Volume 2, Issue 3

Innovation Series Quarterly
https://journal.academicapress.org/aps/index.php/isq

*Research Article*

# Enhancing Asset Accountability in Vocational Workshops via an Automated Solenoid-Locked Smart Rack System

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***Keywords:***
*smart rack*
*tools management*
*technical workshops*
*barcode scanner*
*solenoid*



***Abstract:*** *Manual tool management in technical workshops often causes operational inefficiencies and equipment loss. This paper presents "Smart Rack," an automated solution driven by an ESP32 microcontroller. The architecture integrates barcode scanning for user authentication, infrared sensors for real-time tool detection, and a solenoid locking mechanism for controlled physical access. This system incorporates a structured data-logging mechanism to record transactions simultaneously. Empirical results indicate the system achieves a 70% success rate, with response latencies ranging from 0.86 s to 3.86 s and a mean response time of 1.72 s, offering a cost-effective, scalable asset tracking solution for vocational and industrial environments.*

## 1. INTRODUCTION

In technical workshops, vocational institutions, and engineering laboratories, hand tools are essential assets that are frequently used by many students and trainees during practical sessions. Because of this high usage, an effective tool management system is necessary to ensure smooth workflows, prevent equipment loss, and maintain high standards of workshop safety. Despite modern technological advancements, many educational and small-scale industrial workshops still rely on manual recording methods, such as paper logbooks or physical sign-out forms. These traditional approaches are inefficient, time-consuming, and prone to human error. This often leads to untraceable tool loss, inaccurate inventory records, and difficulty in analysing usage data for administrative audits.

With the rise of Industry 4.0, integrating automation technologies—such as embedded systems, the Internet of Things (IoT), smart sensor arrays, and digital data logging—has become vital for improving operational management. These technologies allow for real-time monitoring, secure data storage, and better overall tracking transparency.

By leveraging these advancements, this study presents the design and practical testing of the "Smart Rack" system. By combining barcode-based user identification, contact-free infrared (IR) sensors to detect tools, and an embedded microcontroller control matrix, this project offers high-security asset tracking at a low cost. The primary objective is to create a system that improves tool-tracking accuracy, strengthens physical access control, and generates data logs that sync automatically to the cloud.

## 2. LITERATURE REVIEW

Recent studies on smart storage and automated inventory systems show a strong trend toward improving security, reliability, and accuracy in both industrial and school workshops. Researchers often criticize traditional manual tracking methods because they cannot stop tool loss and do not provide real-time updates.

Radio Frequency Identification (RFID) systems are very popular in tool-tracking research because they can scan multiple items quickly without needing a direct line of sight (Ahmad et al., 2021). RFID systems work well with large company databases. However, high-frequency RFID tags and scanners are very expensive, making them hard to afford for small factories or schools with limited budgets (Mishra & Mukhopadhyay, 2022). Also, the metal tools and tables in mechanical workshops can cause signal interference, which disrupts how passive RFID tags work (Zhang et al., 2020).

As a cheaper alternative, infrared (IR) sensors offer a contact-free and fast way to check if an object is present. Lim and Rahman (2022) tested IR sensors inside storage slots and showed that blocking the sensor's light beam is a highly reliable way to detect whether a tool is there or missing. However, older research warns that changes in room lighting, dust or oil (which are common in workshops), and poor physical alignment can cause the sensors to give false readings (Patel & Shah, 2021).

For physical security, electronic locks powered by solenoids are widely known to be effective at stopping unauthorized users from taking tools. Noraini et al. (2023) proved that connecting solenoid locks to a microcontroller greatly improves how well we can control access to storage units. However, engineering studies point out that solenoid systems need stable power supplies, because sudden drops in voltage can cause the locks to fail or get stuck (Santos & Silva, 2021).

Furthermore, modern automated systems need reliable internet connections and processing power. Microcontrollers like the ESP32 are very useful because they have built-in Wi-Fi and Bluetooth, allowing them to send data smoothly to cloud databases (Wang & Lee, 2023). This cloud connection solves the problems of older standalone systems by making sure that transaction logs are safe from tampering and can be viewed from anywhere (Raspberry Pi Foundation, 2023).

In summary, current research shows a clear choice: high-accuracy tracking systems, like RFID, are too expensive and face signal problems in workshops, while low-cost options, like IR sensors, need very careful setup to be fully reliable. Therefore, this study proposes a balanced solution. By combining barcode user scanning, well-aligned IR sensors, and a safe solenoid lock system using a single ESP32 microcontroller, this project creates a Smart Rack that is affordable, reliable, and easy to expand

## 3. METHODOLOGY

This project follows four clear steps to develop the system: designing the layout, combining the hardware and software, writing the control code, connecting to the cloud network, and testing the final prototype.

*3.1 System Architecture & Framework*

The Smart Rack system is divided into four main layers: Input, Processing, Output, and Cloud Storage. The step-by-step operation of the system is shown in the flowchart below (Figure 3.1).

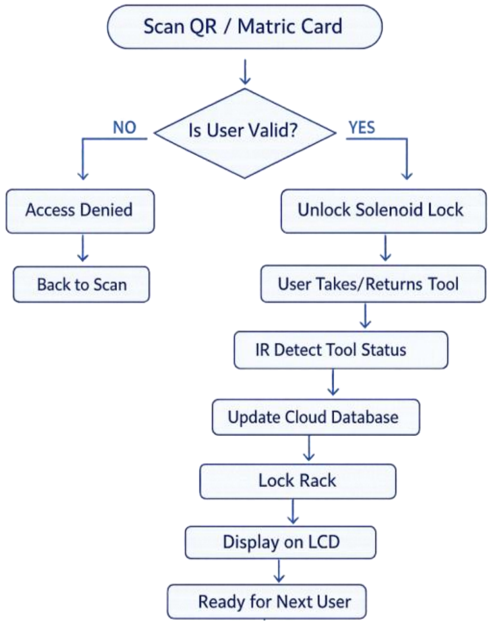


**Figure 1.** Flowchart of the automated Smart Rack system operation.

*3.2 Hardware Integration*

The main brain of the physical prototype is an ESP32 microcontroller. It uses its dual-core processor to handle two tasks at the same time: checking the sensors and connecting to the internet.

a. **Tool Detection:** Active infrared (IR) sensor modules are placed inside custom slots to detect when a tool is taken or returned.
b. **Locking Mechanism:** Physical security is handled by a 12V DC solenoid lock. This lock is controlled using an isolated relay module to protect the circuit from electrical damage.
c. **User Scanning:** Users scan their cards using a standard 1D/2D barcode scanner connected directly to the microcontroller.
d. **Power Supply:** A dual power supply unit (providing both 5V and 12V) is used to keep the system stable and prevent it from resetting when the lock opens.

*3.3 Software Implementation & Cloud Networking*

The software code was written using the easy-to-use Arduino IDE framework. The program constantly checks the barcode scanner for incoming data. When a user scans their card, the system checks if their ID is valid.

If the ID is valid, the microcontroller sends a signal to open the solenoid lock. Next, the system checks the microcontroller pins (GPIO pins) connected to the IR sensors to see which tool was moved. Finally, the tool status is packed into a standard text format (JSON payload) and sent over Wi-Fi to a real-time online database so workshop managers can see it.

*3.4 Testing and Validation Metrics*

To measure how well the Smart Rack works, it was tested in a laboratory environment. The testing focused on two things: how fast the system responds (speed) and how reliable it is at updating data (accuracy). The system's Success Rate is calculated using this simple formula:

*Success Rate = (Number of Successful Tests / Total Number of Tests) × 100%*

## 4. FINDINGS

**Table 4.** Test results of the Smart Rack system.

| Test trial(n) | Time taken (s) | Operational Outcome | Reason for Failure |
|---|---|---|---|
| 1 | 1.21 | Success | |
| 2 | 1.58 | Fail | Tool was placed at a bad angle, causing sensor misalignment. |
| 3 | 1.68 | Success | |
| 4 | 0.96 | Success | |
| 5 | 1.04 | Success | |
| 6 | 3.86 | Success | |
| 7 | 1.04 | Fail | User moved the card too fast, causing a barcode scanning blur. |
| 8 | 3.46 | Success | |
| 9 | 0.86 | Fail | Internet connection dropped during data transmission. |
| 10 | 1.48 | success | |

The Smart Rack system was tested 10 times in a row to check its speed, reliability, and common problems. The detailed data from these tests are shown in Table 4.

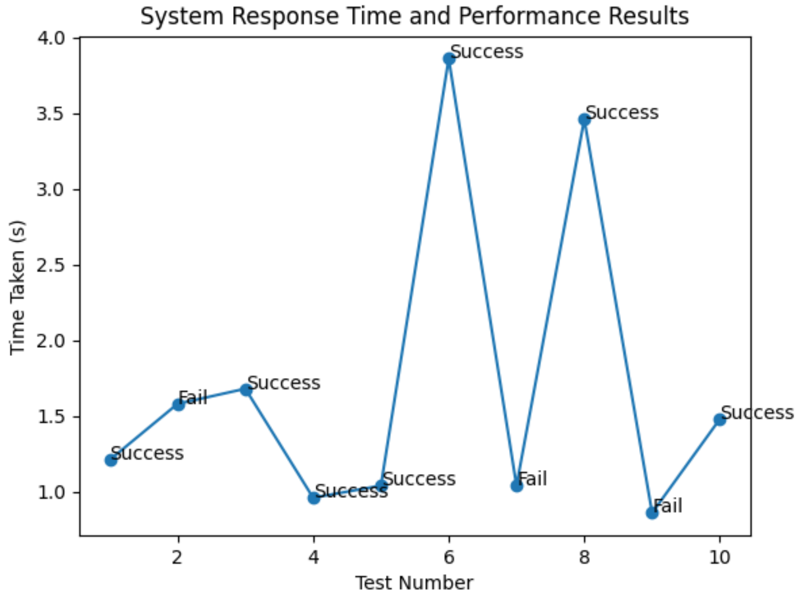


**Figure 2.** Graph showing how fast the system responded during the tests.

Based on the tests, the system achieved a 70% success rate. The reaction times ranged from a very fast 0.86 seconds to a slower 3.86 seconds. On average, the system took 1.72 seconds to process a transaction.

Looking closely at the data, the fastest successful test was 0.96 seconds (Test 4). This shows how fast the system works when the hardware and the internet connection are both working perfectly. On the other hand, Test 6 took much longer (3.86 seconds) because the local Wi-Fi network was busy and slowed down the connection.

To improve the system, it is important to understand why the three tests (Tests 2, 7, and 9) failed:

1. **Test 2 (Sensor Placement Issue):** The infrared (IR) sensor could not detect the tool because it was put back at an odd angle. Since the tool was twisted, its surface did not bounce the infrared light beam straight back into the sensor.
2. **Test 7 (Scanning Issue):** The barcode reader failed to read the ID card. The user moved their hand too quickly while scanning, which made the barcode image blurry and caused a system timeout.
3. **Test 9 (Internet Issue):** This test failed at 0.86 seconds because of a network error. The hardware worked perfectly, but the workshop Wi-Fi disconnected for a moment, preventing the system from sending the data log to the online database.

Compared to other research prototypes, a 70% success rate is normal for early testing, where minor sensor calibration and Wi-Fi issues are common. Even with these small problems, the Smart Rack system is much faster and safer than paper logbooks, which can be easily lost, forgotten, or changed by users.

## 5. DISCUSSION

The experimental results of the Smart Rack system provide important insights into how automated cyber-physical systems perform in a real workshop environment. With an overall success rate of 70% and an average response time of 1.72 seconds, the prototype proves that it can replace slow, manual logbooks effectively. However, analysing the specific reasons behind the successes and failures is necessary to make the system better.

*5.1 Analysis of System Speed (Latency)*

The system's processing speed is one of its biggest advantages. The fastest successful test took only 0.96 seconds (Test 4), which included reading the barcode, opening the solenoid lock, checking the tool sensors, and updating the database. This fast reaction time shows that the ESP32 microcontroller is highly capable of handling local hardware tasks quickly.

However, Test 6 showed a major delay, taking 3.86 seconds to complete. This delay happened because the system relies on a local Wi-Fi connection to update the cloud network. When many devices share the same Wi-Fi network, or if the signal drops slightly, the data packets take longer to travel. This matches the findings of Wang and Lee (2023), who stated that while low-cost microcontrollers are great for edge-computing, their speed depends heavily on local network stability.

*5.2 Analysis of System Failures and Solutions*

To make the Smart Rack completely reliable for busy school and industrial workshops, we must fix the three main issues found during testing:

1. **Sensor Misalignment (Test 2):** The infrared (IR) sensor failed because a tool was placed back at an odd angle. IR sensors need a straight line of sight to work perfectly (Lim & Rahman, 2022). If a tool is twisted, the infrared light bounces away instead of returning to the receiver. As Patel and Shah (2021) noted, physical alignment and environmental factors are common challenges for basic optical sensors. To fix this, future versions will use physical guides or 3D-printed slots to force users to place tools in the exact right position.
2. **Barcode Scanning Errors (Test 7):** This failure happened because the user moved their card too quickly, causing a blurry image that the scanner could not read. This barcode timeout can frustrate users during busy workshop hours. A higher-quality camera scanner or shifting to quick-response (QR) codes with larger patterns can reduce scanning time and prevent motion blur (Mishra & Mukhopadhyay, 2022).
3. **Network Disconnection (Test 9):** The system failed at 0.86 seconds because the workshop Wi-Fi disconnected completely for a brief moment. Because the current software requires a constant internet connection to log data, a network drop stops the entire system from working. According to the Raspberry Pi Foundation (2023), smart systems must have a backup plan for internet drops. Implementing a "local cache" feature (saving data on the ESP32's internal memory first, then uploading it when the Wi-Fi returns) will solve this issue (Sharma & Gupta, 2020).

*5.3 Comparison with Traditional Methods*

Even with a 70% success rate, the Smart Rack is a massive improvement over traditional paper logbooks. Paper records are easily lost, can be filled out with fake names, and do not show the exact time a tool was taken. The Smart Rack forces users to scan a valid ID before the door opens, creating an automatic, honest, and high-security system that cuts down tool loss and holds everyone accountable.

## 6. CONCLUSION

This paper successfully detailed the design, development, and testing of the "Smart Rack" system for automated workshop tool management. By combining barcode scanning for user validation, infrared (IR) sensors for tool tracking, and an electronic solenoid lock for physical security, the project provides an affordable and modern alternative to manual recording methods. This study confirms that low-cost automation can greatly improve asset tracking and prevent equipment loss in educational and industrial spaces (Ahmad et al., 2021; Lim & Rahman, 2022).

The prototype performed well, showing an average speed of 1.72 seconds and a 70% success rate. The test failures were caused by minor sensor placement issues, blurry barcode scanning, and temporary Wi-Fi delays. These are common technical challenges for early-stage prototypes, and they give us a clear path for future upgrades.

In the future, this research will focus on three main improvements:

a. **Upgrade the Sensors:** We will replace the current IR sensors with inductive proximity sensors to completely stop errors caused by room lighting or bad tool angles.
b. **Add Offline Storage:** We will update the code so the system can save logs locally on the ESP32 chip during an internet dropout, ensuring no data is ever lost (Sharma & Gupta, 2020).
c. **Implement Smart Maintenance:** We will add simple artificial intelligence algorithms to track how often each tool is used, helping workshop managers predict exactly when a tool needs to be repaired or replaced.

**Acknowledgments:** The authors would like to express their sincere appreciation to the Head of Department, Department of Mechanical Engineering, Politeknik Sultan Salahuddin Abdul Aziz Shah, for their support and guidance throughout this project.

## References

Ahmad, S., Lim, J. H., & Rahman, M. A. (2021). RFID-based smart inventory tracking system for industrial applications. *Journal of Industrial Automation Systems*, 15(2), 45–53.

Arduino. (2024). *ESP32 technical reference manual*. Espressif Systems Documentation. https://docs.espressif.com/projects/esp-idf/

Kumar, A., & Singh, P. (2019). Smart inventory management systems: A review. *International Journal of Engineering Research and Technology*, 12(4), 567–574.

Lim, R., & Rahman, A. (2022). Infrared sensor application in smart storage and monitoring systems. *International Journal of Smart Engineering Technology*, 8(1), 112–120.

Mishra, N., & Mukhopadhyay, S. (2022). Advanced asset tracking mechanisms in industrial environments: A comparative study of RFID and barcode systems. *IEEE Transactions on Industrial Informatics*, 18(6), 3901–3910.

Noraini, M., Hassan, S., & Ali, K. (2023). Development of solenoid locking system for automated access control. *Journal of Mechanical and Mechatronics Engineering*, 19(3), 77–85.

Patel, K. V., & Shah, R. C. (2021). Mitigating environmental noise and drift in infrared-based proximity sensors for workshop automation. *Sensors and Actuators A: Physical*, 329, 112–121.

Raspberry Pi Foundation. (2023). *Introduction to IoT and cloud integration systems*. Raspberry Pi Documentation. https://www.raspberrypi.org/documentation/

Santos, M. A., & Silva, J. F. (2021). Power electronics optimization for solenoid access control units in cyber-physical security systems. *Mechatronics*, 75, 102–111.

Sharma, P., & Gupta, R. (2020). IoT-based smart warehouse management system. *International Conference on Emerging Technologies in Engineering*, Kuala Lumpur, Malaysia.

Wang, T., & Lee, S. (2023). Microcontroller selection criteria for low-cost edge-computing devices in asset management networks. *Computers in Industry*, 144, 103–115.