DEVELOPMENT AND IMPLEMENTATION OF THE MOTHER AND CHILD SHUTTLE SYSTEM FOR WAREHOUSE MANAGEMENT AND OPERATION

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ABSTRACT: The increasing complexity of warehouse operations and the rapid growth of e-commerce demand advanced Automated Storage and Retrieval Systems (AS/RS) that are efficient, flexible, and reliable. This study presents the design and implementation of a Mother and Child Shuttle System integrated with a hybrid communication architecture and an intelligent control interface. The system is developed based on kinematic and dynamic analysis to optimize shuttle motion using an acceleration–constant velocity–deceleration profile, ensuring stable operation and accurate positioning. A block-based control architecture incorporating PLC, sensors, motor drivers, and wireless communication enables coordinated system operation. The hardware prototype, including the Mother Shuttle, Child Shuttle, and storage rack, is successfully constructed and validated under real conditions, demonstrating stable performance and effective component integration. In addition, a user-friendly interface is developed to support real-time monitoring, control, and alarm management, enhancing system reliability and operational safety. The proposed system provides a practical solution for improving efficiency and scalability in modern warehouse automation.

KEY WORDS: Automated Storage and Retrieval System (AS/RS), Mother–Child Shuttle System, Warehouse Automation, PLC Control System, Intelligent Monitoring Interface.

1. INTRODUCTION

The increasing complexity of global supply chains and the burgeoning e-commerce sector have driven significant advancements in warehouse automation, necessitating highly efficient and adaptable material handling solutions [1]–[3]. Traditional storage systems often encounter limitations in throughput, retrieval speed, and optimal space utilization, prompting a shift towards more sophisticated Automated Storage and Retrieval Systems (AS/RS) [3]–[5]. Among these, Mother and Child Shuttle Systems, also known as Multi-Shuttle Systems, represent a strategic solution designed to address these operational challenges by offering high-density storage and flexible multi-level access, coupled with automated inbound and outbound material handling processes [2], [6], [7]. The integration of these advanced systems with Warehouse Management Systems (WMS) and Internet of Things (IoT) technologies further augments real-time data monitoring and operational transparency, crucial for enhancing competitiveness [1], [3], [8].

The demand for intelligent storage systems is underpinned by several critical operational requirements. Modern warehouses require increased automation to mitigate reliance on human labor and improve overall efficiency [1], [9]. Optimizing space utilization and minimizing handling times are paramount for large-scale operations [10], [11]. Precision in storage and retrieval processes is also essential to prevent errors such as product damage or misplacement, which can significantly impact supply chain integrity [5], [9]. Moreover, flexibility and scalability are necessary to accommodate diverse product types and fluctuating operational demands, fostering sustainable system development [6], [12].

Recent technological developments in AS/RS and shuttle-based systems have significantly advanced warehouse automation. The evolution from traditional Automated Guided Vehicles (AGVs) to Autonomous Mobile Robots (AMRs) has introduced enhanced flexibility, enabling robots to independently plan routes and navigate obstacles without fixed infrastructure [13], [14]. This adaptability is particularly beneficial in dynamic warehouse environments. The adoption of open communication standards, such as VDA-5050 (which falls under the broader umbrella of interoperability standards for autonomous systems), facilitates seamless communication and coordination among equipment from various manufacturers [13]. Furthermore, the integration of artificial intelligence (AI), machine learning, and advanced WMS/WES platforms optimizes system performance through intelligent storage allocation, reduced cycle times, and predictive maintenance capabilities [15]–[17]. These technological convergences lay a robust foundation for the future development of intelligent warehouse systems.

Despite these advancements, challenges persist, particularly concerning the integration of diverse devices and ensuring reliable wireless data transmission [18]. Another significant hurdle lies in developing efficient and intuitive methods for managing and monitoring storage and outbound handling processes [19]. To overcome these integration and communication issues, a hybrid communication architecture is often proposed [20]. This architecture typically leverages EtherCAT for real-time hardware-level communication within the Mother Shuttle, ensuring high-speed and deterministic data exchange critical for precise control [20]. Concurrently, TCP/IP protocols are employed for communication between the Mother Shuttle, Child Shuttle, graphical user interfaces (GUI), and control applications, providing flexible and scalable connectivity across the system [20].

For effective system monitoring and control, advanced user interfaces are developed. For instance, a user interface developed on a Windows platform using Python can enable direct user interaction, control of automated devices, and real-time monitoring of crucial information such as item location, system status, and inventory levels in a user-friendly visual format, see Figure 1 [21]. Additionally, mobile applications provide remote access, allowing operators to supervise and control the system in real time [1], [19]. These interfaces often incorporate real-time alert mechanisms to notify operators of anomalies or system malfunctions, facilitating timely and informed decision-making [19].

The operational processes of such systems typically involve inbound and outbound handling. The inbound handling process dictates the sequence of operations for storing goods into the system, coordinating actions between the Mother Shuttle and Child Shuttle, see Figure 2 [22]. Conversely, the outbound handling process manages the retrieval of goods from storage locations in response to operational demands, ensuring efficient and accurate material flow within the warehouse, see Figure 3 [23]. These processes are often optimized using sophisticated scheduling algorithms and simulation models to maximize efficiency and minimize cycle times [12], [22], [24]–[26]. For example, the four-way shuttle-based storage system employs parallel operations of multiple elevators and four-way shuttles, requiring robust scheduling solutions for inbound tasks to maintain efficiency [22]. Mathematical models and improved genetic algorithms are utilized for task planning and path optimization within these systems [24]. Simulation studies are widely employed to assess and optimize the performance of multi-level shuttle systems, considering factors like time and energy consumption [12], [27].

Fig. 1. Operating the system through the control interface

Automated Storage and Retrieval Systems (AS/RS) have been widely adopted across various industries since the 1960s, continually evolving with technological advancements to reduce labor costs, enhance productivity, increase storage density, and improve inventory accuracy [5]. Shuttle-based AS/RS, in particular, offer benefits such as high flexibility, robustness, and suitability for e-commerce operations due to their ability to work 24/7 and manage varying demand requirements [2], [6], [7]. The performance of these systems can be further enhanced through strategic storage assignment optimization, for example, by utilizing class-based storage policies in multiple-deep shuttle systems [28], [29]. Energy efficiency is also a growing concern, with studies exploring energy harvesting through regenerative braking systems on AS/RS to minimize carbon emissions [17], [30].

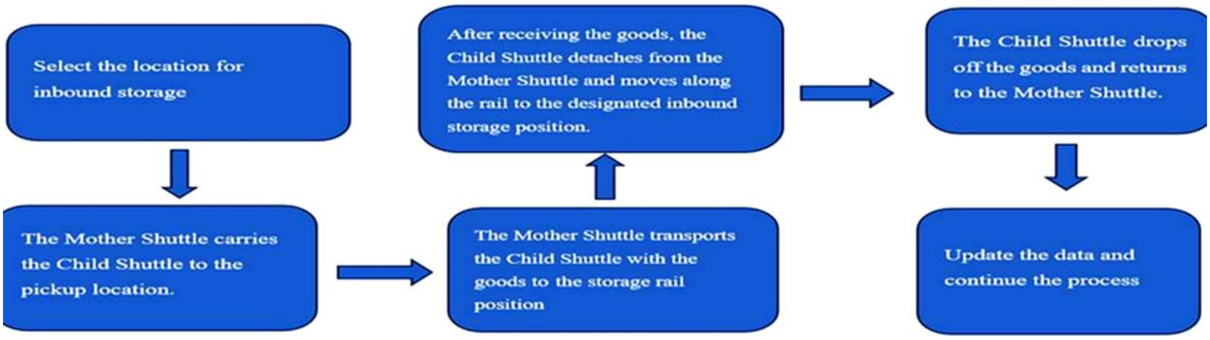

Fig. 2. Inbound or outbound handling process of the system

The development of digital twins and simulation models is also crucial for validating AS/RS designs and predicting their performance [31], [32]. Such tools allow for comprehensive evaluations before physical implementation, considering factors such as throughput, cycle time, and energy consumption [12], [17], [27]. Such tools allow for comprehensive evaluations before physical implementation, considering factors such as throughput, cycle time, and energy consumption [15].

In summary, the design and development of an integrated Mother and Child Shuttle System with a hybrid communication architecture and an intelligent control interface aim to significantly enhance warehouse automation efficiency, improve real-time monitoring capabilities, and support scalable, flexible, and high-performance logistics operations in response to the dynamic demands of modern supply chains.

2. METHODS

2.1. Kinematic Basis for Shuttle Motion Calculation

The motion of the Mother Shuttle and Child Shuttle in the proposed AS/RS system is analyzed based on kinematic and dynamic principles to ensure optimal storage and retrieval time. Since the shuttle movement occurs predominantly in the horizontal direction, frictional force becomes the primary factor influencing system performance, where its magnitude depends on the total mass and gravitational force acting on the load.

The shuttle velocity profile follows a typical acceleration–constant velocity–deceleration pattern, as illustrated in the velocity–time diagram (Figure 3). During the initial interval (t_0–t_1), the shuttle accelerates until it reaches its maximum velocity (V_m). This is followed by a constant velocity phase (t_1–t_2) within the main operating zone. Finally, in the interval (t_2–t_3), the shuttle decelerates and stops at the target position. This motion profile ensures both time efficiency and operational stability.

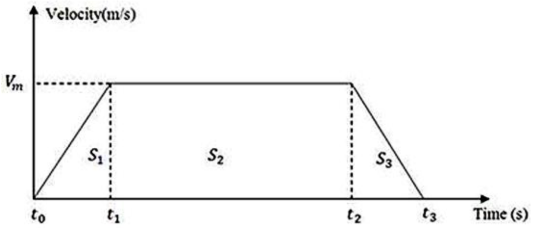

Fig. 3. Velocity–time diagram of the shuttle during pallet transportation

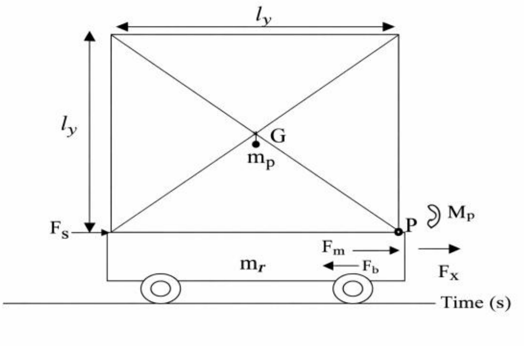

Fig. 4. Motor and braking forces during shuttle movement

The stopping behavior of the shuttle is governed by the interaction between static friction, inertial forces, and braking forces generated by the motor. If the braking force is insufficient to counteract the inertial force, the system may transition from static to kinetic friction, potentially causing inaccurate stopping. These force interactions during shuttle movement are depicted in Figure 4, which illustrates the relationship between driving force, frictional force, and braking force.

Furthermore, during acceleration and deceleration, inertial forces act in opposition to the applied driving force, which may lead to load instability. Therefore, acceleration and deceleration limits must be carefully determined to prevent pallet slippage. The relationships among acceleration, maximum velocity, and motor power are derived from Equations (1)–(7), which serve as the basis for defining the system's operational parameters.

$$F_x = (m_p + m_r)a = F_m - F_b \quad (1)$$

$$v = v_0 + at \quad (2)$$

$$x = x_0 + v_o t + \frac{1}{2}at^2 \quad (3)$$

$$F_x \leq F_S = \mu m_p g \quad (4)$$

$$V_m = at \quad (5)$$

$$F_x = (m_p + m_r)a \quad (6)$$

$$P = F_x V_m \quad (7)$$

2.2. Block Diagram Design

To ensure proper system integration, a block-based control architecture is developed to represent the interaction among key system components, as shown in Figure 5. This architecture consists of several interconnected subsystems that enable coordinated and reliable operation.

The system begins with the power supply block, which provides the main 220 VAC input and converts it into 24 VDC to power the PLC, sensors, and communication devices. The input block collects signals from various devices, including push buttons, position sensors, and photoelectric sensors, enabling real-time system monitoring.

The PLC functions as the central control unit, processing all input signals and generating output signals to control actuators. These control signals are transmitted to the driver block, which regulates motor operation through precise PTO pulses. The motor block then converts these signals into mechanical motion to drive the shuttle system. Additionally, the indicator block provides visual status information, facilitating system monitoring by the operator.

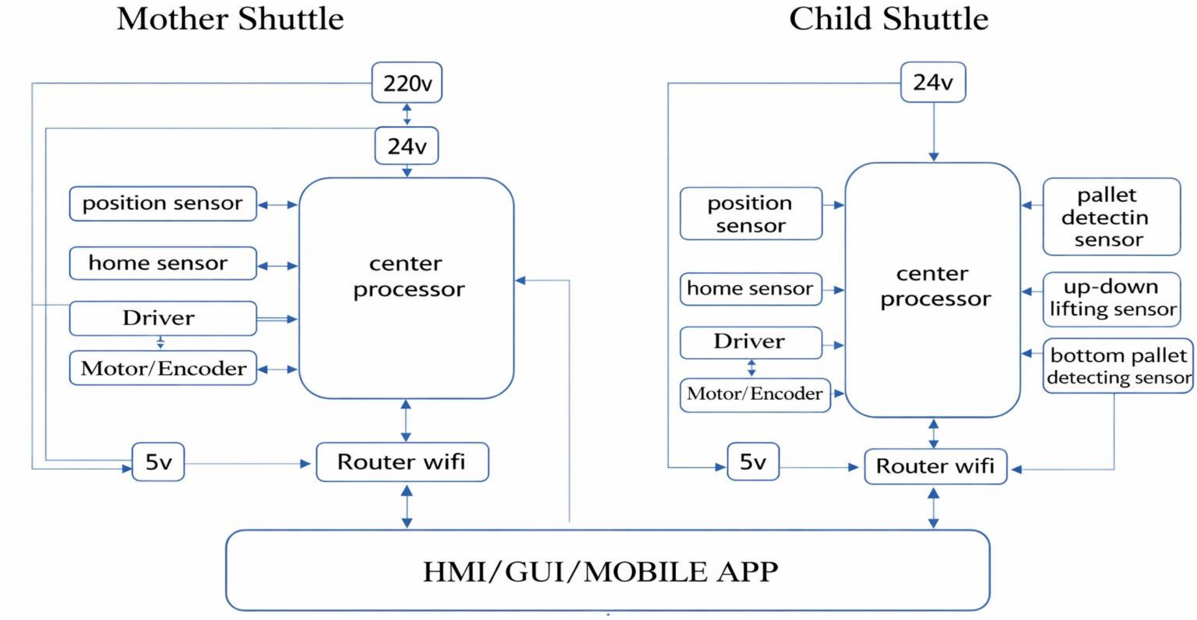

Fig. 5. Block diagram of the Mother Shuttle and Child Shuttle system

2.3. Hardware Design

The hardware design of the system consists of the Child Shuttle, Mother Shuttle, and the storage rack system, which are developed in an integrated manner to support automated material handling operations.

The Child Shuttle is designed with dimensions of 320 × 320 mm and consists of three main components: the top section for rail sensor mounting, the side panels for drive and guide wheels, and the front panel for sensors and control buttons. The overall configuration of the Child Shuttle is presented in Figure 6.

The Mother Shuttle is designed with larger dimensions of 645 × 432 × 153 mm to accommodate the Child Shuttle and additional supporting components. This structure ensures stable transportation of the Child Shuttle along the rail system. The complete design of the Mother Shuttle is shown in Figure 7.

The storage rack system occupies an area of approximately 4 m² and can accommodate up to nine pallets simultaneously. Additional components, including a Wi-Fi router, limit switches, and sensors, are integrated to enable real-time monitoring and wireless communication within the system.

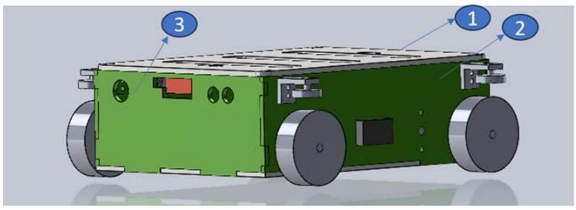

Fig. 6. Photograph of the overall Child Shuttle design

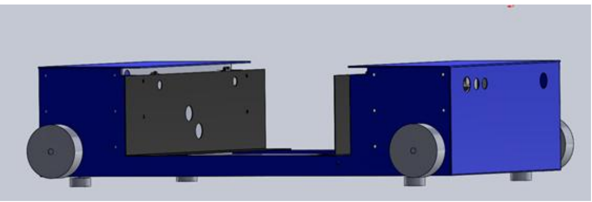

Fig. 7. Overall design view of the Mother Shuttle

2.4. Software and Control System

The control system is developed to coordinate the operation of the Mother Shuttle and Child Shuttle through PLC-based programming. The PLC program for the Child Shuttle is designed to handle pallet transportation between the Mother Shuttle and storage locations, as illustrated in the state diagram (Figure 8). Meanwhile, the PLC program for the Mother Shuttle controls the movement of the Child Shuttle from the home position to designated working positions and back, as shown in Figure 9.

In addition to PLC-based control, a user interface is developed to facilitate system monitoring and control. The startup screen (Figure 10) provides general system information and user authentication based on access levels. The classification of user access rights is summarized in Table 1, which distinguishes the roles of engineer, operator, and supervisor.

The main control interface (Figure 11) consists of three primary sections: the control panel, warehouse status, and system status, all of which provide real-time operational information. Additional interfaces include the outbound operation interface (Figure 12), alarm history interface (Figure 13), reporting interface (Figure 14), and shuttle management interface (Figure 15). These integrated interfaces enable comprehensive system monitoring and efficient decision-making.

Table 1: The classification of user access rights

Serial Number	User ID	Access rights
1	Engineer	Access to all screens except the Report screen
2	Operation	Access to the following screens: Control Panel, Alarm, Product Management
3	Supervisor	Full access to the entire system

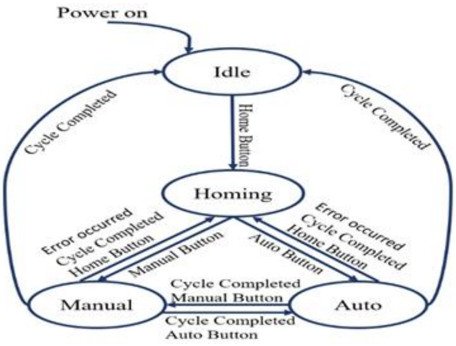

Fig. 8. State diagram of the PLC program for the Child Shuttle

Fig. 9. State diagram representing the PLC control program of the Mother Shuttle


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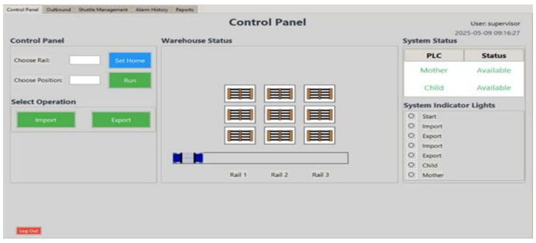
FINAL PROJECT
Smart Warehouse System

Username:
Password:

Instructor:
Assoc. Prof., PhD Ngo Van Thuyen
Members:
Le Quoc Tuan - 21151182
Lam Xuan Minh Nhat - 21151142

Fig. 10. Interface startup screen


Control Panel
User: supervisor
2025-05-09 09:16:27

Control Panel
Choose Rail:
Choose Position:
Select Operation

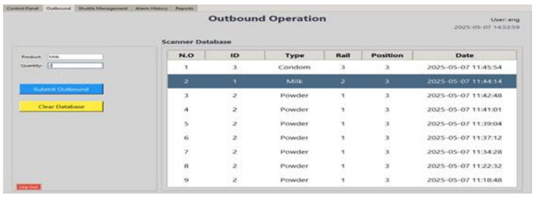
Warehouse Status

System Status

PLC	Status
Mother	Available
Child	Available

System Indicator Lights
○ Start
○ Import
○ Export
○ Import
○ Export
○ Child
○ Mother

Fig. 11. Main system control interface

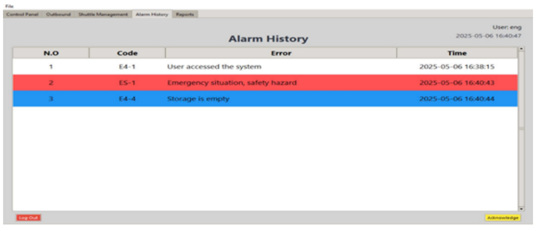

Outbound Operation
User: eng
2025-05-07 14:53:59

Product: Milk
Quantity:

Scanner Database

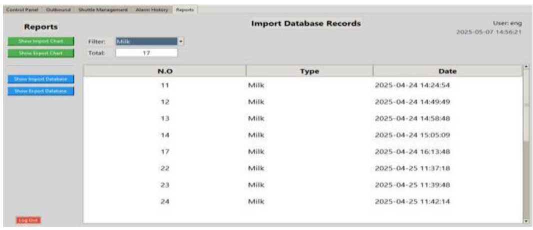
N.O	ID	Type	Rail	Position	Date
1	3	Condom	3	3	2025-05-07 11:45:54
2	1	Milk	2	3	2025-05-07 11:44:14
3	2	Powder	1	3	2025-05-07 11:42:48
4	2	Powder	1	3	2025-05-07 11:41:01
5	2	Powder	1	3	2025-05-07 11:39:04
6	2	Powder	1	3	2025-05-07 11:37:12
7	2	Powder	1	3	2025-05-07 11:34:28
8	2	Powder	1	3	2025-05-07 11:22:32
9	2	Powder	1	3	2025-05-07 11:18:48

Fig. 12. Outbound operation interface


Alarm History
User: eng
2025-05-06 16:40:47

N.O	Code	Error	Time
1	E4-1	User accessed the system	2025-05-06 16:38:15
2	ES-1	Emergency situation, safety hazard	2025-05-06 16:40:43
3	E4-4	Storage is empty	2025-05-06 16:40:44

Fig. 13. Alarm history interface


Reports
Import Database Records
User: eng
2025-05-07 14:56:21

Filter: Milk
Total: 17

N.O	Type	Date
11	Milk	2025-04-24 14:24:54
12	Milk	2025-04-24 14:49:49
13	Milk	2025-04-24 14:58:48
14	Milk	2025-04-24 15:05:09
17	Milk	2025-04-24 16:13:48
22	Milk	2025-04-25 11:37:18
23	Milk	2025-04-25 11:39:48
24	Milk	2025-04-25 11:42:14

Fig. 14. Report interface


Shuttle Management
User: eng
2025-05-06 16:39:19

Force Run
Mother Shuttle
Child Shuttle

Mother Shuttle Status
Status: Available
Position: Home
Pallet Detected: Yes
Shuttle Detected: Yes

Child Shuttle Status
Status: Available
Position: Home
Pallet Detected: No
Lifting: No

Fig. 15. Mother Shuttle control interface

2.5. Error Handling and System Safety

To ensure system reliability, an integrated error handling mechanism is implemented within the control interface. The system is capable of detecting various abnormal conditions, such as communication failures between shuttles, pallet detection errors, and storage capacity limitations.

Each error condition is classified using specific codes that include trigger conditions, memory addresses, warning messages, and corrective actions. These details are summarized in Table 2, which serves as an operational guideline for system diagnosis and troubleshooting.

This approach enhances operational safety while minimizing downtime through rapid and accurate fault identification.

3. RESULTS

3.1. Hardware Construction Results

The physical implementation of the proposed system demonstrates a high level of conformity with the initial design specifications. The assembled prototype closely follows the 3D design developed in SolidWorks, with only minor deviations occurring during the assembly process. These discrepancies were addressed through calibration, resulting in stable system performance that satisfies the predefined operational requirements.

The overall configuration of the implemented system is presented in Figure 16, which illustrates the integration of the Mother Shuttle, Child Shuttle, and storage rack within a unified operational environment. This configuration confirms that the mechanical structure and spatial arrangement are consistent with the design objectives.

Further validation of the hardware implementation is demonstrated through the operation of the shuttle system within the storage rack, as shown in Figure 17. The figure highlights the coordinated movement of the Mother Shuttle and Child Shuttle during material handling operations. The successful interaction between these components indicates that the mechanical design, motion transmission, and sensor integration function effectively under real operating conditions.

Fig. 16. Overall view of the physical model

Fig. 17. Shuttles operating within the system

3.2. Software Construction Results

The software implementation focuses on the development of a user interface and control system that enable real-time monitoring and operation of the shuttle system. Upon system initialization, the main control interface is displayed, as shown in Figure 18, providing users with access to essential system functions and operational data.

The system is capable of dynamically updating warehouse conditions, as illustrated in Figure 19, where real-time changes in storage status are reflected within the interface. This capability is further reinforced in the control panel view (Figure 20), which provides a comprehensive visualization of warehouse operations, including system status and pallet distribution.

In addition to monitoring functionalities, the system includes a dedicated shuttle management interface that allows users to observe and control shuttle operations. The interface, shown in Figure 21, provides detailed information regarding shuttle positions and operational states. During system operation, transitions between shuttle states are clearly visualized, as presented in Figure 22, enabling users to track system behavior in real time.

To enhance system reliability and safety, an alarm monitoring and access control mechanism is implemented. The functional testing of this feature is presented in Figure 23, which demonstrates the system's ability to detect, display, and manage error conditions. The alarm history interface records system events and supports troubleshooting by providing relevant diagnostic information. Additionally, access control ensures that only authorized users can interact with critical system functions, thereby improving operational security.

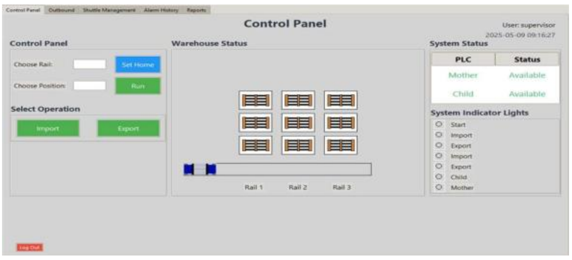


Fig. 18. Main control screen upon system login

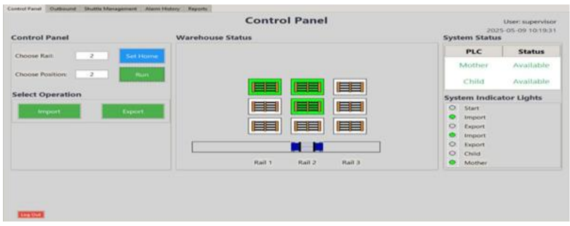


Fig. 19. Updated warehouse status

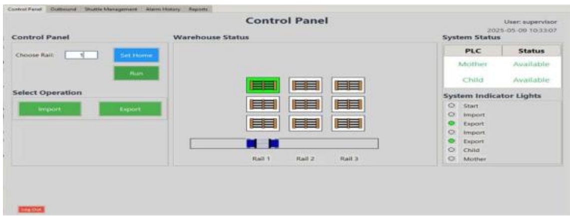
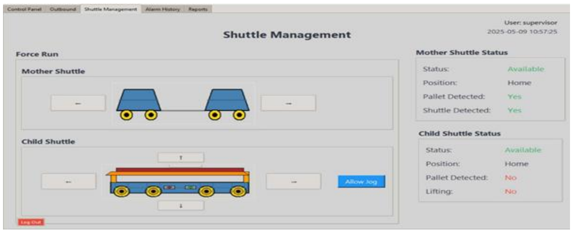


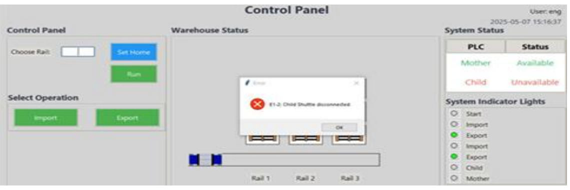
Fig. 20. Warehouse status update on the Control Panel screen



Status: Available
Position: Home
Pallet Detected: Yes
Shuttle Detected: Yes

Status: Available
Position: Home
Pallet Detected: No
Lifting: No

Fig. 21. Shuttles Management screen



E1-2: Child Shuttle disconnected

Fig. 22. Shuttles Management screen during Shuttle state transition

Status: Available
Position: Home
Pallet Detected: Yes
Shuttle Detected: Yes

Status: Available
Position: Home
Pallet Detected: Yes
Lifting: No

Fig. 23. Functional Testing and Access Control for Alarm Features and the Alarm History Screen

4. CONCLUSION

This study presents the design, development, and implementation of an integrated Mother and Child Shuttle System for automated storage and retrieval applications, incorporating a hybrid communication architecture and an intelligent control interface. The proposed system effectively addresses key challenges in modern warehouse operations, including the need for high-density storage, real-time monitoring, and efficient material handling.

From a kinematic perspective, the analysis of shuttle motion demonstrates that the adoption of an optimized acceleration–constant velocity–deceleration profile ensures stable and efficient operation while minimizing the risk of load instability. The integration of frictional and inertial considerations into the system design further enhances motion control accuracy and stopping reliability.

The hardware implementation confirms that the developed prototype closely aligns with the design specifications, with successful integration of the Mother Shuttle, Child Shuttle, and storage rack system. Experimental results show that the system operates stably under real conditions, with effective coordination between mechanical components and sensor-based feedback.

On the software side, the PLC-based control system and user interface provide robust functionality for real-time monitoring, control, and data management. The developed interface enables intuitive interaction, dynamic warehouse status updates, and comprehensive visualization of system operations. Furthermore, the implementation of an error handling mechanism and access control system significantly improves system reliability, safety, and operational security.

The proposed system demonstrates strong potential for enhancing warehouse automation by improving operational efficiency, system flexibility, and monitoring capabilities. Future work may focus on integrating advanced optimization algorithms, digital twin technology, and artificial intelligence to further enhance system performance, scalability, and adaptability in increasingly complex logistics environments.

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