Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 2	Month	: April
p-ISSN	: 1693-5462	Volume	: 24	Year	: 2026

Processing dates: received on 2025-10-13, reviewed on 2025-12-15, accepted on 2025-12-31 and online availability on 2026-04-25

A laboratory-scale 3-axis automated storage and retrieval system prototype for electronic component management

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Abstract

Efficient storage and retrieval of electronic components remain challenging in laboratory-scale environments due to reliance on manual handling. This study presents the development and experimental evaluation of a laboratory-scale three-axis Automated Storage and Retrieval System (ASRS) prototype designed for electronic component management. The proposed system uses a combination of servo and stepper motors to provide controlled motion along the X, Y, and Z axes. It is managed by a Programmable Logic Controller (PLC) integrated with a Human–Machine Interface (HMI). Manual operation is used for system calibration and motion adjustment, while automatic operation facilitates sequential storage and retrieval processes. We evaluated the system's performance by measuring positional accuracy and deviation at multiple target rack locations. The results show that the system achieves positioning accuracy of 84.62% - 95.38%, with absolute deviations between 0.3 and 1 cm. These findings demonstrate that the ASRS prototype is a feasible solution for effective laboratory-scale automation in storage applications and for PLC-based educational purposes.

Keywords:
ASRS, PLC, HMI, servo motor, stepper motor

1 Introduction

The development of automation technology in the era of Industry 4.0 and Society 5.0 has significantly improved efficiency, accuracy, and sustainability in logistics and manufacturing systems. One key automation technology in material handling and inventory management is the Automated Storage and Retrieval System (ASRS). This system enhances storage accuracy, reduces operational errors, and optimizes space utilization. Furthermore, several review studies have summarized ASRS architectures, control strategies, and performance characteristics across various industrial applications.

ASRS has been widely implemented in various industrial sectors, including automotive, electronics, and pharmaceuticals, and continues to evolve through modern configurations such as shuttle-based systems and multi-axis gantry mechanisms [7], [8], [10], [25]. These configurations are designed to improve positioning accuracy and reduce operational cycle time, including optimization of ASRS travel time [3], [6], [10], [14], [23]. Travel time analysis and motion characteristics of ASRS have also been a long-standing research focus in the design and performance evaluation of automated storage systems [9], [24].

Several studies have reported the development of laboratory-scale and miniature ASRS prototypes. These compact systems effectively demonstrate fundamental automation and positioning principles while requiring less space and cost [30]. Such advancements allow for the application of automated storage systems in laboratory and educational settings.

In recent years, ASRS has also been used as a learning and training platform for automation, particularly in vocational education and engineering laboratories. Utilizing ASRS in education provides students with hands-on experience in PLC programming, motion control, and the integration of mechanical systems with Human–Machine Interfaces (HMI) [14], [20], [28]. This underscores the importance of ASRS as a practical tool for teaching industrial automation.

In general, an ASRS consists of mechanical subsystems integrated with a Programmable Logic Controller (PLC) and an HMI. The PLC executes control logic and coordinates motion, while the HMI provides real-time monitoring and system control [12], [13], [15]-[17]. Integration of PLC and HMI with servo and stepper motors has been reported to enhance system precision and operational reliability [11], [18], [19]. However, recent ASRS developments incorporating Internet of Things (IoT), intelligent connectivity, and artificial intelligence are predominantly focused on large-scale industrial applications, leading to increased system complexity and implementation costs [21], [22], [26], [27].

Based on the above review, there remains a research gap related to the development of simple and easily implementable laboratory-scale ASRS that are equipped with quantitative positioning performance evaluation, particularly for electronic component management. This gap is significant for vocational education institutions and laboratory learning environments that require practical automation systems without excessive complexity.

This study aims to develop a three-axis ASRS prototype on a laboratory scale, integrated with PLC and HMI technologies. The main contribution of this research is to provide a practical automation platform for managing electronic components. Additionally, it serves as an effective learning tool for PLC-based industrial automation education.

2 Research methodology

2.1 System overview and block diagram

The 3-Axis ASRS is designed using a gantry-type configuration comprising X, Y, and Z axes, enabling automatic and precise storage and retrieval of electronic components from multi-level racks (Fig. 1). The X-axis is actuated by a 400 W Delta ASDA-B2 servo motor for fast and precise horizontal motion, while the Y- and Z-axes are driven by two NEMA-17 stepper motors using TB6600 drivers. The integration of these motor drivers and control components within the system wiring configuration is presented in Fig. 2.

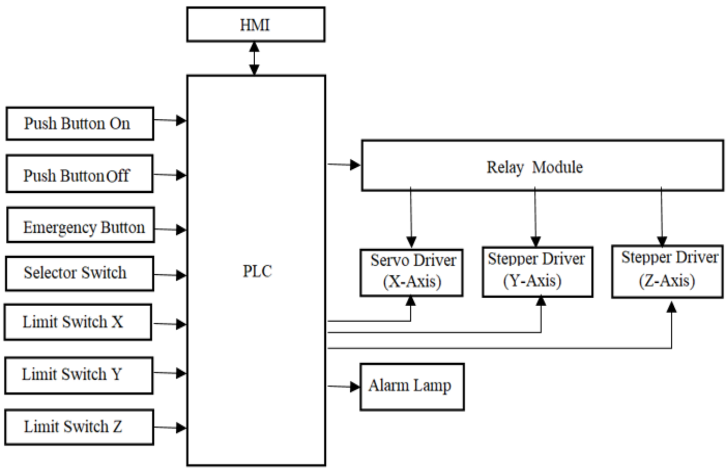


Fig. 1. Block diagram of the 3-axis ASRS for electronic component management

An Omron CP1E-N30DT-A PLC serves as the main controller that manages operational sequences and motion logic. A 7-inch Omron NB7W-TW00B HMI provides a user-friendly interface that displays position coordinates, system status, and control commands via Modbus RS-232 communication.

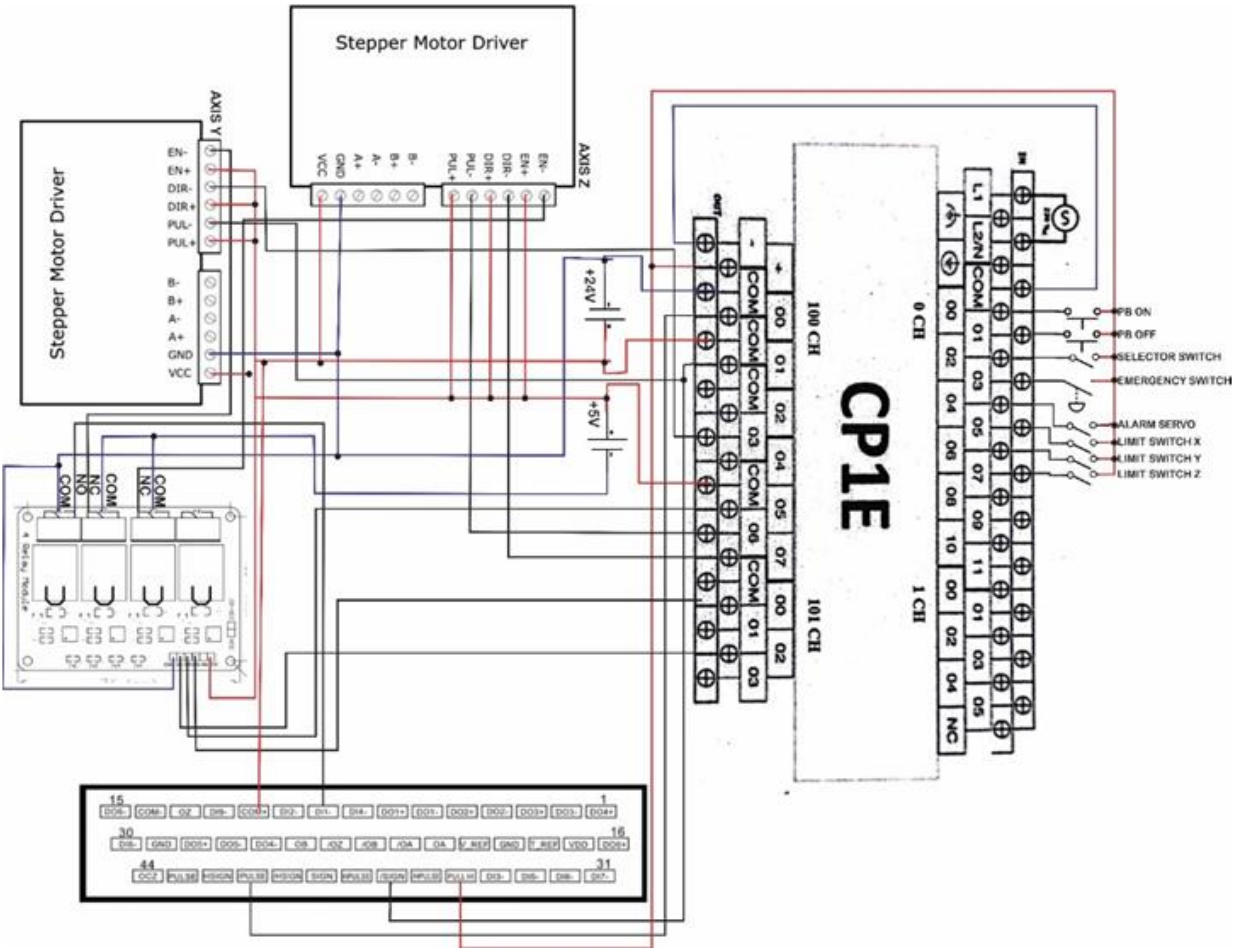


Fig. 2. The wiring design of the electronic installation for the 3-axis ASRS

The control panel module is shown in Fig. 3. For safety and reliability, limit switches are installed at the endpoints of all three axes to prevent over-travel and collisions. Additional control elements include a selector switch for manual or automatic mode selection, ON/OFF push buttons for motor activation, and an emergency stop switch for immediate shutdown in critical conditions. The list of system components is summarized in Table 1.

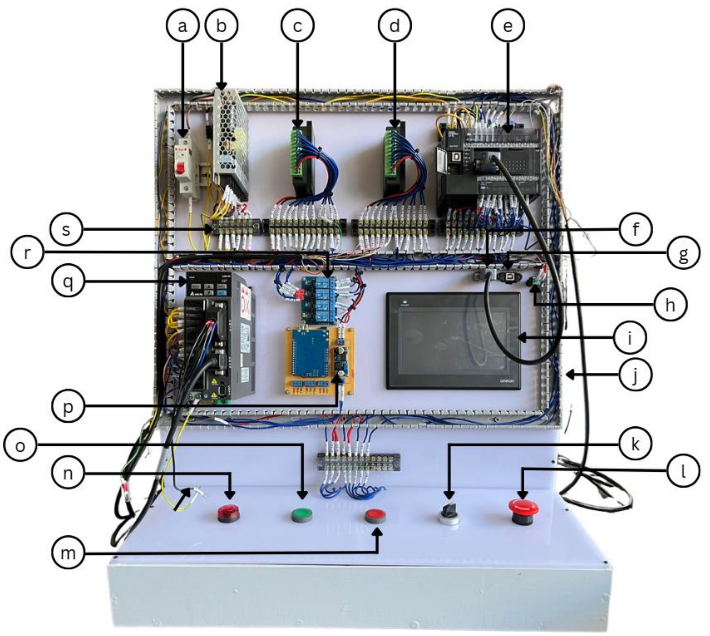


Fig. 3. Control panel module of the 3-Axis ASRS

Table 1. List of components and their letter notations used in the ASRS

No.	Letter notation	Component description
1	a	Miniature circuit breaker
2	b	Power supply
3	c	TB6600 stepper driver
4	d	TB6600 stepper driver
5	e	Omron CP1E-N30DT-A PLC
6	f	RS232 cable connector
7	g	USB Type-B Port
8	h	DC Jack
9	i	Omron NB7W-TW00-B HMI
10	j	Cable duct
11	k	Selector switch
12	l	Emergency switch
13	m	Push button OFF
14	n	Buzzer
15	o	Push button ON
16	p	LM2596 step-down module
17	q	Servo driver
18	r	4-Channel relay module
19	s	Terminal block

2.2 HMI interface design

The HMI system comprises six display screens: the home, preparation, manual, automatic, option, and information screens. The home screen displays the system title and developer identification.

The preparation screen (Fig. 4) includes bit lamp indicators to show whether the X-, Y-, and Z-axis motors are in the active (enable) state or not. An alarm message is provided to notify the operator when the OFF push button, ON push button, selector switch, or emergency button is pressed (ON) or released (OFF). Bit lamp indicators are also used to display the selected operation mode, either manual or automatic. In addition, bit buttons for Manual, Auto, Information, and Back are available to navigate to the corresponding screens.

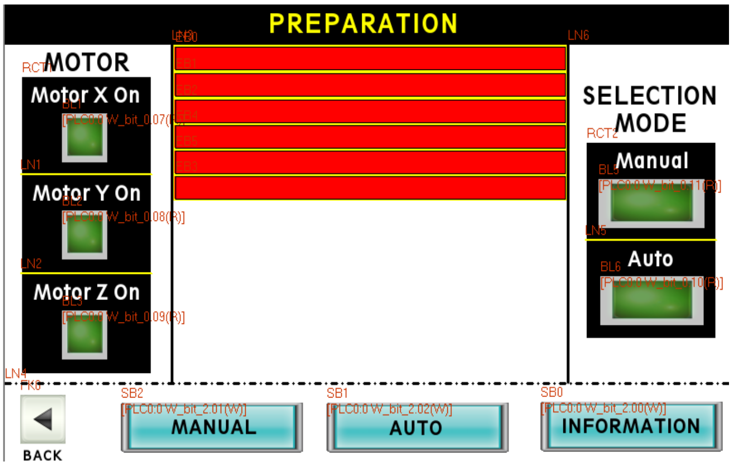


Fig. 4. Preparation screen

The manual screen (Fig. 5) features bit buttons for controlling the servo motor on the X-axis (left and right), the stepper motor on the Y-axis (up and down), and the stepper motor on the Z-axis (forward and backward). It also has buttons to operate the buzzer in ON and BLINK modes. A dedicated button for the *Home Position* moves the gripper to its initial reference position. When the gripper successfully reaches this home position, the corresponding *bit lamp indicator* lights up as a status signal. Additionally, the manual screen includes a *Back* button to return to the previous screen and an *Information* button to access the information screen.

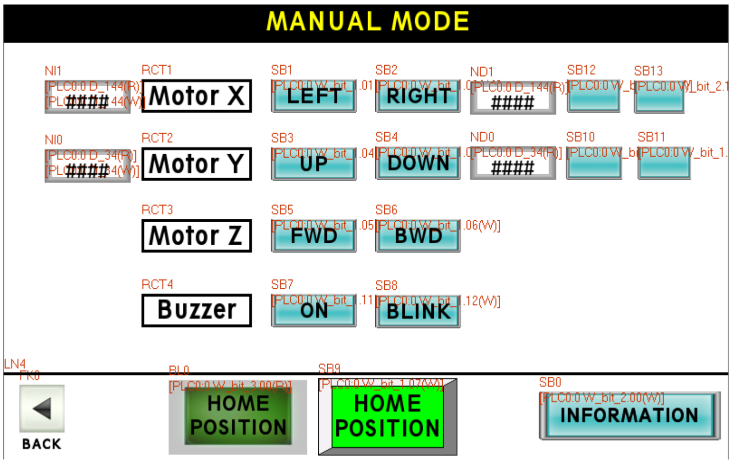


Fig. 5. Manual screen

The auto screen displays bit buttons labeled from A1 to H3, which function as rack selection controls for automatic retrieval operations. The auto screen can be seen in Fig. 6.

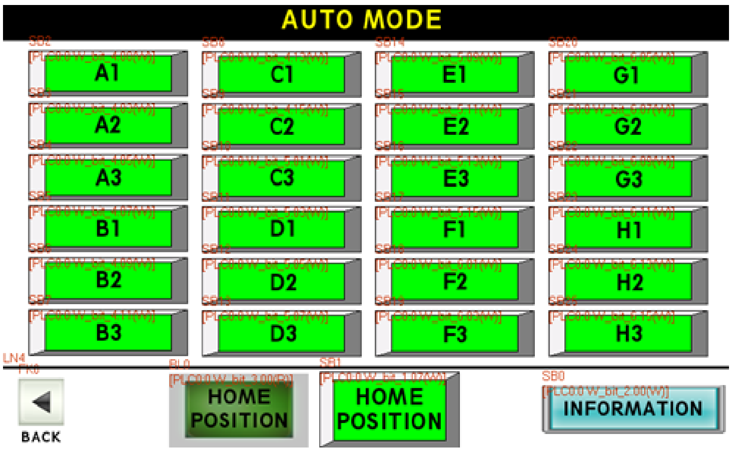


Fig. 6. Auto screen

The option screen (Fig. 7) includes bit buttons for rack retrieval and rack storage operations. Below these buttons, there are additional controls for selecting the operating speed used during the retrieval and storage processes, accompanied by indicators showing the selected speed level of 25%, 50%, 75%, or 100%.

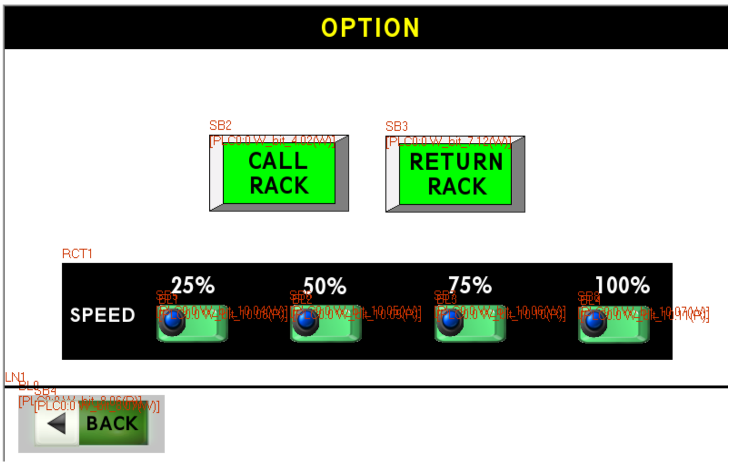


Fig. 7. Option screen

Fig. 8 and Fig. 9 show the information screen, which includes bit lamps indicating the components that are currently active (ON). A bit button labeled Home is also provided to return to the home screen

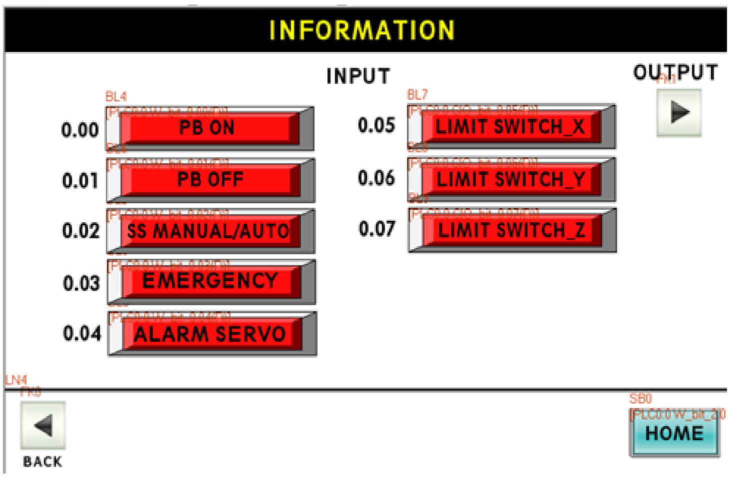


Fig. 8. Input information screen

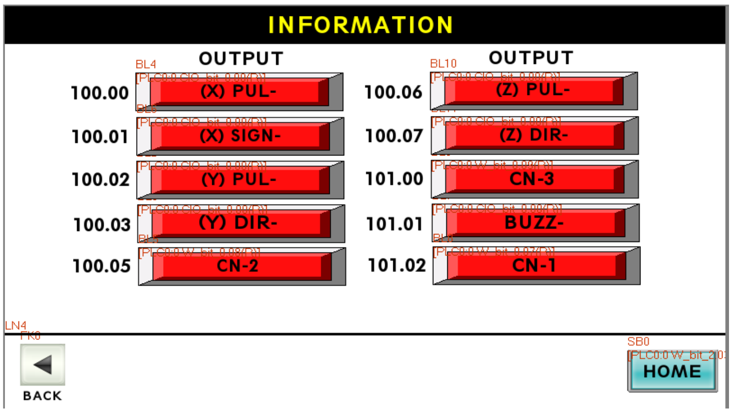


Fig. 9. Output information screen

2.3 Experimental setup and testing procedures (final version)

To evaluate the performance of the developed three-axis ASRS prototype, a structured three-stage experimental testing protocol was implemented. This protocol clearly separates functional verification from quantitative performance evaluation, where each stage produces measurable and objective performance data related to the system operation.

2.3.1 Pulse-to-displacement calibration

Pulse-to-displacement calibration was conducted to determine the relationship between the pulse output generated by the PLC and the resulting linear displacement of the mechanical axes. This calibration was performed for the X-axis, driven by a servo motor, and the Y-axis, driven by a stepper motor.

During the test, the pulse count was gradually varied from 0 to 3500 pulses. We measured the corresponding linear displacement of the gantry using a manual reference ruler. The collected data allowed us to calculate the displacement resolution for each axis, which serves as a reference for defining rack coordinate positions in the control program.

2.3.2 Time-based motion analysis

The Z-axis gripper motion was controlled by activation duration instead of pulse count, prompting a time-based motion analysis. We assessed the relationship between motor activation time and linear forward-backward displacement.

The Z-axis motor was activated for periods ranging from 0 to 13 seconds. We measured the resulting displacement with a ruler and recorded the activation time using a stopwatch. This test was repeated several times to evaluate the consistency and repeatability of the gripper motion under time-based control.

Table 2. These metrics were defined to ensure that the developed system is suitable for its intended application in laboratory-scale electronic component management and PLC-based education.

2.3.3 Automated positioning and cycle testing

Automated positioning accuracy was evaluated by comparing the programmed rack target coordinates (A1–H3) with the actual final position of the gripper after motion execution. The gripper position was visually and physically verified at each target location to identify any positioning deviation.

In addition, full automatic storage and retrieval cycles were executed at four different operating speed levels (25%, 50%, 75%, and 100%). For each speed level, the total cycle time was recorded to assess the effect of operating speed on system performance and operational efficiency.

2.4 Success parameters and performance metrics

The performance of the ASRS prototype was evaluated using explicit quantitative success parameters, as summarized in

Table 2. ASRS testing metrics and validation criteria

Parameter	Success criteria (target)	Evaluation method
X-axis resolution	0.0126 cm/pulse	Linear regression analysis
Y-axis resolution	0.01 cm/pulse	Linear regression analysis
Z- axis displacement	Repeatable within ±1 cm	Repeated measurement analysis
Positioning accuracy	Alignment with target rack coordinates (A1–H3)	Visual & Physical Verification
Operational reliability	No storage error observed during test cycles	Automated cycle monitoring
Speed effect	Cycle time decreases with increasing speed level	Cycle time recording

3 Results and discussion

The assembled 3-Axis ASRS prototype is shown in Fig. 10. The system was tested under various operating conditions to evaluate displacement accuracy, position control, and automatic operation reliability.

Fig. 10. Final prototype of the 3-Axis ASRS

3.1 Servo motor displacement test on the X-Axis

This experiment aims to determine the relationship between the number of pulses supplied to a servo motor and its linear displacement along the X-axis. The servo motor, controlled by a Delta ASDA-B2 driver, receives pulse signals from a PLC.

The test involved varying the number of pulses and directly measuring the linear displacement of the gantry with a ruler. Before testing, the servo motor was set to the home (zero) position. The system was then supplied with specific pulse counts (e.g., 0, 100, 1000, 2000, and 3200 pulses), and the actual displacement of the gantry was measured in centimeters. The results of this test are presented in Table 3. Based on the test results of Table 3, the average displacement resolution of the X-axis stepper motor can be calculated by Eq. (1).

Table 3. Servo motor displacement test on the X-axis

Number of pulses	Displacement (cm)
0	3.5
100	4.5
1000	16.4
2000	29.0
3200	44.0

$$Resolution = \frac{\Delta Distance}{\Delta Pulses} = \frac{44 - 3.5}{3200 - 0} = \frac{40.5}{3200} = 0.0126\, cm/pulse \quad (1)$$

Thus, for every one pulse, the X-axis servo motor produces a linear displacement of approximately 0.0126 cm. This resolution is in line with previous research findings that emphasize the accuracy of servo systems in automatic placement tasks [11], [15]. This level of linearity supports the effectiveness of the system in meeting the precision positioning requirements of small-scale ASRS applications. However, factors such as belt tension and mechanical wear have the potential to affect calibration results during long-term use [8].

3.2 Stepper motor displacement test on the Y-axis

This experiment was conducted to determine the displacement of the stepper motor on the Y-axis based on the number of pulses generated by the PLC. The Y-axis is driven by a NEMA 17 stepper motor controlled through a TB6600 driver. Similar to the X-axis test, this experiment is essential to determine the conversion value between the number of pulses and the actual displacement, ensuring accurate system movement during component storage or retrieval operations.

The procedure began with the stepper motor positioned at its home (zero) point. The system was then commanded to move with several pulse variations. Each time the motor moved, the displacement of the Y-axis was measured manually using a ruler. The measurement data were recorded and analyzed to determine the average displacement per pulse. The results of the test are shown in Table 4. Based on the test results of Table 4, the average displacement resolution of the Y-axis stepper motor can be calculated by Eq. (2).

Table 4. Stepper motor displacement test on the Y-axis

Number of pulses	Displacement (cm)
0	6.5
100	7.5
1000	16.5
2000	26.5
3500	41.5

$$Resolution = \frac{41.5 - 6.5}{3500 - 0} = \frac{35}{3500} = 0.01\, cm/pulse \quad (2)$$

Hence, each pulse produces a displacement of approximately 0.01 cm. This information is crucial for programming the Y-axis position in the ASRS system, ensuring precise and accurate movements to the rack locations.

This performance aligns with the characteristics of stepper motors controlled by micro-stepping controllers like the TB6600, which deliver good positioning accuracy for low to medium-speed applications [12]. However, under high-load or rapid-acceleration conditions, stepper motors may experience step loss, leading to errors that static calibration testing may not fully detect [9].

3.3 Stepper motor displacement test on the Z-axis

This experiment aims to determine the relationship between the activation time of the Z-axis stepper motor and the actual displacement distance. Unlike the previous pulse-based tests, the Z-axis test was performed based on the motor's active duration, since in the initial mode, the gripper motion (forward and backward) was controlled by setting the activation time rather than pulse count.

The Z-axis uses a NEMA 17 stepper motor controlled through a TB6600 driver, with the direction and enable signals managed by the PLC. The test procedure involved activating the motor for specific durations (in seconds) and measuring how far the gripper moved using a ruler. The experiment began with the Z-axis stepper motor at its initial position, then the motor was activated for 0, 5, 10, and 13 seconds. The displacement distance of the gripper was recorded and analyzed to determine the relationship between activation time and linear displacement. The test results are presented in Table 5.

Table 5. Stepper motor displacement test on the Z-axis

Time(s)	Displacement (cm)
0	2.3
5	6.4
10	11.2
13	17.4

From the table, it can be observed that the longer the motor is activated, the further the gripper moves forward. This indicates that the Z-axis stepper motor movement in this test is still continuous with respect to time and not yet based on pulse counting. Although this method works, its precision and repeatability are lower than pulse-based control or closed-loop systems because it does not take into account load variations or small speed fluctuations [18]. The relationship obtained can be used as an initial reference, but to improve the accuracy of pick-and-place operations, which are crucial in handling sensitive electronic components, it is recommended to apply pulse-based control or integrate a simple feedback sensor, such as a limit switch at the pick-up point, in further development [27].

3.4 Rack position accuracy test

After successfully operating the ASRS system in manual mode and confirming accurate movement on each axis, a final test was conducted to evaluate the system's accuracy in reaching the desired rack positions selected through the HMI interface. This test aimed to verify that the combined movement of the X- and Y-axes could accurately position the gripper at the rack location corresponding to the coordinates programmed in the PLC.

During the test, the operator entered predefined pulse values using the number input interface. The PLC processed these input signals and sent commands to the X-axis servo motor and the Y-axis stepper motor. The movements of the axes followed the predetermined pulse values derived from previous displacement tests. After the motors stopped, the position of the gripper was visually compared to the actual rack location. The results of this test are summarized in Table 6.

Table 6. Rack position accuracy test

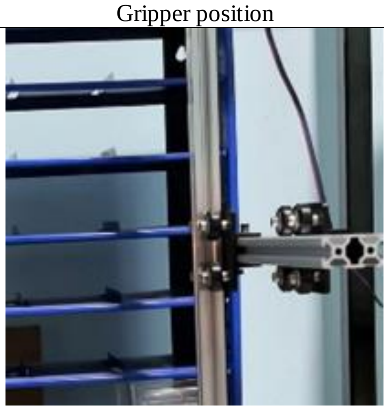
X-axis pulses	Y-axis pulses	Gripper position
370	0	A1
1100	0	A2
1800	0	A3
370	1100	B1
370	1750	C1
370	2450	D1
370	3780	E1
370	4460	F1
370	5110	G1
370	5765	H1

The results show that the ASRS system was able to move the gripper accurately to the target rack positions based on the input pulse values for both the X- and Y-axes. The successful positioning demonstrates effective synchronization between PLC programming, motor controllers, and mechanical assembly. The integration of mechanical modules and control systems in this functional prototype addresses gaps in the development of modular and accessible ASRS frameworks for educational purposes and small-scale applications [14], [17], [28].

3.5 Servo driver jogging mode test

This test was conducted to verify that the servo motor on the X-axis can be manually controlled using the jogging mode feature available through the HMI and PLC, as well as to evaluate the response of the Delta ASDA-B2 driver in receiving control signals from the system. The jogging mode is an essential feature for testing and maintenance, as it allows the user to directly move the actuator without running the automatic program. This feature is particularly useful during initial calibration, home position adjustment, and monitoring of motor direction and motion stability. The jogging mode is configured in parameter P4-05 of the driver. The results of this test are shown in Table 7.

Table 7. Servo driver jogging mode test

Jogging mode button	Gripper position
Right	

Left 

3.6 Servo driver jogging mode test

The automatic mode test aims to ensure that the ASRS system can perform the entire storage and retrieval process sequentially, autonomously, and in accordance with the commands sent from the HMI, without any direct manual intervention. This mode serves as the primary operation mode of the ASRS, integrating all subfunctions such as rack selection, motor movements along the X, Y, and Z axes, and the rack return cycle to its initial position.

Before the test was conducted, all components, including the X-axis servo motor, Y-axis, and Z-axis stepper motors, HMI, and PLC, were ensured to be in a ready condition. The operator selected one of the target rack positions (e.g., A1–H3) through the HMI interface and pressed the "Call Rack" button to initiate the automatic operation cycle. The results of this test are presented in Table 8 to Table 10.

Table 8. Automatic rack retrieval test (A3 position)

Speed	Retrieval time (min)	Storage time (min)	Storage error (%)
25%	1.52	1.47	0.00
50%	1.50	1.47	0.00
75%	1.49	1.46	0.00
100%	1.49	1.47	4.62

Table 9. Automatic rack retrieval test (D1 position)

Speed	Retrieval time (min)	Storage time (min)	Storage error (%)
25%	1.53	1.50	0.00
50%	1.51	1.52	4.62
75%	1.52	1.51	15.38
100%	1.52	1.51	15.38

Table 10. Automatic rack retrieval test (G2 position)

Speed	Retrieval time (min)	Storage time (min)	Storage error (%)
25%	1.54	1.55	0.00
50%	1.58	1.55	0.00
75%	1.56	1.55	0.00
100%	1.56	1.55	0.00

Based on the test results presented in Table 6 to Table 10, the 3-Axis ASRS prototype was able to function according to its design specifications. The system operates in two modes: manual mode, which is used for gripper position calibration and movement adjustment, and automatic mode, which performs continuous rack storage and retrieval cycles. However, a minor positioning error was observed in the gripper mechanism, with deviations ranging from approximately 0.3 to 1 cm from the ideal target position.

The motor movement tests showed a high degree of precision. The servo motor on the X-axis achieved a resolution of 0.0126 cm per pulse, while the stepper motor on the Y-axis produced a resolution of approximately 0.01 cm per pulse. These results confirm a linear relationship between the number of pulses and the displacement distance, allowing for accurate determination of the rack position coordinates. For the Z-axis, the time-based movement control provided a sufficient reference for the gripper's forward and backward motion, although it was slightly less precise than the pulse-based control method.

Overall, the ASRS system effectively integrated the PLC, HMI, and motor drivers to operate cohesively. The success rate of 84.62% to 95.38% indicates that the system functions well as both an automatic storage prototype and a learning module for laboratory [14],[21],[28]. applications. However, further improvements in gripper positioning accuracy are recommended to enhance the overall performance and reliability of the system.

4 Conclusions

The three-axis ASRS developed for managing electronic components shows that a laboratory-scale automated storage solution can be effectively achieved using PLC and HMI technologies. The system features three motion axes (X, Y, and Z) powered by servo and stepper motors, enabling organized and systematic storage and retrieval of component racks.

Experimental results show that the ASRS operates reliably in both manual and automatic modes. In automatic operation, the system is capable of executing repetitive rack retrieval and return cycles with a positioning accuracy ranging from 84.62% to 95.38%, despite storage deviations of 4.62%–15.38%. These performance variations are primarily influenced by mechanical tolerances, open-loop motor control characteristics, and dynamic effects at higher operating speeds. Nevertheless, the synchronization between PLC control logic, motor drivers, and mechanical system response enables stable and repeatable operation, indicating that the proposed ASRS is suitable as a laboratory-scale automation platform.

Future development may focus on improving system accuracy and robustness through the implementation of closed-loop feedback control, the integration of additional sensors for real-time position correction, and the development of more adaptive gripper mechanisms. Furthermore, the incorporation of Internet of Things (IoT)-based monitoring could support remote supervision and data-driven performance optimization. These enhancements are expected to extend the applicability of the proposed ASRS for both industrial automation education and further research on automated storage systems.

References

[1] A. Edouard, S. Bourdin, and A. Brun, "Automated storage and retrieval systems: An attractive solution for an urban warehouse's sustainable development," Sustainability, vol. 14, no. 15, p. 9518, 2022, doi: 10.3390/su14159518.

[2] B. Salah, S. A. Khan, I. Abunadi, and W. Abualfaraa, "Automated stacker cranes: A two-step storage reallocation method using simulation," Processes, vol. 9, no. 1, p. 2, 2021, doi: 10.3390/pr9010002.

[3] Y. Li, X. Li, and B. Y. Ekren, "Shuttle-based storage and retrieval system: A literature review," Sustainability, vol. 14, no. 21, p. 14347, 2022, doi: 10.3390/su142114347.

[4] M. Eder, T. Lerher, and M. Sraml, "Performance evaluation of SBS/RS with single-aisle shuttles," International Journal of Advanced Manufacturing Technology, vol. 106, pp. 4161–4176, 2020, doi: 10.1007/s00170-019-04735-z.

[5] W. Dong, X. Chen, and M. Chen, "ASRS design with variant 3D racks," European Journal of Operational Research, 2024.

[6] G. Lupi, M. Peron, and I. F. A. Vis, "Space efficiency and throughput in AVS/RS systems," International Journal of Advanced Manufacturing Technology, vol. 131, pp. 1449–1466, 2024.

[7] R. Chen, H. Yang, and J. Leung, "Retrieval request scheduling in shuttle-based ASRS," Computers & Industrial Engineering, vol. 182, p. 109357, 2023, doi: 10.1016/j.cie.2023.109357.

[8] R. Manzini, M. Gamberi, A. Regattieri, and A. Persona, "Design and control of automated storage and retrieval systems," International Journal of Advanced Manufacturing Technology, vol. 28, no. 7, pp. 766–774, 2006, doi: 10.1007/s00170-005-0600-6.

[9] K. J. Roodbergen and I. F. A. Vis, "A survey of literature on automated storage and retrieval systems," European Journal of Operational Research, vol. 194, no. 2, pp. 343–362, 2009, doi: 10.1016/j.ejor.2008.01.038.

[10] Y. Jaghbeer et al., "Automated order picking systems: Design and performance links," International Journal of Production Research, vol. 58, no. 20, pp. 6520–6537, 2020, doi: 10.1080/00207543.2020.1716756.

[11] M.-Y. Wei, C.-Y. Chuang, and C.-J. Wu, "Design and control of a 3-axis servo platform," Energies, vol. 16, no. 10, p. 4208, 2023, doi: 10.3390/en16104208.

[12] J. R. Mahmood and O. I. Khalaf, "PLC/HMI-based implementation of a real-time relaying laboratory," Electronics, vol. 9, no. 1, p. 118, 2020, doi: 10.3390/electronics9010118.

[13] F. Mo, D. Wang, B. Johansson, and T. Lundholm, "PLC orchestration automation for human–machine collaboration," Computers in Industry, vol. 153, p. 103000, 2023, doi: 10.1016/j.compind.2023.103000.

[14] M. Al-Yaman et al., "A modular PLC laboratory for hands-on industrial learning," Engineering Science and Technology, an International Journal, 2025.

[15] B. Y. Ekren and A. Akpunar, "Flexible vs. non-flexible shuttle travel policies in SBS/RS," Sustainability, vol. 15, no. 1, p. 762, 2022, doi: 10.3390/su15010762.

[16] Z. U. Rizqi et al., "Multi-objective simulation–optimization for integrated AS/RS planning," Computers & Industrial Engineering, vol. 190, p. 109963, 2024, doi: 10.1016/j.cie.2024.109963.

[17] Z. U. Rizqi et al., "Dynamic crane scheduling for green automated warehousing," Computational Optimization and Applications, 2025.

[18] M. Xu et al., "Flexible robotic grippers with magnetorheological materials," Materials, vol. 17, no. 19, p. 4858, 2024, doi: 10.3390/ma17194858.

[19] A. Alhijaily et al., "Multi-arm gantry system for cooperative manufacturing," International Journal of Computer Integrated Manufacturing, vol. 37, no. 12, pp. 1408–1424, 2024, doi: 10.1080/0951192X.2024.2314567.

[20] M. A. Koondhar et al., "The role of PLC in automation, industry, and education: A review," International Journal of Engineering Research and Technology, vol. 12, no. 7, pp. 68–78, 2023.

[21] M. Pekarcikova et al., "Educational robotics for Industry 4.0/5.0 using Wlkata Mirobot," Machines, vol. 13, no. 9, p. 753, 2025, doi: 10.3390/machines13090753.

[22] A. Edouard, S. Bourdin, and A. Brun, "Smart connected sensing with AS/RS," Sustainability, vol. 14, no. 15, p. 9518, 2022.

[23] Y. Li and X. Li, "AS/RS travel time with horizontal deployment in class-based storage," IIE Transactions, 2025.

[24] K. J. Roodbergen and I. F. A. Vis, "Travel time analysis of a new AS/RS concept," Computers & Operations Research, vol. 32, no. 6, pp. 1515–1544, 2005, doi: 10.1016/j.cor.2003.12.008.

[25] I. Battarra et al., "A design framework for shuttle-based automated storage and retrieval systems," IFAC-PapersOnLine, 2024.

[26] T. Nguyen, P. Luu, and J. Kim, "Integration of PLC-based ASRS with cloud monitoring for smart factories," IEEE Access, vol. 13, pp. 134512–134523, 2025, doi: 10.1109/ACCESS.2025.134512.

[27] R. Sharma and V. Kumar, "IoT-enabled warehouse automation using PLC and HMI," Sensors, vol. 24, no. 8, p. 3022, 2024, doi: 10.3390/s24083022.

[28] L. Wang, H. Zhang, and D. Yu, "Learning-based control framework for educational ASRS platforms," IEEE Transactions on Learning Technologies, vol. 18, no. 2, pp. 145–157, 2025, doi: 10.1109/TLT.2025.1152309.

[29] T. Lerher, "Modern automated storage and retrieval systems: A review," Journal of Mechanical Engineering, vol. 62, no. 1, pp. 55–63, 2016, doi: 10.5545/sv-jme.2015.2856.

[30] S. Zhang, Y. Guo, and J. Liu, "Design and performance analysis of a miniature automated storage and retrieval system," International Journal of Advanced Manufacturing Technology, vol. 102, nos. 5–8, pp. 2141–2152, 2019, doi: 10.1007/s00170-019-03327-1.