



DESIGN AND CONSTRUCTION OF A MOBILE RACKING SYSTEM

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(Received: 03 March 2026; Accepted: 11 June 2026; Published on-line: 01 July 2026)

Abstract: In the era of modern manufacturing, optimizing warehouse space is essential to enhance storage efficiency. This research implements a Mobile Racking System (MRS), a sophisticated solution capable of increasing storage density by up to 80% through dynamic rack maneuvering. The system architecture comprises a fixed guide rail network for structural stability and smooth locomotion, and multi-tier mobile units integrated with obstacle-detection sensors. A critical feature of this design is the intelligent safety barrier system, which monitors personnel and forklift access to ensure rigorous operational safety during aisle-opening sequences. The entire process is controlled and supervised via a Human-Machine Interface (HMI), enabling real-time data processing and fault diagnostics. Experimental results validate the system's high precision and reliability, demonstrating a positioning accuracy of ± 0.05 mm and an emergency stop response time of less than 0.1 seconds. This integrated approach not only maximizes storage capacity but also significantly reduces operational overhead, proving particularly effective for specialized environments such as industrial cold storage.

Keywords: Mobile Racking System, Space Optimization, Warehouse Management, Safety Barriers, HMI Control.

1. INTRODUCTION

The rapid expansion of e-commerce, global logistics networks, and just-in-time manufacturing has created a growing demand for more efficient warehouse management systems. Conventional storage methods often suffer from limited space utilization, low operational flexibility, and high labor requirements. Consequently, modern logistics facilities are increasingly adopting automated and intelligent storage technologies to enhance warehouse performance. One solution that has gained considerable attention is the mobile racking system, which improves storage density by eliminating permanently fixed aisles and allowing access corridors to be created only when necessary. This approach enables warehouses to significantly increase storage capacity while maintaining accessibility to stored goods [1].



The emergence of Industry 4.0 has further accelerated the adoption of smart warehousing technologies. Modern warehouses increasingly integrate cyber-physical systems, intelligent control platforms, and automated material-handling equipment to improve operational efficiency and data transparency. For example, Zhang and Abellera (2025) proposed a cyber-physical framework combining autonomous mobile robots with distributed inventory control, demonstrating improvements in order fulfillment speed and inventory tracking accuracy [2]. These advancements demonstrate the growing impact of intelligent automation on improving warehouse efficiency and operational performance.

Among the available automated storage solutions, mobile racking systems are particularly attractive for facilities where space optimization is critical. In contrast to static pallet racks, mobile racks are mounted on motorized bases that move along floor rails, enabling dynamic aisle generation depending on storage access requirements. Previous research has indicated that mobile racking layouts can significantly increase storage density compared to conventional warehouse configurations [1].

Several studies have also investigated the integration of electromechanical control technologies in movable racking systems. Janthong et al. (2020) developed an automated movable rack prototype using a computer-based control system implemented through LabVIEW, where servo motors were used to drive rack movement and facilitate automated access to storage compartments [3]. Their results demonstrated that the combination of mechanical structures and programmable control systems can effectively support automated warehouse operations.

Beyond mechanical automation, research has also focused on improving the safety and reliability of racking infrastructures. Hussain et al. (2022) introduced a deep learning-based inspection framework utilizing the MobileNetV2 architecture to detect structural defects in pallet racking systems. The proposed method achieved high accuracy in damage detection while reducing the need for manual inspection procedures [4]. There have also been studies that examined the operational performance of mobile rack warehouses. For example, simulation-based research has shown that the efficiency of mobile rack systems depends strongly on storage allocation strategies and order-picking policies, which can influence rack movement frequency and system throughput [5]. In addition, experimental studies have demonstrated that movable rack prototypes driven by servo motors and controlled through computer-based systems can successfully automate rack movement and provide a practical platform for studying automated warehouse operations [3].

Although numerous studies have investigated warehouse automation technologies and storage optimization strategies, the majority of existing works primarily emphasize large-scale Automated Storage and Retrieval Systems (AS/RS) and high-level conceptual frameworks. Recent review and foresight studies have highlighted that modern AS/RS solutions increasingly integrate advanced technologies such as IoT, robotics, and intelligent control, thereby achieving significant improvements in operational efficiency and storage density [6]. However, despite these advancements, their practical deployment remains constrained by high initial investment costs, system complexity, and stringent infrastructure requirements, which limit their accessibility and scalability, particularly for small and medium-scale applications [7].

Consequently, practical implementations that simultaneously integrate mechanical design, motorized rack actuation, and industrial control systems in a compact and experimental environment are still relatively scarce. Most prior research tends to focus either on comprehensive industrial-scale systems or on theoretical optimization approaches, with limited attention given to cost-effective and experimentally validated prototypes. This gap underscores



the need for scalable and accessible experimental platforms that can effectively demonstrate the operational principles of automated mobile racking systems without inheriting the excessive complexity associated with commercial AS/RS solutions.

Therefore, this research presents the design and construction of a mobile racking system prototype integrated with industrial automation technologies. The proposed system incorporates a mechanical rack movement mechanism, servo-based actuation, sensor-based safety detection, and a programmable logic controller (PLC) as the main control unit. The objective of this study is to develop a functional experimental model capable of simulating automated warehouse storage operations while providing a practical platform for investigating control strategies and warehouse automation concepts.

2. THEORETICAL BACKGROUND

2.1. Overview of Warehousing Systems

In the context of supply chain automation, the optimization of storage space plays an important role in improving operational performance while reducing logistics costs. Commonly used warehousing systems include Static Pallet Racking or Selective Racking, Automated Storage and Retrieval System or AS/RS, and Mobile Racking System. Static Pallet Racking is a storage rack system with a simple structure, easy implementation, and relatively low cost. However, this system has limitations in terms of space utilization efficiency because it requires fixed aisles between each row of racks. As a result, a portion of the warehouse area cannot be fully utilized for goods storage.

On the other hand, the Automated Storage and Retrieval System offers high storage density and fast processing because it is supported by an automated system for storing and retrieving goods. Nevertheless, the implementation of AS/RS requires a high initial investment and a more complex maintenance system, making it unsuitable for certain warehouse operational scales. As an intermediate solution, the Mobile Racking System provides a more flexible and efficient option. This system allows rows of racks to move along guide rails to open temporary aisles according to access needs. Through this mechanism, storage space can be used more optimally because the number of fixed aisles can be reduced. Therefore, the Mobile Racking System can serve as an effective solution to increase storage density, maintain operational flexibility, and keep implementation costs more reasonable compared with a fully automated system.

2.2. Structure of the Mobile Racking System

A typical Mobile Racking System consists of three main components that work together to ensure efficient storage operation, stable rack movement, and operator safety. The first component is the racking and mobile base system, in which the storage racks are mounted on movable bases equipped with motors and wheels. These mobile bases function as the driving mechanism that allows the rack rows to move along a designated path. In addition, the mobile bases are commonly equipped with safety features, such as foot sensors, to detect obstacles or objects during rack movement and prevent potential accidents.

The second component is the guide rail system, which is installed precisely on the warehouse floor to direct the movement of the rack units. This rail system ensures that the racks move in a straight and stable alignment, minimizing the risk of deviation, vibration, or structural instability. Accurate rail installation is essential because improper alignment may affect the movement performance of the system and increase the risk of rack displacement or collapse.



The third component is the safety sensor barrier system, which plays a critical role in protecting operators, forklifts, and other equipment within the working area. This system typically consists of photoelectric sensors and proximity sensors installed at the entrance and along the movement path of the mobile racks. These sensors continuously monitor the presence of personnel or forklifts in the operating zone. When an object or person is detected, the sensor signals are used to activate an interlock or emergency stop mechanism, preventing rack movement and ensuring a high level of operational safety. Therefore, the integration of mobile bases, guide rails, and safety sensor barriers enables the Mobile Racking System to operate efficiently, reliably, and safely in modern warehouse environments.

2.3. Control and Drive System

To meet the requirements for precision, stability, and reliable motion control, this study applies a combination of two motor types supported by a central PLC-based control system. The main movement mechanism of the mobile racking system uses an AC servo motor because this type of motor provides high torque, smooth operation, and accurate positioning through a closed-loop control system. The encoder feedback allows the controller to continuously monitor the motor position and correct any deviation during operation. This capability is essential for ensuring that the rack movement remains stable, precise, and safe across different speed conditions. In this system, the Mitsubishi MR-J3-A10 servo driver is used to receive pulse signals from the PLC and control the servo motor using the position control method.

In addition to the servo motor, a stepper motor is used for auxiliary mechanisms, such as the rack-connecting slider. The stepper motor is suitable for this function because it is simple to program, can produce precise incremental movements, and performs effectively for small-load applications. Although it operates based on an open-loop control principle, the stepper motor remains appropriate for mechanisms that require repetitive and accurate positioning without high torque demand. Its simple control characteristics also make it easier to integrate into the overall automation system.

The entire motion and safety operation is coordinated by the Siemens S7-1200 PLC, which functions as the central controller or the main brain of the system. The PLC receives input signals from sensors, push buttons, and other control devices, then processes these signals based on the programmed control logic. After processing the control algorithm, the PLC generates high-speed Pulse Train Output signals to control both the servo and stepper motors. Programming, configuration, monitoring, and system diagnostics are carried out using the integrated TIA Portal platform. Through this combination, the system can achieve accurate motion control, stable rack movement, and reliable automation performance for the Mobile Racking System.

2.4. Communication and Monitoring Protocols

The communication system is designed to ensure reliable data exchange between the PLC and the supervisory computer. In this system, PROFINET, which is based on Ethernet communication, is used as the main communication standard because it provides high-speed, stable, and real-time data transmission. Through PROFINET, operational data, control commands, sensor signals, and system status information can be exchanged efficiently between the Siemens S7-1200 PLC and the supervisory computer. This communication structure supports accurate monitoring and responsive control of the Mobile Racking System. In addition, the Modbus protocol is also considered as a backup communication option, particularly for connecting the PLC with other peripheral devices that may not support



PROFINET communication. Therefore, the combination of PROFINET and Modbus provides flexibility and compatibility in the overall automation system.

The supervision and control function is implemented through an HMI/SCADA interface developed using WinCC in the TIA Portal environment. This interface provides an intuitive and user-friendly platform for operators to monitor and control the system. Through the HMI/SCADA display, operators can observe the operational status of the system, rack positions, motor conditions, and safety alerts in real time. The interface also allows operators to send control commands according to operational needs, either in Manual mode or Auto mode. In Manual mode, the operator can directly control specific system movements for testing, maintenance, or adjustment purposes. Meanwhile, in Auto mode, the system operates automatically based on the programmed control sequence in the PLC. With this integrated supervision and control system, the Mobile Racking System can be operated more efficiently, safely, and reliably.

3. DESIGN AND METHODOLOGY

3.1. System Overview

The Mobile Racking System is designed to improve storage density by reducing the need for permanent aisles between rack rows. In conventional warehouse layouts, fixed aisles occupy a significant portion of the available floor area, thereby limiting storage efficiency. To overcome this limitation, the proposed system allows the rack rows to move along a guided track so that an access aisle is only opened when required. The main structure of the system consists of mobile rack rows, a guidance system, a safety system, and a control interface. The mobile rack rows are formed by storage rack frames mounted on movable bases equipped with motors and drive wheels. These bases enable the racks to move horizontally along the designated path. The guidance system uses rails fixed to the warehouse floor to maintain straight-line movement and prevent misalignment, vibration, or collapse during operation. In addition, the safety system is integrated with sensor barriers to detect obstacles or personnel entering the rack movement area. When an obstruction is detected, the system automatically activates an emergency stop to prevent accidents. The operation and monitoring of the system are carried out through an HMI screen, which allows the operator to control rack movement and observe system conditions in real time.

3.2. Mechanical Design

The experimental model was developed as a scaled-down version of an industrial Mobile Racking System while still representing the essential operational characteristics of the actual system. The prototype consists of three independent rack units, with each rack having dimensions of 120 cm in length, 80 cm in width, and 80 cm in height. Each rack is divided into three storage tiers, allowing the system to accommodate a total of 36 miniature pallets. The pallet used in this model has dimensions of 12 cm × 8 cm × 1.5 cm, which provides a proportional representation of the storage load arrangement in a warehouse environment. The foundation structure has dimensions of 98 cm × 78 cm × 3 cm and integrates parallel guide rails to support the linear movement of the rack units. In addition, a protective frame with dimensions of 98 cm × 78 cm × 87 cm is installed around the system to provide structural support and serve as the mounting location for sensors, indicator lights, and the electrical control cabinet. The overall frame structure and mechanical arrangement of the system are shown in Figure 1.

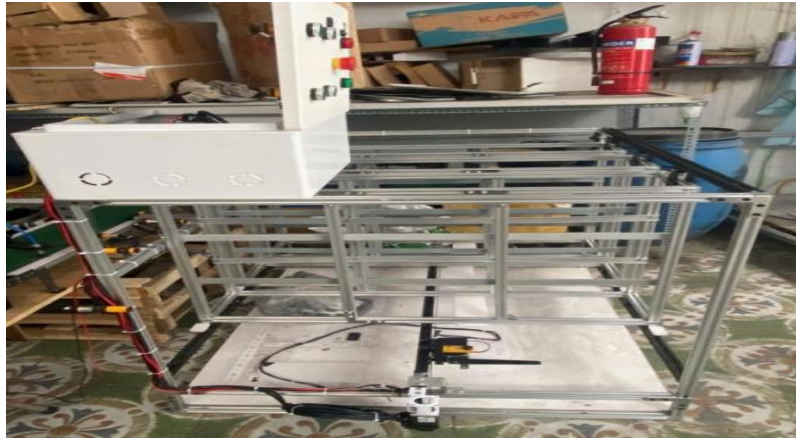


Fig. 1. System frame section.

3.3. Electrical and Control System Design

The electrical and control system is designed based on a functional block architecture to ensure stable operation, accurate motion control, and resistance to electrical interference. The system integrates a central controller, actuator components, sensors, and a supervision interface to coordinate the movement of the mobile racks. The Siemens S7-1200 CPU 1214C DC/DC/DC PLC is used as the central processing unit because it supports flexible expansion and provides high-speed Pulse Train Output functions for motion control applications. This PLC receives input signals from sensors and push buttons, processes the programmed control logic, and sends output commands to the actuators.

The actuator system consists of a Mitsubishi HF-KP13 servo motor and a stepper motor. The servo motor is used to control the main rack movement because it provides high positioning accuracy, stable torque, and closed-loop feedback through an encoder. This feedback enables the system to monitor the motor position continuously and correct movement deviations during operation. Meanwhile, the stepper motor is applied to the horizontal sliding mechanism because it has a simple control structure and is suitable for small-load positioning tasks. The sensor block uses E3F-DS100C4 infrared sensors with a detection range of 7–100 cm. These sensors are installed at the base area to detect obstacles instantly and support the safety interlock function. The wiring connection between the Siemens S7-1200 PLC and the Mitsubishi servo driver is illustrated in Figure 2.



Fig. 2. PLC–servo driver wiring for Siemens S7-1200 and Mitsubishi servo system.



3.3.1. Control Hardware Architecture

The control hardware architecture is arranged to support precise motion control and safe operation of the Mobile Racking System. The Siemens S7-1200 PLC acts as the main controller that coordinates the input and output signals of the entire system. Input signals are obtained from push buttons, infrared sensors, limit switches, and emergency stop devices, while output signals are sent to the servo driver, stepper motor driver, indicator lights, and other control components. The Mitsubishi HF-KP13 servo motor, controlled through its servo driver, is responsible for the primary rack movement because accurate positioning is required to ensure that the rack stops at the correct coordinate. The encoder feedback from the servo motor enables closed-loop position correction, making the movement more reliable and stable. The stepper motor is used for the supporting horizontal sliding mechanism, where simple incremental movement is sufficient. By combining PLC-based pulse control, servo feedback, and sensor-based safety detection, the hardware system can achieve accurate rack movement while maintaining operational safety.

3.3.2. Software Architecture and Supervision

The software architecture and supervision system are developed using the SIMATIC WinCC platform, which is integrated directly with TIA Portal. This integration allows real-time synchronization between the PLC program and the HMI/SCADA interface. Through the HMI display, operators can monitor system status, rack position, movement direction, safety conditions, and fault information. The interface also provides coordinate monitoring with a resolution of 0.01 mm, allowing precise observation of rack position during operation. In addition, the software includes fault status management to identify abnormal conditions such as sensor detection, travel limit activation, or emergency stop events. The homing and save-position functions are also provided to ensure that the system can return to the reference position and store predefined rack coordinates. Therefore, the software architecture not only supports system control but also improves monitoring accuracy, maintenance convenience, and operational reliability.

3.4. Control Logic

The operational process of the Mobile Racking System is designed using two main control modes, namely Manual Mode and Auto Mode. Manual Mode allows the operator to control each mechanism independently through push buttons on the HMI or control panel. This mode is mainly used for testing, adjustment, troubleshooting, and maintenance activities. However, manual operation is still restricted by limit switches and safety sensors to prevent excessive travel and protect the mechanical components from damage. Therefore, even when the system is operated manually, safety interlocks remain active.

In Auto Mode, the system operates according to the programmed control sequence in the PLC. Before movement is executed, the system first verifies all safety conditions, including the status of the emergency stop button, personnel detection sensors, and obstacle detection sensors. The PLC also checks whether the system is in a jam condition or whether the rack has reached its travel limit. If all safety requirements are satisfied, the PLC generates pulse commands to drive the servo or stepper motor toward the predefined destination position. During movement, the system continuously monitors sensor feedback and rack position to ensure that the operation remains safe and accurate. If an abnormal condition occurs, the control logic immediately stops the movement and displays the fault status on the HMI. The overall control program structure and operational logic of the system are presented in Figure 3.

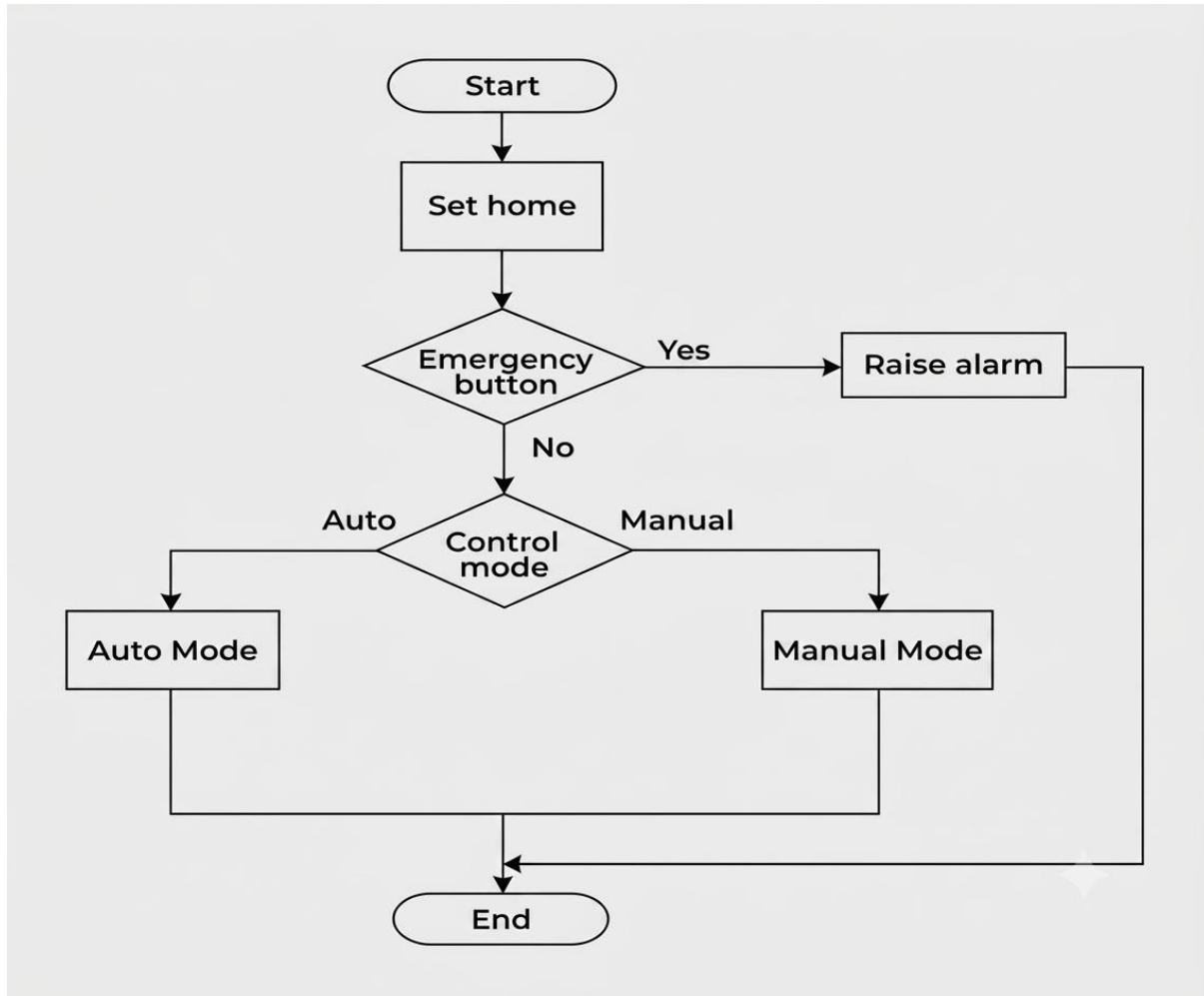


Fig. 3. Control program overview diagram.

4. EXPERIMENT AND RESULTS

4.1. Introduction

This chapter describes the realization process of the Mobile Racking model, starting from the design blueprint and continuing to the development of the physical prototype. The implementation process focuses on integrating mechanical construction, electrical control, sensor protection, and monitoring systems into one coordinated automation model. The system combines a high-power servo drive mechanism for rack displacement with a stepper motor mechanism for precise actuator movement. This combination is intended to ensure that the rack movement can be performed smoothly, accurately, and safely. In addition, the control system is designed to support both manual and automatic operation modes, allowing the prototype to represent the basic operational characteristics of an industrial mobile racking system.

4.2. Mechanical Construction

The mechanical structure of the Mobile Racking model is constructed using high-quality aluminum profiles as the main load-bearing frame. Aluminum profiles are selected because they provide sufficient structural rigidity while maintaining a lightweight, neat, and modular design. This material also makes the assembly process easier because the components can be adjusted, connected, and modified according to the required prototype configuration. The



frame is designed to support the movement of three racking units while maintaining stability during operation.

The guideway system is formed by floor-mounted aluminum profiles that are aligned precisely and arranged in parallel. This guide rail arrangement ensures that the rack wheels can move in a straight and stable path. Proper rail alignment is essential to minimize friction, reduce mechanical binding, and prevent rack misalignment during movement. If the guide rails are not installed accurately, the rack may experience vibration, deviation, or jamming, which can reduce the reliability of the system.

The primary drive system uses a Mitsubishi AC servo motor combined with a timing belt transmission. The timing belt is tensioned along the frame length and functions as the main mechanism for moving the traction assembly toward the target rack position. The servo motor is selected because it provides high positioning accuracy, stable torque, and fast response during translational motion. This drive configuration allows the slide table to move smoothly to the required position before the rack-shifting operation is carried out.

The actuating mechanism is supported by a NEMA 17 stepper motor mounted directly on the mobile slide table. This motor controls a horizontal bar or shifter that performs the physical connection between the traction unit and the selected rack. During operation, the servo motor first moves the slide table to the desired rack position. After the correct position is reached, the stepper motor activates the horizontal bar so that it engages with the rack joint. Once the connection is established, the servo motor pulls or pushes the rack to open the required aisle. This sequence enables the system to move only the selected rack while maintaining controlled and safe operation.

4.3. Electrical and Sensor System Implementation

The electrical and sensor system is implemented to ensure that the Mobile Racking model can operate accurately, safely, and reliably. The system consists of a central control cabinet, motor drivers, protection components, power supply units, and a multi-layered sensor network. The overall electrical configuration is designed to support coordinated motion control between the servo motor and the stepper motor, while the sensor system provides real-time feedback for safety monitoring and system protection.

4.3.1. Central Control Cabinet

The central control cabinet functions as the main control center of the Mobile Racking model. A Siemens S7-1200 PLC with CPU 1214C is used as the central processor to coordinate the operation of the entire system. The PLC is responsible for processing input signals from sensors and control devices, executing the programmed logic, and generating pulse outputs to control both the Mitsubishi AC servo motor and the stepper motor. This configuration allows the system to achieve synchronized motion control between two different motor types.

Inside the control cabinet, the Mitsubishi MR-J4-10A servo driver and the TB6600 stepper driver are arranged systematically on DIN rails. This arrangement improves cable organization, simplifies inspection, and supports proper heat dissipation during operation. The servo driver receives command signals from the PLC and controls the Mitsubishi AC servo motor, while the TB6600 driver controls the NEMA 17 stepper motor based on pulse and direction signals. In addition, CHINT circuit breakers and switching power supplies are installed to provide stable electrical protection and voltage supply for the control equipment. This cabinet layout ensures that the electrical system is safe, organized, and convenient for maintenance.



4.3.2. Sensor System

The sensor system is designed as a multi-layered protection network to ensure intelligent operation and operator safety. Photoelectric sensors are strategically installed to identify the aisle condition between the three racks. The feedback signals from these sensors allow the PLC to determine the current rack position and update the warehouse status on the monitoring interface. These sensors also play an important role in detecting human presence or obstacles when an aisle is open. If a person or object is detected in the movement area, the PLC automatically locks all motion commands to prevent unsafe rack movement.

In addition to photoelectric sensors, proximity sensors are installed at the entry boundaries and travel limit areas. These sensors function as dynamic protection devices during rack movement. If abnormal intrusion or an unsafe condition is detected, the PLC immediately triggers an emergency stop for both the servo motor and the stepper motor. This fast feedback mechanism is important because the moving rack has inertia, and delayed stopping could increase the risk of collision. The E3F-DS30C4 infrared photoelectric sensor used in the safety system is shown in Figure 4.

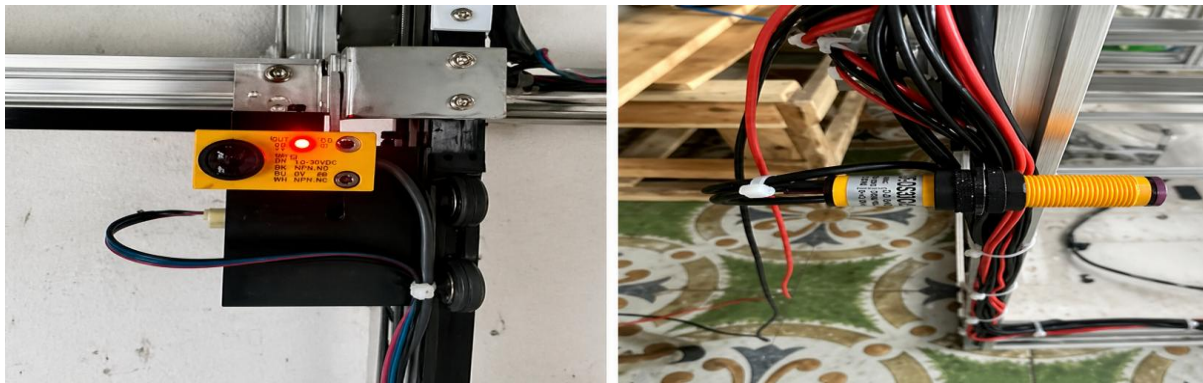


Fig. 4. E3F-DS30C4 infrared photoelectric sensor.

4.4. Parameter Settings and Software Configuration

The parameter settings and software configuration are carried out to ensure that the motion system can operate with accurate positioning, stable response, and safe movement. The configuration process includes setting the stepper motor parameters in TIA Portal, adjusting the Mitsubishi servo parameters using MR Configurator2, and developing the monitoring interface using WinCC. These settings are important because the accuracy and stability of the Mobile Racking model depend not only on the mechanical structure but also on the correct configuration of the control software and motor parameters.

4.4.1. Stepper Motor Configuration for the Horizontal Bar Mechanism

The stepper motor for the horizontal bar mechanism is controlled using Technology Object Axis_M2 in TIA Portal. This configuration manages the Pulse Train Output synchronously so that the stepper motor can move the shifter mechanism according to the required distance. The control mode is set to PTO, where pulse A and direction B are generated by the Siemens S7-1200 CPU 1214C. The pulse output is assigned to address %Q0.2, while the direction output is assigned to address %Q0.3. The movement unit is configured in millimeters to simplify position programming and monitoring.

The stepper driver is set to 1,000 pulses per motor revolution based on the TB6600 driver switch configuration. The load movement is defined as 10.0 mm per revolution, meaning that

each pulse produces a displacement of 0.01 mm. This resolution allows the horizontal bar to move precisely when engaging or disengaging with the rack joint. The maximum velocity is set to 250.0 mm/s, while the start and stop velocity is set to 1.0 mm/s. The acceleration and deceleration are configured at 249.0 mm/s² with a ramp-up and ramp-down time of 1.0 second. This gradual acceleration profile ensures smooth movement, reduces mechanical shock, and prevents interference with the sensor system. Hardware limit switches using proximity sensor signals are also applied to restrict the physical travel of the mechanism. In addition, active homing is used to establish the absolute origin of the horizontal bar when the system starts.

4.4.2. Mitsubishi Servo Parameters Using MR Configurator2

The Mitsubishi servo parameters are configured using MR Configurator2 to optimize dynamic response and ensure synchronization with the PLC command signals. Parameter PA01 is set to 0000, indicating that the servo operates in position control mode. This mode is suitable for the Mobile Racking model because the rack movement must stop accurately at predefined coordinates. The electronic gear parameters PA06 and PA07 are set with a numerator value of 70,000 and a denominator value of 1,000. These values determine the relationship between the input pulse command and the actual motor movement.

Parameter PA14 is configured to match the physical direction of the timing belt movement. This adjustment ensures that the command direction from the PLC corresponds correctly to the actual movement direction of the slide table. The acceleration and deceleration parameters PC01 and PC02 are initially set to 5 ms for testing purposes. However, for heavy-load operation, these values can be increased to produce smoother movement and reduce vibration. Parameter PC16, which controls the electromagnetic brake sequence, is set to 70 ms to ensure that the brake is released before rotation begins and engages immediately after the motor stops. The gain parameters are also adjusted to improve system stability, with the load inertia ratio PB06 set at 2.2, the position loop gain PB08 set at 150 rad/s, and the speed loop gain PB09 set at 3,000 rad/s. These settings help the servo motor respond accurately to the PLC command while maintaining stable rack movement.

4.4.3. WinCC Monitoring Interface Implementation

The monitoring interface is developed using WinCC Runtime Advanced to provide real-time supervision and control of the Mobile Racking model. The interface displays the real-time coordinates of the slide table, the open or closed status of each rack, and the current velocity of the moving mechanism. Through this display, the operator can observe the system condition during both manual and automatic operation. The interface also supports Auto Mode, where the operator can select the pickup or target location, and Manual Mode, where the operator can jog the motors using directional control buttons. The WinCC interface used for monitoring and controlling the Mobile Racking model is shown in Figure 5.

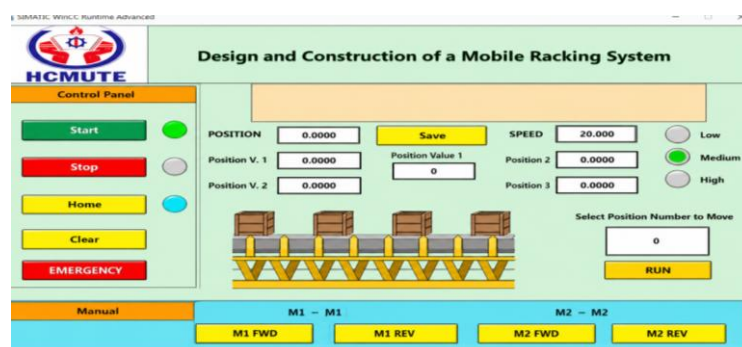


Fig. 5. Interface of WinCC.



4.5. Results

4.5.1. Research Results

After conducting theoretical research on Mobile Racking systems and motion control technologies, several important results were achieved. The study successfully applied Pulse Train Output from the Siemens S7-1200 PLC to control two different motor systems, namely the Mitsubishi AC servo motor and the stepper motor. This result demonstrates that the PLC can coordinate both high-precision servo movement and stepper-based actuator movement within one integrated control system. The implementation of PTO control also confirms that the system can generate accurate pulse commands for motion positioning.

The study also produced operational algorithms for both Manual Mode and Auto Mode. These algorithms define the movement sequence of the racking units according to the required aisle-opening scenarios. In Manual Mode, the operator can control the mechanism independently for testing, adjustment, or maintenance. In Auto Mode, the system executes the movement sequence automatically after verifying the safety conditions. This control logic ensures that the rack movement can be performed accurately and safely.

Another important result is the successful integration of a multi-layered safety system using photoelectric and proximity sensors. These sensors allow the PLC to detect unauthorized intrusion, obstacle presence, and unsafe movement conditions. When a dangerous condition is detected, the system automatically stops the motor operation and prevents further movement. This protection system improves operator safety and reduces the risk of mechanical collision during rack operation.

4.5.2. Experimental Results

The completed Mobile Racking model shows a high level of similarity with the initial 3D design and meets the established technical requirements. The aluminum profile frame provides good rigidity while maintaining lightweight characteristics and a clean appearance. The guide rail system is aligned precisely, allowing the three rack units to move smoothly without significant mechanical jamming or vibration. This result indicates that the mechanical construction is adequate to support stable rack movement.

The timing belt drive system combined with the Mitsubishi MR-J4-10A AC servo operates stably during translational motion. The servo motor is able to move the slide table at different speed levels while maintaining good positioning accuracy. Meanwhile, the NEMA 17 stepper motor that controls the rack shifter operates smoothly without missing steps. This performance is supported by proper acceleration and deceleration settings, which reduce shock during movement and improve actuator reliability.

The electrical system is also implemented in a systematic and organized manner. The Siemens S7-1200 CPU 1214C PLC, servo driver, stepper driver, circuit breakers, and power supply units are arranged logically inside the control cabinet. This arrangement makes inspection and maintenance easier while improving cable management and electrical safety. The calibrated gain and electronic gear parameters allow the servo motor to stop accurately at the set coordinates. In addition, the photoelectric and proximity sensors provide fast feedback to the PLC and successfully activate the emergency stop mechanism when intrusion is detected.

The monitoring interface developed using WinCC Runtime Advanced supports flexible switching between Manual Mode and Auto Mode with very low control latency. The displayed position values achieve a resolution of four decimal places, while the experimental error is approximately ± 0.05 mm compared with actual measurements. The interlock system and



emergency warning functions operate reliably, locking pulse output commands within 0.1 seconds after an incident is detected. Continuous operation tests at different speed levels show no communication errors or data conflicts. These results demonstrate that the Mobile Racking model has good stability, accurate motion control, and reliable safety performance.

5. CONCLUSION

Upon completion of the research and implementation, the project successfully achieved all initial objectives regarding the design and fabrication of the Mobile Racking System. Experimental results indicate stable operation, with the extruded aluminum frame structure ensuring high structural rigidity and aesthetic standards. In terms of control engineering, the study successfully mastered precision position control by utilizing high-speed Pulse Train Output (PTO) from the Siemens S7-1200 PLC to synchronize the Mitsubishi AC Servo and Stepping motors. Notably, the system achieved remarkable accuracy with a positional error margin of only ± 0.05 mm and an emergency stop response time of less than 0.1 seconds, facilitated by a multi-layered sensor protection network. The WinCC Runtime Advanced interface not only provides intuitive monitoring but also ensures active safety through integrated interlock mechanisms. While successfully optimizing storage space by 80%, the system maintains significant potential for further enhancement by integrating QR code management and IoT connectivity to meet the rigorous standards of modern Smart Factories.

ACKNOWLEDGMENT

This research was funded by Ho Chi Minh City University of Technology and Engineering (HCM-UTE), Vietnam, under grant No. SV2026-224. We want to give thanks to Ms. Eng. Tan-Doi Nguyen (HCM-UTE) for her supervision. Link of system operation is: youtube.com/watch?v=PtJfSOsRXmM&feature=youtu.be.

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