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Development of Control System for a Prefabricated Board Transfer Palletizer Based on S7-1500 PLC

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Abstract: A palletizing machine is extensively utilized in the production of prefabricated boards. However, due to its large and complex system, as well as its low level of automation, the development of the control system of current transfer palletizing machines has proven challenging. To address these issues, a palletizer control system based on S7-1500 PLC has been designed. This design encompasses the hardware electrical system, software control system, and human–machine interaction system for the palletizer. A structured programming strategy has been adopted to simplify the system and enhance its expansion compatibility while improving efficiency and automation levels.

Keywords: control system; palletizer; S7-1500 PLC; human–machine interface

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1. Introduction

The prefabricated building mode, utilizing premanufactured panels assembled on-site, has gained widespread adoption with advancements in manufacturing and construction industries. The precast board is a reinforced concrete product that requires storage and maintenance prior to its utilization. It possesses significant volume and high quality. Traditionally, the transfer of precast boards to the warehouse kiln involves manual interaction with lifting equipment, resulting in low operational efficiency and safety factors. With the advancement of science and technology, the introduction of prefabricated board transfer palletizers has revolutionized the way in which prefabricated boards are transferred. Serving as cutting-edge transfer equipment, this palletizer effectively replaces traditional methods, resulting in reduced manpower and material resource consumption while simultaneously enhancing working efficiency and safety standards.

In recent years, although China has made significant advancements in palletizing technology, its palletizing machines still lack universality and stability compared to those developed in foreign countries. Additionally, there is a considerable gap in terms of intelligent automation. Therefore, many large enterprises are more inclined to choose imported palletizers with more mature development, higher efficiency, and accuracy. However, the price of imported palletizers remains high, which puts great pressure on enterprises [1,2].

The above-mentioned issues are addressed through the design of a control system for a prefabricated board transfer palletizer, which is based on S7-1500 PLC (Programmable Logic Controller, SIEMENS AG Berlin, Germany). Additionally, an HMI (Human–Machine interface) is incorporated to facilitate monitoring of the palletizer, thereby enhancing the overall automation level of the system.

2. Palletizer Structure and Working Principle

The palletizer adopts a gantry-type lifting structure, consisting primarily of a transverse movement system, a lifting system, a bracket, a pushing mechanism, transverse movement positioning devices, lifting positioning devices, and a lifting door mechanism, as depicted in Figure 1.

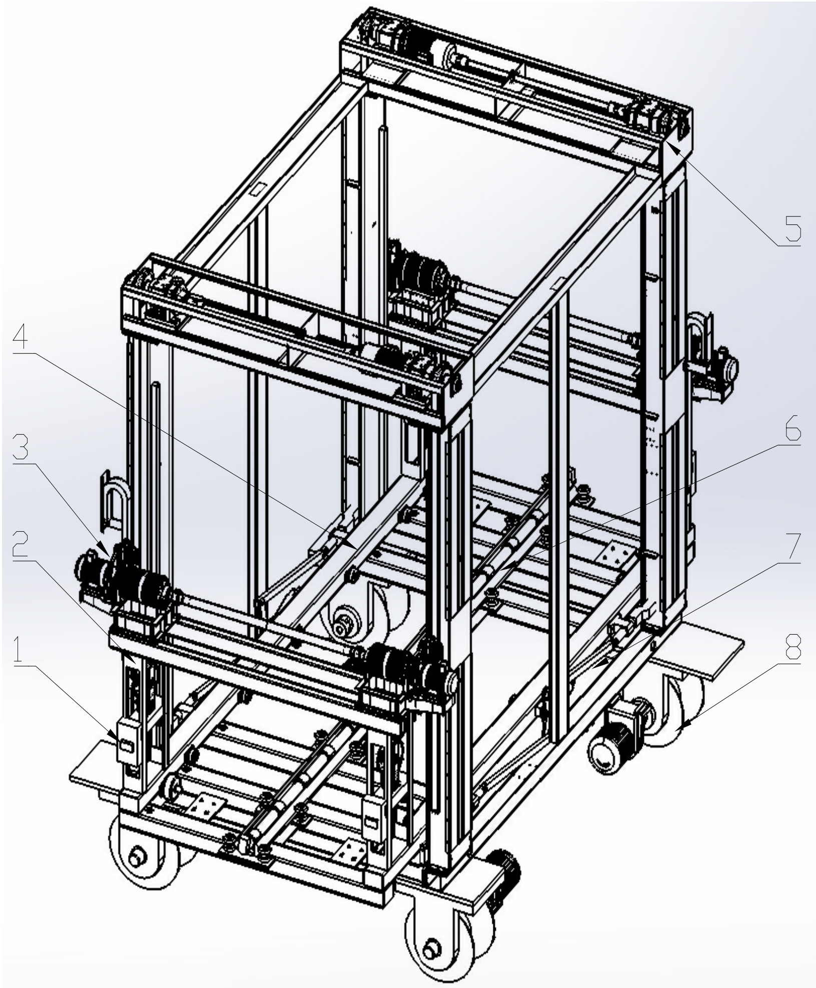

Figure 1. Palletizer structure diagram: 1—door lifting clamp, 2—door lifting mechanism, 3—door lifting motor, 4—carrier platform, 5—platform lifting system, 6—pushing mechanism, 7—lifting positioning device, and 8—frame transverse movement system.

The transverse movement system utilizes two variable frequency brake motors to drive the palletizing locomotive wheels, while four sensors are strategically positioned at the bottom of the frame (as depicted in Figure 2), including a positioning sensor and three deceleration sensors. The positioning sensor corresponds to the positioning stop block located in front of the kiln position, while the deceleration sensor corresponds to three respective deceleration stop blocks. Once the palletizer reaches its designated position, the corresponding sensor will be triggered, enabling the system to accurately determine the current column position of the palletizer.

Lifting system: A variable frequency brake motor drives a set of lifting devices through the pulley block to facilitate platform elevation, while an absolute encoder is installed between the platform and the frame to accurately measure the vertical displacement of the platform.

Positioning devices: These consist of hydraulic-driven frame transverse positioning devices and platform lifting positioning devices, both of which can extend and retract the positioning mechanism. The insertion of the frame transversal positioning devices into the ground positioning slots ensures fixed placement of the palletizer column. Similarly, when the platform lifting positioning devices are inserted into the column positioning slots, it guarantees fixed placement of the palletizing layer.

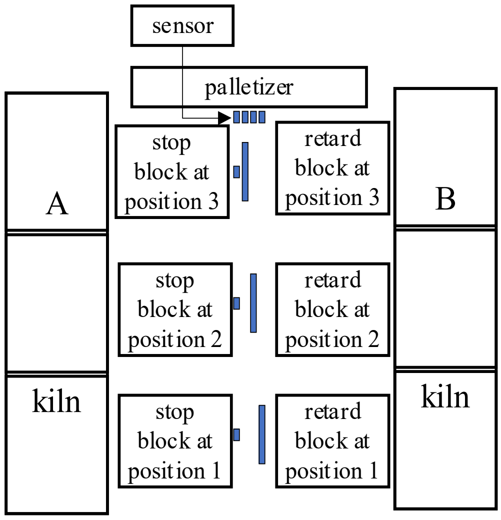

Figure 2. Distribution diagram of lateral displacement sensor.

Door lifting mechanism: The door lifting mechanism consists of a set of lifting devices driven by a variable frequency brake motor through the pulley block. These devices drive the hydraulic door lifting clamp, which extends into the kiln door card slot. When the door lifting device is raised or lowered, it opens or closes the kiln door, allowing prefabricated boards to enter and exit.

Pushing mechanism: The pushing mechanism operates through a gear rack mechanism powered by a variable frequency brake motor. This motor drives the pushing device to move horizontally while the top hook undergoes rotational movement driven by hydraulic pressure.

3. Hardware System

3.1. Control Requirements

The storage and maintenance kilns are positioned on the left and right sides of the palletizer, as depicted in Figure 3. Kiln A is located on the left side, while kiln B is situated on the right side. Each maintenance kiln section consists of three columns with seven lay-ers each, resulting in a total of 21 kiln positions.

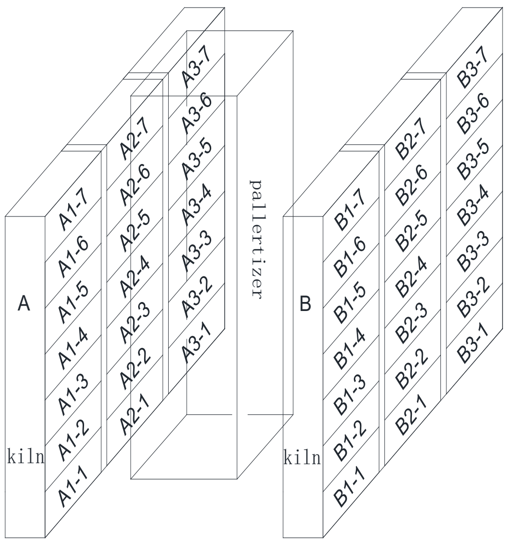

Figure 3. Warehouse Kiln Location Distribution Map.

The transfer process utilizes a standard template to simultaneously transport the prefabricated board (hereinafter referred to as the "prefabricated board") along with the template during palletizer operation.

When operating, the palletizer moves between kiln A and kiln B, with A1-1 and A2-1 serving as warehousing positions for prefabricated boards that need to be transported into the kiln. The palletizer takes the prefabricated board from the roller conveyor line and transports it to the designated maintenance kiln position through a series of movements, including transverse movement, lifting, opening the door, conveying, pushing, and closing the door. The B1-1 position serves as the exit kiln for prefabricated boards. When a maintenance operation is completed, the palletizer retrieves the prefabricated board from the kiln by following a sequence of actions: opening the door, hooking, closing the door, conveying, lifting, transverse movement, and finally transferring it to the roller conveyor line at the kiln position for further processing. Afterward, the palletizer resets itself to its initial state.

The initial state of the palletizer is that the bracket platform is securely fixed and docked at the A1-1 kiln position. The pushing device is in the screw-off mode and positioned in the middle of the bracket. The door lifting mechanism is in a lowered state, while the door lifting clamp remains retracted. Additionally, both the frame transverse movement positioning devices and platform lifting positioning devices are extended.

3.2. Important Hardware

The schematic diagram of the palletizer control system is illustrated in Figure 4.

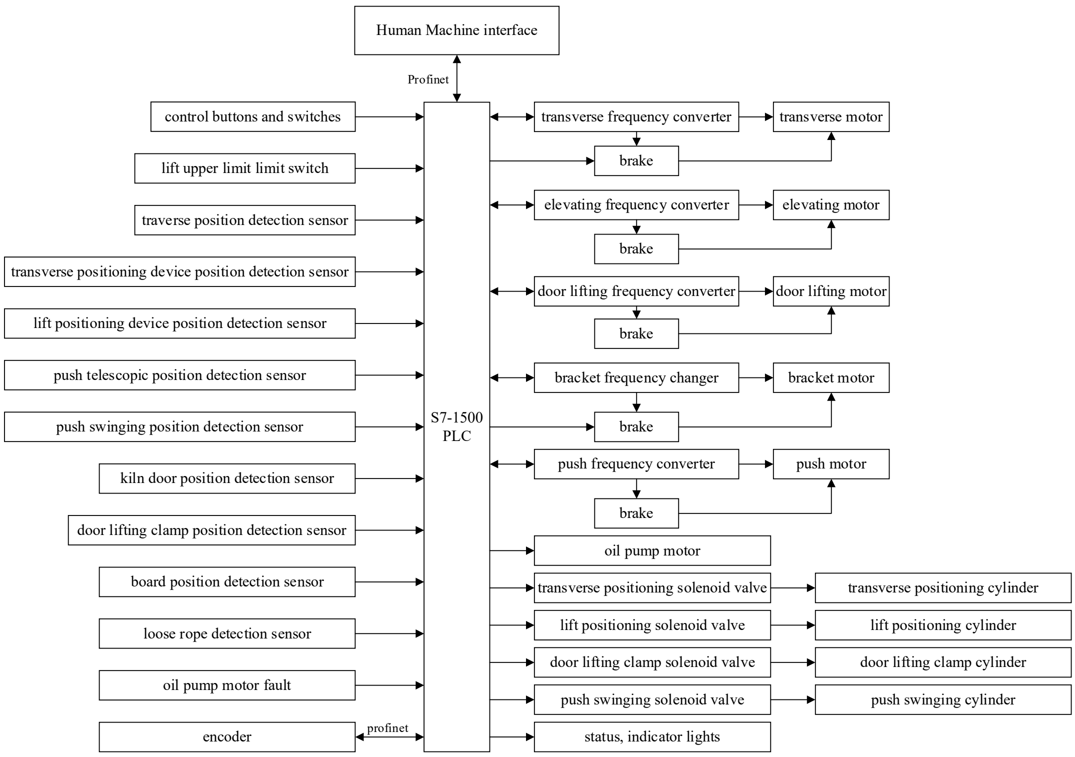

Figure 4. The overall framework diagram of the control system.

- The Controller

The palletizing system is characterized by its large and intricate nature, requiring the collection and control of a total of 73 digital input (DI) signals and 30 digital output (DO) signals simultaneously. Additionally, it necessitates complex data operations and communication with other equipment. The Siemens S7-1500 PLC possesses strong data computing capabilities, a wide range of interfaces, support for various communication protocols, flexible selection and configuration options, as well as easy expandability [3]. After careful consideration, the PLC control system is constructed using the Siemens S7-1513-1 PN CPU module, a 190 W 120/230 VAC power module (PM), two high-feature digital input modules DI 32 × 24 VDC HF, one high-feature digital input module DI 16 × 24 VDC HF, and one high-feature digital output module DQ 32 × 24 VDC/0.5 A.

- The Touch Screen

In order to enable users to monitor real-time information of the palletizer control system and configure various operating parameters [4], the PFXGP4502WADW touch screen from Proface has been selected as the man-machine interface in this system. The screen measures 10.4 inches and supports multiple communication modes, including serial port and Ethernet. The touch screen design software GP-Pro EX 4.09 SP1 offers a wide range of control device libraries, graphical controls, and functional controls that enable the configuration of diverse dynamic and control functions [5–7]. Through the touch screen interface, operators can send control instructions to the PLC for palletizer control. Simultaneously, the touch screen allows the reading of PLC data to monitor the palletizer operation status and provide fault alarms.

- The Encoder

The vertical displacement of the palletizer platform during the lifting process is measured using the EVM58N-031IZR0BN-1213 absolute multi-turn encoder manufactured by PEPPERL + FUCHS in Mannheim, Germany. This encoder has a maximum detection capability of 4096 turns and is equipped with a 6 mm shaft diameter. It supports the Siemens Telegram 81 message format and offers a resolution of 8192 (13 bits) per single revolution. To ensure accurate measurement, a traction wire with a diameter of 2 mm and length of 10,500 mm has been selected [8]. The encoder is securely mounted on the lower frame, and the traction line is connected to the platform. As the platform moves up and down, it drives the encoder to accurately measure longitudinal displacement.

The PLC achieves communication with the touch screen and encoder through the Profinet bus, while the S7-1500 CPU module integrates a standard RJ-45 Ethernet interface. This communication method exhibits characteristics such as long transmission distance, supporting cable lengths of up to 100 m, fast transmission and response speeds, as well as flexible expansion [9].

- The Inverters

The transverse movement of the frame, the lifting of the carriage platform, the driving of the carriage, the movement of the pushing device, and the lifting of the door lifting mechanism are all powered by variable frequency motors with different power and braking capabilities.

The frame traverse motors consist of two 2.2 KW three-phase AC asynchronous motors equipped with speed regulation and brake control. These motors are controlled by the VFC 5610-5K50-3P4-MNA-7P frequency converter manufactured by Bosch Rexroth in Germany. The inverter is equipped with a heavy-duty rated power of 5.5 kW, torque and speed control modes, digital and analog input and output controls, as well as support for Modbus communication [10].

The primary parameters of the inverter are configured as follows:
E0.00 = 21 first frequency setting source: multi-speed setting
E0.01 = 1 first running instruction source: multifunctional digital input
E0.07 = 20 digital setting frequency, the motor's slow-running frequency
E3.40 = 30 multi-speed frequency 1, the motor's high speed operating frequency
E0.09 = 50, the upper limit of the output frequency
E0.26 = 4.0 acceleration time 1, the time taken to accelerate from 0 to a slower speed
E0.27 = 4.0 deceleration time 1, the time taken to decelerate from a slower speed to 0
E3.10 = 6.0 acceleration time 2, the time taken to accelerate from 0 to a high speed
E3.11 = 6.0 deceleration time 2, the time taken to decelerate from a high speed to 0
E0.50 = 1 stop mode, free stop 1

E1.15 = 0 two-wire operation control: forward/stop, reverse/stop
E1.00 = 35 X1 input selection: forward running (FWD)
E1.01 = 36 X2 input selection: reverse running (REV)
E1.02 = 1 X3 input selection: multi-speed control input 1
E1.03 = 34 X4 input selection: fault reset
E2.01 = 0 DO1 output selection: the inverter is ready for operation
E2.15 = 1 relay 1 output selection: the inverter is running
C0.00 = 0 control mode: v/f control

The connection between the transverse motor of the frame and the frequency converter is illustrated in Figure 5, where KA serves as an intermediate relay controlled by PLC. By disconnecting the KA3 contact and connecting either KA1 or KA2 contact, the motor operates at a slow speed, while connecting both KA3 and either KA1 or KA2 contacts enables fast forward or reverse rotation of the motor. Additionally, a fault reset on the inverter can be performed by activating the KA4 contact.

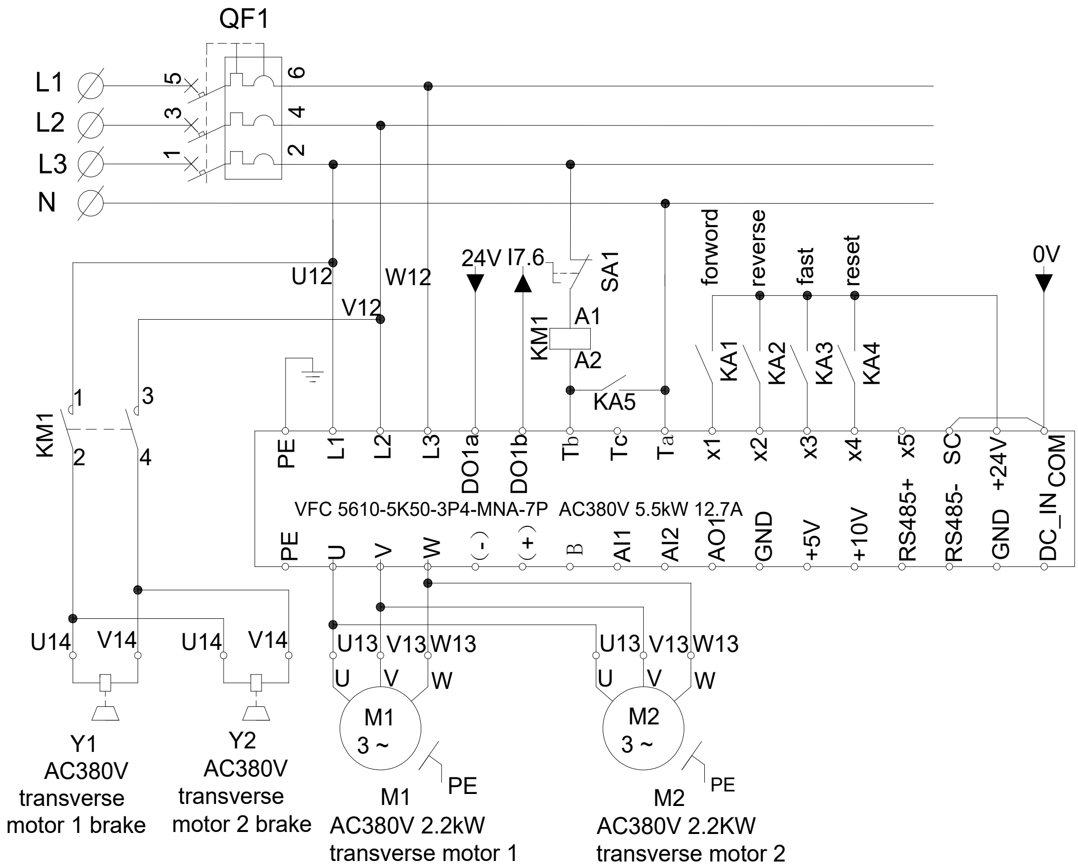

Figure 5. Wiring diagram for the motor and frequency converter.

The frame's transverse movement motor brake utilizes an electromagnetic lock brake system. The electromagnetic lock brake is a mechatronic device that utilizes electromagnets to generate and control braking forces, enabling efficient braking operations through the application and release of electromagnetic force. When the brake receives electrical power, it disengages, and when power is lost, it engages to secure the frame. During motor startup, premature disengagement of the brake can lead to slippage, while delayed disengagement can cause motor blockage and potential failure of the frequency converter. During the motor shutdown, early engagement of the brake results in excessive impulse current and increases the risk of frequency converter failure; on the other hand, delayed engagement prevents timely stopping of the motor [11].

To address this issue, the contactor KM1 coil is controlled by the inverter relay output terminal, while the brake action is regulated by the KM1 contact. In the diagram, the Tb, Ta, and Tc terminals of the inverter respectively represent the common end of relay output, normally open contact output end, and normally closed contact output end. During motor operation, power is supplied to the KM1 coil to release the brake. Conversely, when motor operation ceases, power to the KM1 coil is cut off and thus engages the brake. However, in order to accurately position the frame, the brake cannot be immediately engaged after the motor stops running. Instead, it should be engaged when the frame continues to move forward by inertia and reaches the desired positioning position. Therefore, a free stop 1 mode is set (wherein when the stop instruction is effective, the frequency converter stops outputting and the motor comes to a free stop), and an intermediate relay KA5 is introduced. The PLC controls KA5 to close, ensuring that electricity keeps the brake in a loose state. When the frame reaches its positioning position, PLC control disconnects KA5, causing power loss to engage the brake. In addition, a switch SA1 is connected in series in the KM1 circuit, and SA1 can be disconnected to control the KM1 coil power loss when KA5 fails to make the KM1 coil power loss.

In addition to controlling the external electromagnetic brake via the relay output port, the carrier platform lifting motor inverter is also connected to a DC brake resistor. The control principle for the remaining motor is identical to that of the transverse motor within the frame; however, it does not necessitate separate PLC control for braking.

4. Palletizer Software System Design

4.1. Kiln Positioning

The direction of the palletizing locomotive frame's movement, whether forward or backward, is determined by the relative position between the current column and the target column. The elevation or descent of the carriage platform depends on the relative position between the current layer of the palletizer and the target layer. The current column of the palletizer is determined based on data from its chassis sensors as well as the deceleration and positioning blocks arranged on the ground. When both the No. 1 deceleration block and the No. 1 positioning block are detected by the sensor, it indicates that the palletizer is currently positioned in column 1, with column 2 and column 3 determined accordingly. The height reference values for each layer are compared to encoder measurements to determine the current layer of the carriage platform.

The target column and layer of the palletizer are determined through a modulo operation based on the known kiln position number.

According to the division with remainder theorem, if a and b are two integers, where b is greater than zero, then there exist two unique integers, q and r, such that

$$a = b \times q + r, 0 \leq r < b \tag{1}$$

The equation is established [12], where q represents the quotient obtained by dividing a by b, and r denotes the remainder when a is divided by b.

Firstly, each kiln site is assigned a number, with kiln A designated as A1-1~A3-7 corresponding to 0~20, and kiln B designated as B1-1~B3-7 corresponding to 21~41. Subsequently, the target column is computed using Formula (2), while the target layer is determined using Formula (3).

$$\mathrm{c} = \begin{cases} [w/x], 0 \leq w < 21 \\ [(w-21)/x], 21 \leq w \leq 41 \end{cases} \tag{2}$$

$$\mathrm{r} = \begin{cases} w - [w/b] \times x, 0 \leq w < 21 \\ (w-21) - [(w-21)/x] \times x, 21 \leq w \leq 41 \end{cases} \tag{3}$$

The target column, denoted as c where $0 \leq \mathrm{c} \leq 2$; the target layer, denoted as r where $0 \leq \mathrm{r} \leq 6$; the target kiln site number is represented by w; x represents the total number of kiln sites in the layer direction, with $x = 7$; $[w/x]$ denotes the integer part obtained by dividing w by x.

The procedure for determining the layer and column of the kiln position based on the kiln number is illustrated in Figure 6. If the kiln number is less than or equal to 20, it is classified as kiln A; if the kiln number falls between 21 and 41, it is classified as kiln B. If the kiln number exceeds 41, it indicates an incorrect setting and assigns a value of 0 to the kiln number. The layer and column of the target kiln are then calculated using MOD (the instruction to find the remainder) and DIV(the instruction for division).

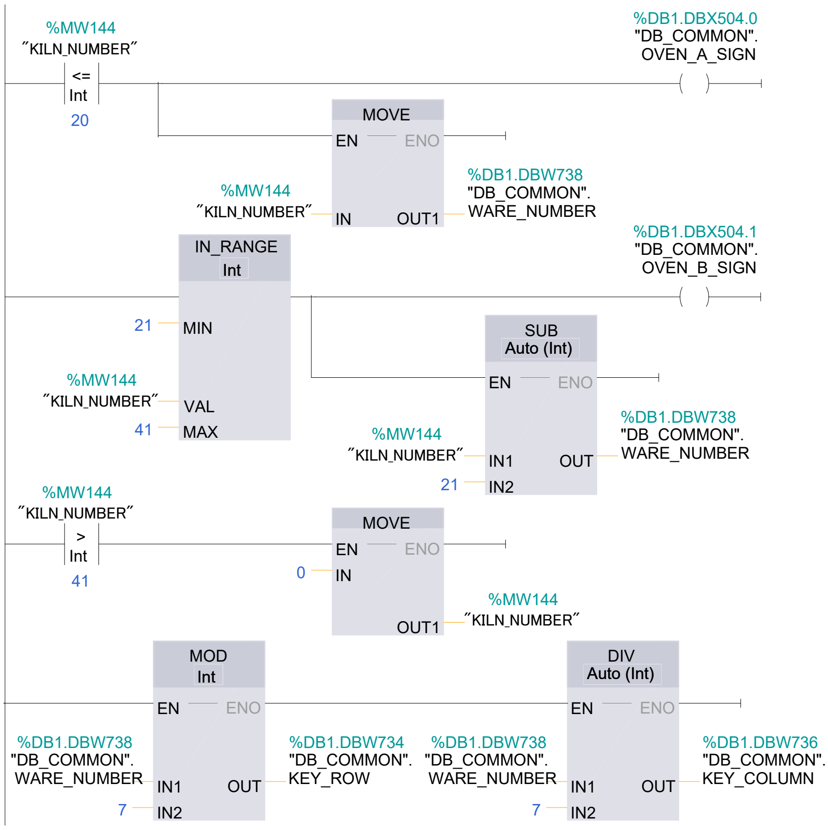

Figure 6. Kiln position target location calculation.

4.2. Control Mode

The control mode of the palletizer is divided into manual mode, maintenance mode, and automatic mode. The mode switch is located on the operating table. Manual mode is primarily utilized for scenarios requiring single-step execution or when complete workflows are not necessary for regular usage. In this mode, the device possesses comprehensive protection functions and can only operate when working conditions are met. Maintenance mode is employed for debugging and performing maintenance operations in case of device exceptions. In maintenance mode, all operations can be executed solely by clicking. Automatic mode is used for normal production, where the palletizing machine automatically carries out operations according to operation instructions issued by the HMI.

4.3. Programming in Automatic Mode

The control system for palletizing adopts a structured programming approach to decompose the functions of the palletizer and write corresponding function subroutines. The main modularized subroutines for palletizer control and its functions are as follows:

1. Initialization subroutine: The palletizer equipment may dock randomly at any position when the control system fails, restarts normally, or completes the work, which deviates from the control system parameter information. Therefore, it is necessary to

perform an initialization reset operation. This includes initiating the palletizer control system startup and control parameters, resetting working mode, motor protection and emergency stop faults, as well as controlling the reset of the palletizer's initial state [13].

2. Subroutine for automatic mode: In the automatic mode, there are various operational modes, including board storage operation, board retrieval operation, frame transverse operation, platform lifting operation, transverse + lifting operation, taking board operation, and sending board operation. The operator selects the appropriate operational mode based on the specific requirements of the palletizer's task at hand. Upon pressing the automatic start button, the palletizer executes its tasks automatically in accordance with a predefined sequence of actions.
3. Frame transversal subroutine: It is responsible for controlling the horizontal transversal motors and positioning devices of the palletizer. This includes controlling motors starting, reversing, speed regulation, and braking, as well as managing the extension and retraction of the transversal positioning devices and detecting their action state.
4. Platform lifting subroutine: It is responsible for controlling the vertical lifting motors and the lifting positioning devices of the carrier platform. This includes controlling motor starting, reversing, speed regulation, and braking, as well as managing the extension and retraction of the lifting positioning devices and detecting their action state.
5. Kiln doors opening and closing subroutine: It is responsible for controlling the lifting motors in the door lifting mechanism and the door lifting claw devices. This includes controlling motor starting, reversing, etc., as well as managing the extension, retraction, and action state detection of the door-lifting claw devices.
6. Push and hook template subroutine: It controls the rotation and movement of the push and hook template mechanism, including starting, reversing, and speed regulation of the push motor, as well as rotating the top hook and detecting its action state.
7. IO processing subroutine: It is responsible for gathering input signals from sensors, operation station buttons, frequency converter operating status, motor operating status, etc., and controlling the frequency converters, motors, hydraulic cylinders, indicator lights, and other equipment through program logic calculation and processing.
8. Communication processing subroutine: Facilitate the communication between the PLC and touch screen, encoder, and other devices while effectively managing the exchange of communication interaction data.
9. Data processing subroutine: It includes calculations for lifting and positioning the palletizer, monitoring the kiln position status, and processing template coding information.

The control program flow for the retrieval and storage of the board is illustrated in Figure 7.

4.4. Human–Machine Interface Design

The man-machine interface is developed using Proface GP-Pro EX 4.09 SP1 software, encompassing six interfaces: system homepage, status display, parameter configuration, alarm information, operation interface, and user management.

The system home page is utilized to display fundamental information regarding the operating system. The status display interface is employed to exhibit real-time operational data of the palletizer. The alarm information interface serves to present warning messages, such as frequency converter faults, motor malfunctions, limit triggers, sensor failures, etc. In case of an alarm occurrence, the corresponding alert information will appear for operator verification and confirmation [14]. The parameter setting interface is utilized to configure the positioning height benchmark and positioning range of each layer's positioning bolts on the platform. The operation interface serves as the primary control panel for managing palletizer operations during regular production activities. The user management interface enables operators to access the system interface using their accounts and passwords, providing functions such as account and password reset, as well as system platform operation authorization [15]. Once logged in, users can freely switch between different operation interfaces.

Figure 7. Board retrieval and storage control program flowchart.

5. System Debugging

The operation interface depicted in Figure 8 illustrates the storage of the board at kiln No. 16 of kiln A. In the figure, the maintenance kiln's kiln positions have four states: red, yellow, green, and gray. Among them, gray represents a non-selectable kiln position because A1-1 and A2-1 are for prefabricated boards entering the warehouse, while B1-1 is for outgoing warehouse purposes. Red indicates that the prefabricated board at the current kiln position has been cured and can be retrieved. Yellow indicates that the prefabricated board at the current kiln position is undergoing maintenance. Green indicates that the current kiln position is empty and available for storage. The interface allows for setting the maintenance time of the prefabricated board and the number of entering kiln templates, as well as displaying information such as the current position of the palletizer, target position, and number of leaving kiln templates. Moreover, operators can directly click on the kiln position graphic on the touch screen to set the desired kiln position number. Additionally, they can use buttons on the touch screen to perform actions like storing the board, retrieving the board, transversing the board, lifting the board individually or in combination, taking the board from A1-1 or A2-1, feeding the board to B1-1, and the shifting board to outgoing position. These controls enable efficient management of palletizing operations; the specific functions and operation steps are as follows:

1. Switching kiln: Select the “A Kiln” or “B Kiln” button to toggle between kilns for operational purposes.
2. Setting Maintenance time: The maintenance time for the prefabricated board can be directly set through the input box labeled “maintenance time”, with the unit being hours.
3. Setting the target kiln number: The target kiln number can be set by directly clicking on the corresponding kiln position, and then the palletizer will initiate kiln operation.
4. Storing board: Firstly, set the target kiln number, then click on the “store board” button to select the corresponding operational mode. Subsequently, click on the “start” button to initiate the palletizer’s storage board operation. Upon completion of this operation, an indicator light illuminates when a board is successfully stored, and the color of the respective kiln position turns yellow. This signifies that a prefabricated board is being maintained at that particular kiln site. When the color of a kiln position turns red, it signifies that a cured prefabricated board is present in that specific kiln site and can be retrieved.
5. Retrieving board: Firstly, set the target kiln number, then click on the “retrieve board” button to select the corresponding operational mode. Subsequently, click on the “start” button to commence the palletizer’s board retrieval operation. An indicator light illuminates when a board is successfully retrieved, and the color of the respective kiln position turns green. This signifies that there are no prefabricated boards present at that particular kiln site, thereby enabling further board storage operations.
6. Moving operation: Begin by setting the target kiln number, then select the corresponding operational mode by clicking on either the “walk”, “lift”, or “walk + lift” buttons. Finally, initiate the operation by clicking on the “start” button, and the palletizer will execute the designated task. Upon completion of the operation, the respective job completion indicator will illuminate.
7. Taking board: Click on the “A2-1 take board” or “A1-1 take board” button to select the corresponding operational mode, then click the “start” button; the palletizer will perform the board-taking operation. Upon completion of the operation, the board-taking completion indicator will illuminate.
8. Move to the exit position: Click the “move to exit position” button to select the corresponding operational mode, and then click the “start” button; the locomotive frame will be moved to the designated exit position. After the move is in place, the board feeding operation can be performed, and the corresponding indicator light will illuminate, signifying the completion of the action.
9. Feeding board: Click on the “B1-1 feed board” button to select the corresponding operational mode, and then proceed by clicking on the “start” button. The palletizer will execute the necessary actions for board feeding. Once completed, the indicator for board feeding completion will illuminate.
10. Stop and reset: Press the “stop” button while the palletizer is in operation to halt all operations. After the palletizer completes the designated task, click on the “clear” button to reset all the indicator lights, operation modes, as well as the number of the kiln template.

The actual operation is shown in Figure 9.

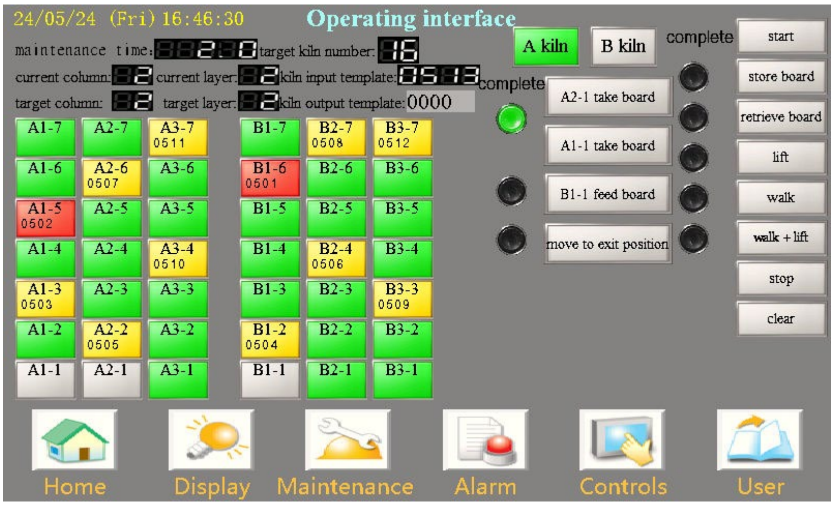

Figure 8. The operation interface during debugging.

Figure 9. Site diagram.

6. Conclusions

The research focuses on the prefabricated board transfer palletizer, and a real-time monitoring system for the palletizer is designed with S7-1500 PLC as the core controller. Additionally, the Proface touch screen is integrated to achieve efficient palletizer operation. Based on the operational requirements and workflow of the palletizer, a software program specifically tailored for its functionality is developed. It includes the assessment of kiln A or kiln B, the computation of kiln location address, the determination of platform position, the calculation of bolt positioning position, the calculation of prefabricated board maintenance time and identification of maintenance kiln status, template number configuration and outputting, control and execution of all operations, display and outputting of all position sensor statuses, as well as potential error alarms. The experimental test demonstrates that the control system of the prefabricated board transfer palletizing machine is capable of real-time data collection and control of field equipment, enabling efficient and reliable transfer operations for prefabricated boards.

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