 months) to assess the long-term reliability of the hardware in diverse institutional environments such as healthcare or manufacturing. Additionally, exploring **multi-robot coordination strategies** would be beneficial for larger facilities requiring synchronized fleet management.

For institutions looking to adopt this technology, a **three-phase roadmap** is suggested:

1. **Pilot-** Deploy a single unit in a high-value asset zone.
2. **Expansion-** Add robots to additional departments based on pilot success.
3. **Optimization-**Fully integrate the system with enterprise ERPs (like SAP or Oracle) to automate high-level financial reporting.

9.3 For the Academic and Global Community

We recommend that the complete hardware designs and firmware be released as an **open-source project on GitHub**. This would allow the global academic community to build upon this work, fostering collaboration and the development of educational modules for robotics and IoT curricula. Finally, looking toward future technology directions, integrating **AI-driven computer vision** for item recognition and **Blockchain** for tamper-proof audit trails could position this system at the forefront of the next generation of institutional resource management.

Video Presentation Links:
Robot Dashboard:
https://tinyurl.com/muzxsn99
Trial Testing video:

https://tinyurl.com/7jkva5ca

10. REFERENCES

[1] Baballe, M. (2021). RFID technology as an alternative to barcode systems. *Journal of Technology Innovation*, *5*(2), 45-58.

[2] Bandara, I., Simpson, O., & Sun, Y. (2024). Optimizing efficiency using a low cost inventory RFID-based management system. In *Proceedings of the International Wireless Communications and Mobile Computing Conference* (pp. 1729-1733). IEEE.

[3] Becerra, P., Mula, J., & Sanchis, R. (2022). Sustainable inventory management in supply chains: Trends and further research. *Sustainability*, *14*(5), 2613. https://doi.org/10.3390/su14052613

[4] Beontag. (2025). *HF vs UHF RFID explained: Differences and applications*. https://beontag.com/solutions/rfid-technology

[5] Bernardini, F., Buffi, A., Fontanelli, D., Macii, D., Magnago, V., Marracci, M., Motroni, A., Nepa, P., & Tellini, B. (2020). Robot-based indoor positioning of UHF-RFID tags: The SAR method with multiple trajectories. *IEEE Transactions on Instrumentation and Measurement*, *70*, 1-15. https://doi.org/10.1109/TIM.2020.3033728

[6] Bi, Z., & Kocak, S. (2020). *Introduction to industrial robotics*. CRC Press.

[7] Buettner, M., Prasad, R., Philipose, M., & Wetherall, D. (2020). Recognizing daily activities with RFID-based sensors. In *Proceedings of the ACM International Joint Conference on Pervasive and Ubiquitous Computing* (pp. 51-60). ACM.

[8] Chawla, V., & Ha, D. S. (2007). An overview of RFID system. *IEEE Communications Magazine*, 45(9), 11-17.

[9] Chen, Y., Zhang, Y., & Li, X. (2020). Machine learning approaches for asset movement prediction in indoor tracking systems. *IEEE Access*, *8*, 134567-134578. https://doi.org/10.1109/ACCESS.2020.3011234

[10] Duan, H., Wang, J., & Liu, P. (2021). Automated response protocols in real-time monitoring systems. *Automation in Construction*, *123*, 103511. https://doi.org/10.1016/j.autcon.2020.103511

[11] Dutta, S. (2023). IoT-based multi-parameter monitoring systems: Architecture and applications. *Internet of Things*, *21*, 100658. https://doi.org/10.1016/j.iot.2022.100658

[12] Erlangga, S. B., Yunita, A., & Satriana, S. R. (2022). Development of automatic real time inventory monitoring RFID system using technology in warehouse. *International Journal on Informatics Visualization*, *6*(3), 632-637. https://doi.org/10.30630/joiv.6.3.1034

[13] Fjodorov, P., Kunicina, N., & Patlins, A. (2024). Smart inventory management systems with automation capabilities. *Procedia Computer Science*, *231*, 456-461.

[14] Husak, M., Bures, M., & Ahmed, B. S. (2023). IoT tracking efficiency in asset management. *Sensors*, *23*(8), 3892. https://doi.org/10.3390/s23083892

[15] International Organization for Standardization. (2011). *Systems and software engineering Systems and software Quality Requirements and Evaluation (SQuaRE) System and software quality models* (ISO/IEC 25010:2011).

[16] Jadhav, S., et al. (2024). Healthcare asset tracking: Enhancing patient safety through RFID. *Medical Systems Review*, 18(1), 77-89.

[17] Jadhav, S., Sharma, R., & Patel, K. (2024). RFID applications in healthcare asset tracking. *Health Informatics Journal*, *30*(1), e14567.

[18] Jiang, C., He, Y., Zheng, S., & Cao, Y. (2020). Indoor positioning based on UHF RFID. *IEEE Access*, *8*, 44567-44578.

[19] Kasim, H., Abdullah, S., & Hassan, R. (2024). Real-time equipment lifecycle management through IoT. *Journal of Industrial Engineering and Management*, *17*(1), 89-103.

[20] Kaur, M., Sandhu, M., Mohan, N., & Sandhu, P. S. (2011). RFID technology: Principles, advantages, limitations and its applications. *International Journal of Computer and Electrical Engineering*, 3(1), 151-157.

[21] Khatib, E., Abualhaj, M., & Abu-Shareha, A. (2024). IoT operational efficiency in tracking systems. *International Journal of Advanced Computer Science and Applications*, *15*(2), 234-242.

[22] Khetani, V., Patel, Y., & Shah, M. (2024). Predictive maintenance in laboratory environments. *Laboratory Automation & Information Management*, *60*(2), 78-89.

[23] Krishnakumar, P., et al. (2023). Supply chain efficiency: RFID vs. barcode systems in retail logistics. *Journal of Logistics Management*, 19(2), 112-128.

[24] Krishnakumar, S., Manian, R., & Dhanapal, R. (2023). RFID applications in supply chain and logistics. *Materials Today: Proceedings*, *72*, 2893-2898.

[25] Kumar, A., Tatwani, S., & Choudhury, A. (2021). Real-time inventory management using Hadoop: A data-driven approach. In *Proceedings of the Conference on Disruptive Technologies* (pp. 145-152). Springer.

[26] Kumar, S., DeGroot, R. A., & Choe, D. (2013). Complexity of RFID adoption in supply chains: Experience from SMEs. *Industrial Management & Data Systems*, *113*(7), 1041-1057.

[27] Kumar, S., et al. (2021). The evolution of inventory management: From manual to digital. *Journal of Supply Chain Management*, 15(3), 45-58.

[28] Liang, X., Zhang, H., & Wang, T. (2019). Comprehensive monitoring solutions integrating RFID with sensing technologies. *Sensors*, *19*(18), 3845.

[29] Ma, Z., Chen, Y., & Li, F. (2020). Synergistic effects of integrating RFID with smart inventory systems. *Computers in Industry*, *118*, 103214.

[30] Mashayekhy, Y., Babaei, A., Yuan, X.-M., & Xue, A. (2022). Impact of Internet of Things (IoT) on inventory management: A literature survey. *Logistics*, *6*(2), 33. https://doi.org/10.3390/logistics6020033

[31] Mishra, R., Kumar, P., & Singh, A. (2023). Integrated asset management ecosystems using IoT. *Journal of Enterprise Information Management*, *36*(4), 1123-1145.

[32] Mohamed, A., Ali, S., & Ibrahim, M. (2023). Integrated laboratory management systems: Real-world implementations. *Educational Technology Research and Development*, *71*(2), 567-589.

[33] Motroni, A., Buffi, A., Nepa, P., & Tellini, B. (2020). UHF-RFID for indoor positioning: A review. *IEEE Transactions on Instrumentation and Measurement*, *70*, 1-14.

[34] Motroni, A., et al. (2021). Sensor fusion for indoor autonomous navigation. *IEEE Transactions on Instrumentation and Measurement*, 70, 1-12.

[35] Natarajan, R., Subramanian, K., & Ramesh, P. (2024). RFID security implementations in institutional settings. *Computers & Security*, *138*, 103645.

[36] Nisa, K., Rahman, A., & Hassan, S. (2024). Real-time monitoring and unauthorized access prevention using RFID. *Security and Communication Networks*, *2024*, Article 5567234.

[37] Pethe, S., et al. (2024). Smart campus initiatives: A review of IoT applications in higher education. *International Journal of Smart Education and Urban Learning*, 11(1), 45-60.

[38] Pethe, S., Sahu, A., Kodarlikar, S., & Vamshidhar, M. (2024). IoT research in supply chain management and logistics: Real-time asset tracking and inventory management. In *Proceedings of the International Conference on Innovations and Challenges in Emerging Technologies* (pp. 1-5). IEEE. https://doi.org/10.1109/ICICET54418.2024.10561315

[39] Raptopoulos, F., Koutras, D., & Papadopoulos, G. (2019). Managing hundreds of RFID-tagged items in indoor environments. *Pervasive and Mobile Computing*, *58*, 101034.

[40] Reddy, M., Sharma, V., & Gupta, A. (2024). System scalability in large-scale IoT deployments. *IEEE Internet of Things Journal*, *11*(5), 8234-8245.

[41] Rodrigues, M., Silva, A., & Costa, J. (2023). RFID in routine maintenance tasks: Benefits and challenges. *Maintenance and Reliability*, *25*(3), 456-468.

[42] Rohei, F., Moscheini, M., & Papagiannakis, G. (2019). Centimeter accuracy indoor localization using RFID. *Journal of Location Based Services*, *13*(3), 167-189.

[43] Rubio, F., Valero, F., & Llopis-Albert, C. (2019). A review of mobile robots: Concepts, methods, theoretical framework, and applications. *International Journal of Advanced Robotic Systems*, 16(2), 1-22.

[44] Sakib, N., Hossain, E., & Ahad, M. A. R. (2022). IoT-based inventory management: Challenges and opportunities. *IEEE Access*, *10*, 34567-34578.

[45] Sasikanth, A., Vamsi, P., & Ravi, K. (2024). Automated laboratory management in educational institutions. *International Journal of Engineering Education*, *40*(2), 345-358.

[46] Shelake, V., Patel, S., & Deshmukh, R. (2024). Integrated tracking systems in research environments. *Research Policy*, *53*(4), 104712.

[47] Sikkandhar, M., Lim, R., Damalerio, R. B., Toh, W. D., & Cheng, M.-Y. (2023). Conductive polymer-based interactive shelving system for real-time inventory management. *Sensors*, *23*(21), 8857. https://doi.org/10.3390/s23218857

[48] Silver, E. A. (1981). Operations research in inventory management: A review and critique. *Operations Research*, *29*(4), 628-645.

[49] Singh, R. (2024). Modern IoT architectures for real-time asset tracking. *International Journal of Computer Applications*, 185(12), 1-9.

[50] Singh, R. (2024). Multi-dimensional IoT monitoring: Architecture and implementation. *IEEE Sensors Journal*, *24*(8), 12345-12356.

[51] Tripathi, A., Kumar, N., & Srivastava, P. (2024). Implementation challenges of IoT systems in SMEs. *Journal of Small Business Management*, *62*(2), 567-589.

[52] Wang, J., Liu, Y., & Chen, Z. (2020). RFID in retail: Automated checkout and personalized shopping. *Journal of Retailing and Consumer Services*, *57*, 102234.

[53] Wang, L., et al. (2021). Accuracy benchmarks for UHF RFID in institutional settings. *Journal of Radio Frequency Identification*, 5(2), 201-215.

[54] Wang, T., Zhao, X., & Li, W. (2021). RFID technology versatility in tracking applications. *Wireless Communications and Mobile Computing*, *2021*, Article 9921456.

[55] Wu, Y., & Lu, H. (2022). Machine learning for autonomic inventory handling. *Expert Systems with Applications*, *201*, 117185.

[56] Xin, Y., Zhang, L., & Wang, H. (2020). Equipment performance analysis using real-time monitoring data. *Journal of Manufacturing Systems*, *56*, 234-245.

[57] Yadav, A., et al. (2024). AI and predictive analytics in inventory optimization. *Journal of Industrial Engineering*, 21(1), 33-47.

[58] Yadav, S., Singh, R., & Kumar, V. (2024). AI-powered demand forecasting in inventory management. *International Journal of Production Economics*, *268*, 109089.

[59] Zelbst, P. J., Green, K. W., Sower, V. E., & Bond, P. L. (2019). RFID-based security systems: Implementation and effectiveness. *International Journal of Physical Distribution & Logistics Management*, *49*(8), 888-904.

[60] Zhang, H., Wang, Y., & Li, J. (2020). Multi-parameter equipment tracking in industrial environments. *IEEE Transactions on Industrial Informatics*, *16*(6), 4123-4132.