2025 Volume 3, Issue 5
Lecture Notes in Education, Arts, Management and Social Science
ISSN(Online): 2705-053X

Design and Optimization of Intelligent Warehouse Equipment: An Example of Artificially Intelligent Pallet Shuttles

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Abstract: This paper focuses on the key technology optimization of intelligent warehouse pallet shuttles. In the lifting mechanism, a scissor-type hydraulic cylinder lifting system is adopted to ensure smooth and precise vertical movement. The design of omnidirectional steering wheels enables 360-degree free rotation, enhancing the vehicle's flexibility and operational convenience. In addition, high-efficiency solar cells are selected, which support battery removal and charging under natural light, not only extending the battery life but also achieving energy conservation and emission reduction. These technological innovations jointly improve the working efficiency, safety, and environmental friendliness of the shuttle.

Keywords: Warehouse equipment; Shuttle; Lifting; Ground operation

Online publication: June 26, 2025

1. Function development

1.1. Lifting function

1.1.1. Mechanical structure design

The support frame of the artificially intelligent pallet shuttle (hereinafter referred to as the "new-type shuttle") is made of aluminum alloy to ensure sufficient strength and stability. The structural form draws on the shuttle transfer-layer lifter of a company in Suzhou. It adopts a structure with symmetrically fixed support columns on both sides of the bottom plate and a top plate connected at the top, effectively improving the equipment stability. Through comparative analysis, the screw-rod drive mechanism is selected for the lifting mechanism due to its advantages of accurate positioning and smooth lifting. Drawing on the shuttle lifting device for shuttle racks of a company in Hefei, the screw-rod drive mechanism is used to drive the lifting base to move vertically along the vertical plate frame, driving the loading platform to lift smoothly. The loading platform is designed according to the size, weight of the shuttle, and the cargo-carrying requirements. The structural strength of the loading platform needs to meet the requirements of the maximum load-bearing weight. A reasonable beam-plate structure is adopted, and the beam bending theory and plate-shell theory in material mechanics are used for strength calculation and verification to ensure that it will not deform or be damaged when bearing full-load goods.

1.1.2. Control system design

In the selection of the controller, a Programmable Logic Controller (PLC) is chosen as the controller. PLC has the advantages of high reliability, simple programming, and strong anti-interference ability, and is widely used in the field of industrial automation control. In terms of sensor layout, limit switches, proximity switches, displacement sensors, etc. are installed to detect information such as the position, speed, and status of the lifting platform, achieving precise control and safety protection. The limit switch can be set at the upper and lower travel limit positions of the lifting platform. When the platform reaches the limit position, the limit switch is triggered and sends a signal to the controller, immediately stopping the movement of the lifting platform to prevent equipment damage and safety accidents caused by the platform exceeding the limit position. The proximity switch can be used to identify the picking or placing state of the lifting mechanism. When the shuttle approaches the loading platform for loading and unloading, the proximity switch detects the signal and notifies the control system to make corresponding preparations. The displacement sensor can monitor the position of the lifting platform in real-time and feed back the position information to the controller to achieve precise position control, ensuring that the shuttle can accurately dock at the target position.

1.2. Ground operation function

1.2.1. Omnidirectional steering wheels facilitate flexible operation

The omnidirectional steering wheels adopt an advanced mechanical structure design, which can achieve 360-degree free rotation. Compared with traditional fixed-direction wheels or limited-angle steering wheels, this omnidirectional steering ability allows the shuttle to be unrestricted by a fixed driving direction on the warehouse floor. When the shuttle needs to quickly switch driving routes between multiple rows of shelves, the omnidirectional steering wheels can quickly respond to the instructions of the control system, turn the wheels in the target direction, and drive to the destination along the shortest path. This flexible steering feature makes the running trajectory of the shuttle more diverse, reduces unnecessary driving distances, and thus saves transportation time.

1.2.2. Sensors enable precise sensing and intelligent control

The distance sensors equipped on the vehicle body can accurately sense the cargo position information on the shelves. By emitting specific signals and receiving the reflected signals, the sensors can determine key information such as the distance to a certain cargo position, whether there is cargo stored, and the type of cargo. When the shuttle performs the task of picking and placing goods, the sensors scan the target cargo position in advance and feed back the information to the control system. The control system plans the driving route and goods-picking actions of the shuttle based on this information, ensuring that the shuttle can accurately dock in front of the target cargo position and pick or place goods in an appropriate manner.

2. Selection of components

2.1. Scissor-type hydraulic lifter

Based on the wide application and construction principle of the scissor-type lifting platform in lifting work, we decided to use a scissor-type hydraulic lifter to achieve the function of "self-lifting". Its working principle is that the telescopic movement of the hydraulic cylinder drives the scissor-type structure to expand or fold, thereby driving the working platform to achieve smooth vertical lifting movement. The hydraulic cylinder, as the only power source in the scissor-type mechanism, is the key component for realizing the platform lifting operation. To ensure the stability of the lifting system and meet the requirement of the maximum rising height in the warehouse, we selected two hydraulic cylinders of the same model, which jointly form the core power part of the lifting system. This dual-cylinder configuration not only ensures the stability during the lifting process but also effectively shares the load, ensuring the safety and reliability of the entire system during operation.

2.2. Omnidirectional steering wheels

To solve the problem of limited running directions of traditional shuttles, in the selection of wheels for the new-type shuttle, we chose polyurethane tires with high-strength aluminum alloy cores as the main components. This material not only provides excellent wear resistance and grip but also has good shock-absorbing performance, effectively reducing running noise and the impact on the ground. Each steering wheel adopts a precision-machined double-bearing design to ensure smooth rotation and durability. The width of a single omnidirectional steering wheel tread is 100mm, and the maximum load-bearing capacity can reach 2000kg, meeting regular application requirements. The shuttle will be equipped with 4 omnidirectional steering wheels, which are arranged at the four corners of the shuttle. Combined with 2 driving wheels in the middle of the chassis, the shuttle can achieve multi-directional steering. This can not only reduce the cost of laying tracks but also follow the principle of "the shortest line segment between two points" in three-dimensional space, shortening the travel distance.

2.3. Distance sensors

The activation timing of the scissor-type hydraulic lifter and omnidirectional steering wheels depends on the distance data measured by the distance sensors. By calculating the spatial distance to the cargo position and combining it with the running speed of the shuttle, the start signals for the scissor-type hydraulic lifter system and omnidirectional steering wheels are determined, and the optimal lifting time and steering plan are determined. For this shuttle, considering that it needs to operate in a relatively closed and controlled warehouse environment and ensure precise control of the goods-picking and placing positions, we use Wintec time-of-flight laser rangefinders. Because they can provide sufficient accuracy within a short distance, their installation is relatively simple, they do not occupy too much space, and the cost is relatively low.

3. Key technologies

3.1. Positioning and navigation system

The new-type shuttle adopts a "3-positioning + 1-navigation" mode in position management. "3-positioning" refers to the laser positioning system, vision positioning system, and encoder positioning system, which are used for the positioning and driving information recording of the shuttle; "1-navigation" refers to the navigation system, which is used to provide and optimize the running path of the shuttle. This mode realizes the intelligence of the new-type shuttle by integrating multiple positioning systems and the navigation system.

3.2. Digital control and communication technology

The new-type shuttle adopts PLC and industrial computer technology to achieve logical control. Combined with the underlying path self-learning algorithm, it ensures high-speed operation, precise positioning, and safety and reliability. The four-way vehicle selects the SIMATIC S7 series PLC as the core controller and makes full use of its rich expandable integration interfaces to integrate sensor modules, power supply modules, wireless communication modules, and actuator modules, etc., realizing the vehicle's motion guidance, drive control, actuator operation, and safety protection. In the dense storage, Zigbee wireless communication is used. The upper-level controller issues task instructions to the four-way vehicle through the Zigbee master module. After the task instructions are transmitted to the PLC for calculation and processing, they are converted into specific control signals and sent to the drive control module that controls the motion of the actuator. In this module, the speed of the drive DC motor is adjusted to control the actuator to complete the corresponding actions. During this process, various sensors and the RFID system feed back the collected positioning, detection, and fault information to the upper-level device through the Zigbee sub-module and are fed back to the warehouse operator by the status display, realizing the two-way transmission of the dynamic information of the four-way vehicle.

3.3. Communication technology

The new-type shuttle adopts the following 5 communication methods in different application scenarios, including industrial Ethernet communication, RS485 communication, WiFi communication, Bluetooth communication, and ZigBee communication.

Industrial Ethernet communication is based on the IEEE 802.3 standard and uses the CSMA/CD (Carrier Sense Multiple Access/Collision Detection) media access control method. Through transmission media such as twisted-pair wires and optical fibers, it realizes high-speed and reliable data transmission. RS485 communication is based on the differential signal transmission principle and uses a half-duplex communication method. Through a pair of differential signal lines, it realizes data transmission between multiple nodes and has strong anti-interference ability. WiFi communication is based on the IEEE 802.11 standard and uses wireless radio-frequency signals to spread in the air to realize wireless connection between devices. Through different frequency bands and channel divisions, it supports the simultaneous access of multiple devices. Bluetooth communication is based on the Bluetooth technical specifications and uses short-range wireless communication. Through the pairing mechanism, it establishes a secure connection between devices and is suitable for low-power-consumption and small-data-volume transmission scenarios. ZigBee communication is based on the IEEE 802.15.4 standard and uses a low-power-consumption and low-rate wireless communication technology, which is suitable for applications with low data volume and large-scale, such as sensor networks.

3.4. Safety protection software

The collision warning and avoidance function is based on the sensor perception principle. The lidar emits laser beams and receives the reflected light. Using the time-of-flight method or phase method, it calculates the distance and azimuth information of the obstacle. The ultrasonic sensor uses the reflection characteristics of ultrasonic waves, emits ultrasonic waves and receives the echo, and calculates the distance to the obstacle based on the time difference. When an obstacle is detected entering the warning area, according to the preset safety distance and speed threshold, the deceleration or braking timing and force are calculated through the control algorithm, and the driving path of the shuttle is adjusted to avoid collisions. The fault detection and diagnosis function is based on the monitoring of the electrical characteristics and operation parameters of the hardware devices. Through sensors, the current, voltage, and temperature of the motor, the voltage, current, and capacity of the battery, and the working status signals of other key components are collected. The collected data is compared and analyzed with the normal operation range. When abnormal signals are detected, the fault type and location are determined according to the fault diagnosis algorithm, and an alarm message is issued. The emergency braking control function is based on the mechanical principle of the braking system. When an emergency braking signal is received, the braking actuator is controlled to quickly apply braking force, making the shuttle stop running in the shortest time. During the braking process, factors such as the vehicle's inertia, mass, and speed are considered to ensure the smoothness and reliability of braking.

4. Function testing

4.1. Road test

The horizontal road test aims to verify the performance of the new-type shuttle in key operations such as full-load starting, straight-line uniform driving, and curve driving, ensuring that it can run smoothly along the predetermined route and within the specified speed limit. Through multiple rounds of repeated tests and observations, it is found that the new-type shuttle shows good operational performance during the entire test process. The shuttle performs well when walking along the preset route. It can not only pass through curves smoothly but also quickly restore the vehicle body to an upright position after turning. In the obstacle-avoidance test, when the shuttle approaches the set obstacle, the laser distance sensor equipped on it detects the obstacle in front in a timely manner and immediately triggers the braking system. The deceleration, stop, and restart during the entire obstacle-avoidance process are carried out as expected, fully demonstrating the precise processing ability of the control system in complex working conditions. By collecting the speed data of the shuttle during operation in real-time, we obtained a detailed speed-time curve. This curve reflects the speed changes of the shuttle at different stages, providing important reference for evaluating the power performance, control accuracy, and overall running stability of the shuttle.

4.2. Lifting test

The lifting test is mainly to verify the lifting performance of the new-type shuttle in the vertical direction, ensuring that it can accurately complete the goods-picking and placing operations at the predetermined height and speed. During the experiment, the vertical displacement of the working platform during the entire unfolding process was recorded in detail. By plotting the above data into a curve, it was found that the platform rose 8,000 millimeters in total, and the error between the actual displacement and the expected displacement was extremely small, meeting the design requirements.

5. Conclusion

This project has successfully improved the overall performance of the shuttle in lifting, ground operation, and energy management through in-depth research and optimization of the technology of the pallet shuttle. In terms of the lifting mechanism, the adoption of the scissor-type hydraulic cylinder lifting system ensures smooth and precise vertical movement, meeting the height requirements for goods-picking and placing operations. The use of omnidirectional steering wheels enables the shuttle to rotate 360 degrees freely, enhancing the flexibility and operational convenience of the shuttle. The subsequent function tests further verify the effectiveness of the design of the new-type shuttle. However, there are still some shortcomings in this project. For example, in practical applications, the shuttle may operate in extremely complex environments (such as areas with high-density obstacles or strong reflection interference), so there is still room for improvement in its response speed and accuracy. These shortcomings will point out the direction for subsequent improvements, promoting the artificial-intelligence-based pallet shuttle and even the entire logistics technology to move towards a more efficient, intelligent, and green direction.

Funding

2024 Hunan Provincial College Students' Innovation and Entrepreneurship Project: Design and Optimization of Intelligent Warehouse Equipment-Taking the Artificially Intelligent Pallet Shuttle as an Example (Project No.: S202413809084).

Key Teaching Reform Project of the Hunan Provincial Department of Education: Research on the Disciplinary Integration and Education Model under the "Intelligence + Empowerment"-Taking the Robot Major and Logistics Management Major as Examples (Project No.: HNJG-20231561).

Disclosure statement

The author declares no conflict of interest.

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