

Original Paper

Design and Application of Express Smart Station System Integrating Embodied Intelligence and AI Navigation

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Abstract

Courier stations in communities and campuses are generally confronted with several common problems, including heavy manual workload, low efficiency of parcel searching and collection, and frequent parcel misplacement and mis-taking. Existing intelligent equipment involves high procurement costs and relies heavily on cloud networks for operation, making it difficult to popularize and deploy in small- and medium-sized stations. Targeting the intelligent transformation of last-mile logistics, this paper conducts research on the design and application of a smart courier station system integrating embodied intelligence and AI navigation. By sorting out relevant existing research results and combining field demand investigations of multiple courier stations, this paper analyzes the common shortcoming of “partial automation yet overall weak intelligence” prevailing in current intelligent station schemes. On this basis, a three-layer architecture consisting of the embodied-intelligence execution layer, AI algorithm decision-making layer and embedded system support layer is adopted to construct an integrated system with five functional modules: embodied-intelligent robot, embedded query, shelf location identification, information management and intelligent navigation. The outcomes of this study are applicable to diverse scenarios. They can provide low-cost and replicable intelligent

transformation solutions for small- and medium-sized courier stations in communities, campuses, towns and other settings, and also offer practical references for the subsequent development of last-mile smart logistics.

Keywords

Embodied Intelligence, AI Navigation, Courier Smart Station1

1. Introduction

1.1 Research Background

China has incorporated the construction of courier last-mile service facilities into the national policy system. In 2019, the State Post Bureau officially implemented the Measures for the Administration of Intelligent Parcel Locker Delivery Services. The document clarifies the definition and service specifications of intelligent last-mile facilities and requires recipients' consent before parcels are placed in lockers or courier stations. These provisions lay an institutional foundation for the standardized development of intelligent last-mile facilities (State Post Bureau, 2019). In line with national strategies such as "Smart Postal Service" and "AI+", supporting policies encourage integrating intelligent delivery facilities into livelihood convenience projects, guide enterprises to participate in last-mile infrastructure construction, and promote the application of technologies including automatic sorting, intelligent receiving and delivery terminals, and unmanned warehousing and distribution. Such regulations set higher standards for service compliance of last-mile facilities and create a favorable policy environment for the intelligent transformation of courier stations.

Domestic e-commerce has expanded steadily in recent years, directly driving the rapid growth of the courier industry. Public statistical data show that China's online retail sales reached 13.79 trillion yuan and 15.42 trillion yuan in 2022 and 2024 respectively, and the proportion of online retail sales of physical goods in the total retail sales of consumer goods exceeded 25%. In 2024, the national postal and courier sector handled 193 billion parcels with a corresponding business revenue of 1.7 trillion yuan. China's courier business volume has ranked first worldwide for 11 consecutive years. The sharp surge in parcel volume in a short period continuously increases the load pressure on the "last-mile" delivery. Currently, conventionally operated courier stations generally suffer from concentrated parcel arrival and pickup time, heavy manual workload, and time-consuming manual parcel search for users. Most commercially available intelligent courier equipment has high procurement costs and relies excessively on cloud networks during operation, making it difficult to meet the lightweight transformation demands of small and medium-sized courier stations in communities and campuses.

At present, academia has accumulated abundant research achievements in the fields of intelligent parcel lockers and last-mile delivery. Wang and Zheng (2022) sorted out the existing problems of intelligent parcel lockers in last-mile delivery and put forward feasible solutions. Wei Bo (2019) affirmed the practical value of intelligent parcel lockers in the "last-mile" delivery and offered specific development suggestions from three dimensions: equipment configuration, differentiated delivery and value-added

services. Zhou et al. (2019) summarized four common last-mile delivery modes and proposed differentiated delivery schemes tailored to the characteristics of different urban functional zones. Chinese scholars have also carried out a number of empirical studies on topics such as service optimization, profit models, site selection modeling and station operation simulation of parcel lockers, and existing findings have laid a theoretical foundation for this research field. Nevertheless, most existing studies focus on traditional logistics issues including site layout, profit models and operation optimization, while few discussions involve the in-depth integration of last-mile delivery facilities with emerging technologies such as artificial intelligence and robot autonomous navigation. Considering current policy requirements, industrial reality and research gaps, this paper introduces embodied intelligence and AI navigation technologies into the smart courier station system. This research meets the practical needs of the rapid growth of the courier industry, complies with national smart logistics policies, and represents a new exploration to promote the autonomous and intelligent upgrading of last-mile delivery, which forms the research origin of this paper.

1.2 Research Significance

The research significance of this paper is discussed from two dimensions, namely theoretical significance and practical significance, with reference to the existing problems in the courier last-mile station industry, the actual status of technological development and the national development orientation of smart logistics.

Theoretical significance: Overseas research on the intelligence of courier last-mile services focuses on warehouse robots, automatic sorting, AGV autonomous navigation and other technologies. Relevant solutions have been deployed in large logistics centers such as Amazon and DHL. However, the overall equipment cost is relatively high, making them unsuitable for lightweight transformation of small stations in campuses and communities. Existing domestic studies cover automatic shelving, indoor positioning, self-service outbound processing and other fields and have achieved a series of results. Nevertheless, the field is generally still at the stage of “partial automation yet overall weak intelligence”. Current devices commonly suffer from insufficient autonomous perception and decision-making capability and poor system flexibility, and some are difficult to implement or expensive. Four obvious shortcomings exist in relevant current research. First, only single-link automation is realized without constructing a full-process intelligent closed loop. Second, robots are mainly designed to perform operational tasks and lack the environmental perception, autonomous decision-making and dynamic adaptation capabilities brought by embodied intelligence. Third, parcel searching relies on fixed paths or light prompts, and the problems of congestion and inaccurate positioning under high-concurrency scenarios remain unsolved. Fourth, most systems are heavily dependent on cloud servers and sophisticated hardware. Low-cost embedded lightweight solutions capable of stable offline operation are scarce. There is an obvious research gap regarding smart courier stations with deep integration of embodied intelligence and AI algorithms.

Practical significance: General courier stations are often faced with practical challenges such as

concentrated parcel arrival and pickup, heavy manual workload and low parcel searching efficiency. Combined with the daily business scenarios of such stations, this study carries out research based on the three-in-one architecture of the embodied intelligence execution layer, AI algorithm decision-making layer and embedded system support layer. Four research methods including literature review, demand investigation, system design and experimental verification are adopted. The whole research is conducted following the route of “investigation and analysis — scheme design — hardware integration — algorithm development — system debugging — effect verification”. This study aims to solve four core problems: slow manual shelving, difficult parcel search for users, high deployment cost and poor offline operation performance. A practical and replicable smart courier station system with functions of batch scanning, intelligent bin allocation, automatic shelving, dynamic navigation and flashing positioning is constructed. It enriches the applied theories of embodied intelligence in last-mile logistics and provides practical schemes for lightweight intelligent transformation of various stations in communities, towns and industrial parks.

3. Demand Analysis and Overall Design Idea

3.1 System Demand Analysis

Courier stations serve as the core nodes of last-mile courier services and undertake full-process businesses including parcel warehousing, storage, shelving, user parcel pickup and outbound registration. With the continuous expansion of courier business volume in recent years, stations adopting the traditional manual operation mode have encountered many practical problems, and existing intelligent transformation schemes also have certain deficiencies. Combined with literature review and field investigation, the author conducts system demand analysis from two categories: functional requirements and non-functional requirements. The relevant conclusions provide references for the subsequent overall system architecture and module design.

Table 1. System Demand Analysis

Demand Category	Research Source	Current Status	Existing Deficiencies	Derived System Requirements
Functional Requirements	Field investigation	Parcels arrive intensively during peak periods, and manual scanning, bin allocation and shelving are adopted in traditional stations.	Manual shelving is labor-intensive and inefficient, with frequent misplacement and omission of parcels.	Warehousing and Shelving: Support batch parcel scanning, intelligent bin allocation based on parcel size, logistics company and tracking number, and realize

				automatic shelving via embodied intelligent robots.
	Field investigation	Parcel location, arrival time and pickup status are recorded manually on paper or simple forms.	Parcel tracking is difficult, overdue parcels cannot be identified timely, and full lifecycle management cannot be realized.	Storage Management: Establish binding relationship between parcels and storage bins, update real-time parcel status, and automatically mark overdue and stranded parcels.
	Field investigation	A large number of users pick up parcels simultaneously during peak hours and search for parcels manually by pickup codes.	Manual searching is time-consuming, causing queue congestion and high risk of parcel mis-taking.	Pickup Guidance: Construct a three-level guidance mode of query navigation and electronic label flashing to support efficient parcel positioning under high-concurrency scenarios.
	Literature + Field investigation	Most small and medium-sized stations lack complete local data recording mechanisms for inbound and outbound operations.	Business data relies heavily on cloud servers, resulting in unavailable data query and statistical functions under offline conditions.	Information Management: Locally store parcel inbound and outbound records, pickup logs and bin status data to support daily operation query and statistics.
Non-functional Requirements	Literature (Cao, 2026;	Most existing intelligent station	Core services will be paralyzed once	Operational Reliability: Adopt

	Sun, 2025) + Field investigation	systems depend highly on cloud network and cloud computing resources.	the network is disconnected, leading to poor business continuity.	embedded local AI offline operation to ensure normal shelving, positioning and pickup services without cloud network support, and maintain stable accuracy under high-concurrency scenarios.
	Literature (Chen, 2024) + Field investigation	Current intelligent transformation schemes adopt high-end robots and complex visual equipment with high overall costs.	Expensive hardware investment limits the popularization and application in small and medium-sized community and campus stations.	Lightweight and Low-cost Performance: Adopt low-cost hardware configuration based on existing shelf reconstruction without large-scale site renovation, suitable for small and medium-sized station transformation budgets.
	Field investigation	Some intelligent devices have complicated operation processes and unfriendly human-computer interaction.	Staff and elderly users face high learning costs and prone to operational errors.	Usability: Simplify robot operation and background management processes, and provide intuitive pickup guidance to reduce user learning thresholds.
	Literature + Field	Station business scenarios vary	Existing systems cannot adapt to	Scalability: Adopt modular system

	investigation	greatly in campuses, communities and towns, while traditional systems have fixed and rigid functions.	diversified scenario demands and lack expandability for subsequent function iteration.	architecture to support subsequent functional expansion such as multi-robot collaboration and parcel data analysis, adapting to diverse station operation scenarios.
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As can be seen from the above analysis, current intelligent transformation schemes for courier stations still have prominent limitations. Most implemented schemes only realize automation of single links such as sorting and outbound processing, without establishing a full-process intelligent closed loop covering shelving, parcel searching and outbound. The robots equipped in most schemes can only execute pre-programmed instructions and lack the environmental perception, autonomous decision-making and dynamic adaptation capabilities required by embodied intelligence. A small number of schemes adopt drones and high-end vision equipment, resulting in high system complexity and procurement costs, which makes large-scale implementation in small and medium-sized stations difficult. Most existing systems rely on cloud servers for operation, and business would be directly interrupted in case of network failures, failing to meet the practical demand for stable offline operation. Addressing these shortcomings, this paper designs an integrated smart courier station system integrating embodied intelligence and AI navigation to fill the gaps of existing schemes.

3.2 System Architecture Design

On the basis of literature review and field investigation carried out in the previous sections, the system requirements have been clarified. This paper constructs a design framework consisting of three layers: the embodied intelligence execution layer, the AI algorithm decision-making layer and the embedded system support layer, forming a three-in-one structure. Instead of adopting the traditional cloud-heavy and low-code development mode, the overall architecture is designed following the hierarchical and modular design concept.

The architecture is divided from top to bottom into the embedded system support layer, the AI algorithm decision-making layer, and the embodied intelligence execution layer. Five business functional modules are configured correspondingly, namely the embodied intelligent robot module, embedded query module, shelf positioning and identification module, information management module, and intelligent navigation module. It can complete full-process business operations including batch parcel scanning, intelligent bin allocation, accurate shelving, dynamic navigation, electronic label flashing positioning and local information management. Covering the complete business chain, the

system meets the practical requirements of offline operation and lightweight transformation for small and medium-sized courier stations.

3.2.1 Three-layer Overall Architecture

(1) Embedded System Support Layer

This layer serves as the hardware and underlying software foundation for the operation of the entire system and undertakes three types of functions: local data storage, hardware driving, and business logic scheduling. Adopting an offline-first design philosophy, it can independently run core businesses without connecting to external cloud servers. The hardware consists of four modules: embedded main control unit, local storage unit, electronic label driving unit and communication interface. The software realizes three functions including local database management, device driving and task scheduling to locally store parcel data, bin data and operation logs. Data synchronization is optional when external network is available. In case of network disconnection, core businesses such as warehousing, shelving and pickup guidance can still operate normally, solving the pain point that traditional intelligent station systems are overly dependent on cloud and cease operation once network failure occurs.

(2) AI Algorithm Decision-making Layer

Located in the middle of the whole system architecture, the algorithm decision-making layer receives various data transmitted from the underlying support layer. It issues operation instructions to the embodied intelligence execution layer and responds to user query requests from the front end. Its core integrated modules include multi-dimensional bin allocation algorithm, indoor positioning algorithm, AI dynamic path navigation algorithm and electronic label control logic. Intelligent bin division is carried out based on three pieces of information: courier company, actual parcel size and tracking number suffix. Positioning calculation and dynamic path planning are generated according to the real indoor environment of the courier station. After receiving users' pickup requests, it outputs corresponding positioning instructions to trigger the flashing of electronic labels on target shelves, providing algorithmic decision support for robot shelving operations and user pickup guidance, and finally forming the perception-decision closed loop of the whole system.

(3) Embodied Intelligence Execution Layer

All physical operations of the system are implemented through the execution layer. Centered on the embodied intelligent robot, this layer integrates three functional modules: visual scanning, environmental perception and motion execution. After receiving bin and path instructions issued in advance by the AI algorithm decision-making layer, this layer sequentially completes physical tasks including batch parcel code scanning and recognition, obstacle perception, autonomous movement and accurate parcel shelving. Different from conventional executive robots, this layer highlights environmental perception and dynamic adaptation capabilities to respond promptly to on-site environmental changes inside the station. It replaces manual labor to perform highly repetitive and high-intensity warehousing and shelving work, reduces the probability of parcel misplacement and omission, and completes the final link connecting digital decision-making to physical operation of the

system.

3.2.2 Five Business Functional Modules

Based on the three-layer architecture, this paper decomposes the system into five business functional modules. The modules are loosely coupled to facilitate subsequent iteration and expansion. The responsibilities of each module are as follows:

The embodied intelligence execution layer contains the embodied intelligent robot module. Integrating scanning recognition, environmental perception and motion execution units, this module receives bin allocation and path instructions issued by the algorithm layer, and completes batch parcel scanning and recognition, autonomous movement and automatic shelving, realizing unmanned operation in the warehousing link.

Embedded Query Module: It runs on local embedded terminals without relying on cloud web pages. It provides a parcel query entrance for parcel pick-up users, forwards the received user query requests to the AI algorithm decision-making layer, and returns pick-up guidance signals to realize local human-computer interaction.

Shelf Positioning and Identification Module: This module is mainly composed of shelf electronic labels and supporting driving hardware. Upon receiving positioning instructions from the algorithm layer, it provides three-level guidance of “query - LED path navigation - shelf electronic label flashing positioning”, helping users quickly locate target parcels, shorten parcel searching time and ease queuing congestion during peak hours.

Information Management Module: Built on the local database of the embedded system support layer, it manages various data including parcel information, bin status, inbound and outbound records, pick-up logs and stranded parcel marks. Station managers can use this module for data query, statistics and other operations, and all data is stored locally.

Intelligent Navigation Module: Affiliated to the AI algorithm decision-making layer, it is equipped with indoor positioning and dynamic path planning algorithms. It can plan moving paths for the shelving tasks of the embodied intelligent robot and provide in-station navigation services for users. It can complete multi-parcel positioning tasks under high-concurrency scenarios.

3.2.3 System Business Operation Logic

The complete operation flow of the system is as follows: After parcels arrive at the station, the embodied intelligent robot module scans the information of all parcels in batches. The AI algorithm decision-making layer runs the bin allocation algorithm to generate corresponding target bins and sends instructions to the robot to perform autonomous shelving. After shelving, the information management module binds parcel information with bin information and stores the data locally. When users input pick-up information via the embedded query module, the relevant requests are uploaded to the AI algorithm decision-making layer. After the intelligent navigation module completes positioning calculation, it triggers the corresponding electronic labels of the shelf positioning and identification module to flash for pick-up guidance. Once users finish picking up parcels, the system updates parcel

status and records outbound logs. The whole flow can run in a closed loop under offline conditions.

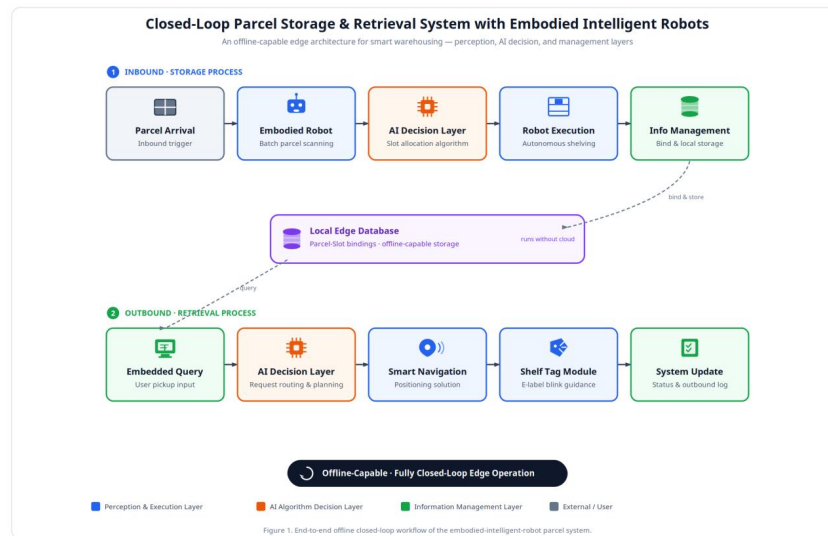


Figure 1. End-to-endoffline Closed-loop Workflow of the Embodied-intelligent-robot Parcel System

The overall architecture proposed in this paper is designed under the idea of lightweight transformation. It does not require large-scale reconstruction of station premises and is suitable for small and medium-sized courier stations on campuses, in communities and towns. It delivers six core capabilities: batch scanning, intelligent bin allocation, accurate shelving, visual navigation, flashing positioning and local outbound management.

4. Detailed Design of Each Functional Module

Chapter 3 has completed system requirement analysis and established the three-layer overall architecture. This chapter elaborates on the detailed design of five core business modules, namely the embodied intelligent robot module, embedded query module, shelf positioning and identification module, information management module, and intelligent navigation module. Prioritizing embedded offline operation, the system reduces reliance on cloud servers. All modules adopt a loosely coupled architecture and realize instruction transmission and data interaction through interfaces, jointly forming a complete business closed loop covering parcel warehousing, shelving, pickup and outbound registration.

4.1 Design of Embodied Intelligent Robot Module

Traditional automated robots can only execute preset fixed instructions. Different from such equipment, the embodied intelligent robot module deployed in the embodied intelligence execution layer serves as the hardware foundation supporting unmanned warehousing operations. The module is optimized for environmental perception. It can capture real-time dynamic information about shelf positions, obstacle

distribution and pedestrian flow inside the station. Receiving instructions such as bin configuration and travel paths issued by the AI algorithm decision-making layer, it sequentially completes warehousing operations including batch parcel scanning and recognition, autonomous movement and accurate goods shelving. Internally, it consists of three components: perception unit, motion execution unit and operation execution unit.

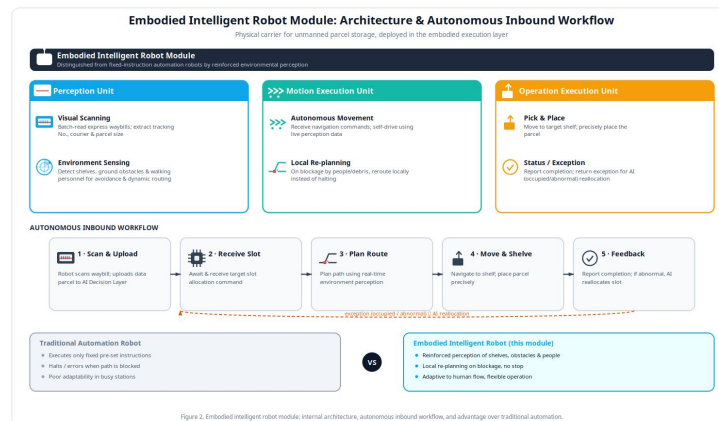


Figure 2. Embodied Intelligent Robot Module: Internal Architecture, Autonomous Inbound Workflow and Advantage over Traditional Automation

The perception unit is equipped with two types of hardware: visual code-scanning components and environment perception sensors. The visual scanning component can batch-read courier waybill information and extract core data including tracking numbers, affiliated courier companies and parcel dimensions. Environment perception sensors collect various real-time environmental information inside the station to identify shelf positions, ground obstacles and moving pedestrians. They supply perceptual input for robot obstacle avoidance and dynamic path adjustment, meeting the environmental perception requirements of embodied intelligence and avoiding poor adaptability caused by traveling along preset fixed routes.

Navigation instructions from the upper layer are transmitted to the motion execution unit, which uses environmental data collected by the perception unit to realize autonomous movement. If pedestrians or sundries block the preset path, the robot will not shut down and report errors directly. Instead, it can replan partial routes, improving operation flexibility in courier stations with frequent pedestrian movement.

Parcel picking, placement and shelving operations are undertaken by the operation execution unit. After acquiring the target bin information, the robot moves to the designated shelf position, places the parcel, and sends a shelving completion signal back to the upper system. If situations such as occupied bins or shelf faults occur during operation, exception information will be uploaded for the AI algorithm decision-making layer to handle and reallocate bins.

4.2 Design of Embedded Query Module

The embedded query module serves as the local user interaction portal. Running on embedded terminal

hardware, it does not rely on cloud web pages or network connections. It can still provide normal query services when the network is disconnected, solving the defect that traditional station query systems stop working once the network fails.

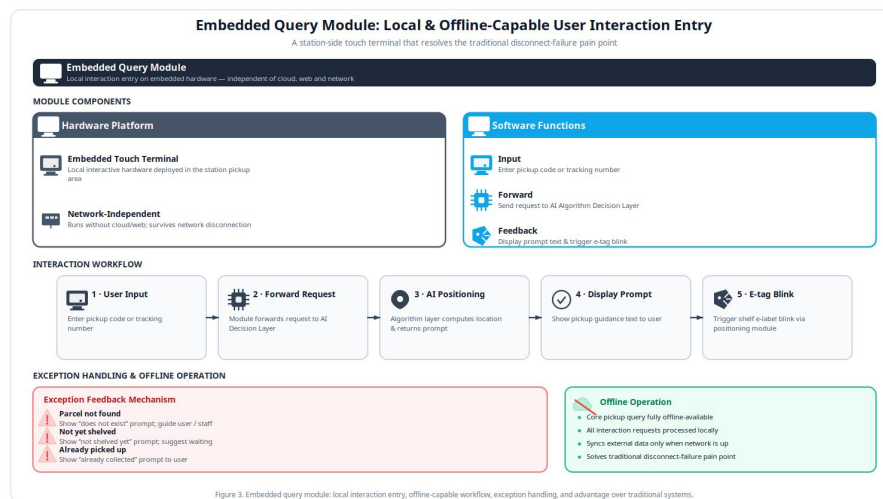


Figure 3. Embedded Query Module: Local Interaction Entry, Offline-capable workflow, Exception Handling, and Advantage over Traditional System

The hardware carrier of this module is a local embedded touch terminal deployed in the parcel pickup area of the station. Its software realizes the functions of pickup information entry, request forwarding and result feedback. There are two ways to initiate a pickup request: users may submit requests by entering a pickup code or courier tracking number. After receiving the request, the module forwards it to the AI algorithm decision-making layer. Once the algorithm layer finishes positioning calculation and returns pickup prompt information, the module displays text prompts for users and simultaneously links the shelf positioning and identification module to trigger electronic label flashing.

The rules of the exception feedback mechanism are as follows. If the queried parcel does not exist, has not been shelved, or has already been collected, corresponding text prompts will pop up on the terminal interface to guide users or station staff to take appropriate measures. All interactive requests are processed locally. External data synchronization is optional only when the network is stable, and the core parcel query service fully supports offline operation.

4.3 Design of Shelf Positioning and Identification Module

The shelf positioning and identification module acts as the hardware carrier to realize the three-level pickup guidance of “query-LED path navigation-shelf electronic label flashing positioning”. Composed of shelf electronic labels and a drive control unit, the module delivers visual pickup guidance upon receiving positioning instructions output by the AI algorithm decision-making layer.

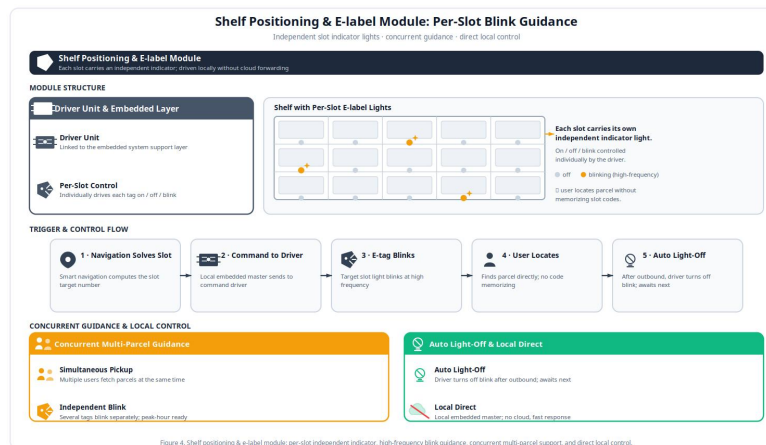


Figure 4. Shelf Positioning & E-label module: Per-slot Independent Indicator, High-frequency Blink Guidance, Concurrent Multi-parcel Support, and Direct Local Control

The warehousing system equips each bin with an independent electronic indicator light. The drive unit connects to the embedded system support layer and can individually control the on, off and flashing states of each bin label. After a user submits a pickup application, the intelligent navigation module calculates the bin number corresponding to the parcel. With the bin number obtained, the intelligent navigation module sends instructions to the corresponding control module, and the electronic label of the target bin flashes at high frequency to directly inform the user of the specific storage location of the parcel. Users do not need to memorize complicated bin codes or search for parcels among shelves.

During parcel pickup peak hours at courier stations, multiple users often collect parcels simultaneously. The device supports parallel guidance for multiple parcels by controlling labels of several bins to flash separately to meet such high-concurrency business demands. After the user takes the parcel and completes outbound registration, the drive unit automatically turns off the flashing light of the corresponding bin and waits for the next batch of business instructions. Directly connected to the local embedded main controller, this module requires no cloud forwarding of instructions and achieves relatively fast response speed.

4.4 Design of Information Management Module

Running based on the local database of the embedded system support layer, the information management module is responsible for system-wide data storage, business recording and data management. All data of parcels, bins and operation logs are stored locally to satisfy the data management requirements throughout the full lifecycle of parcels. It is equipped with four sub-functions: parcel information management, bin status management, business log management and stranded parcel marking.

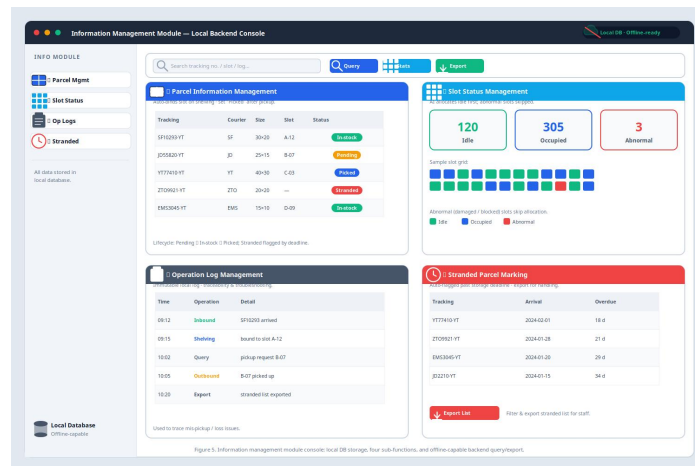


Figure 5. Information Management Module Console: Local DB Storage, Four Sub-function, and Offline-capable Backend Console

(1) Parcel Information Management. The core fields stored in this module include courier tracking number, courier company, parcel dimensions, arrival time, bound bin number, and parcel status (to-be-shelved, in-stock, picked up, stranded). After the robot completes the shelving task, the system automatically binds the corresponding parcel information with the bin number. When the user finishes parcel pickup and outbound operation, the status of the parcel will be directly updated as picked up.

(2) Bin Status Management. The system records the current status of all shelf bins and classifies them into idle, occupied and abnormal. When the AI algorithm decision-making layer performs bin allocation, it first retrieves bin status data and preferentially selects idle bins for assignment. If a bin has unregistered occupation, shelf damage or other faults, it will be marked as abnormal and excluded from subsequent bin allocation candidates.

(3) Business Log Management. This module retains full-process operation records including warehousing, shelving, query, pickup and outbound processing. The generated local operation logs cannot be deleted arbitrarily, enabling station operators to trace business activities and troubleshoot incidents of mis-taken or lost parcels.

(4) Stranded Parcel Marking. The system automatically judges based on parcel arrival time and marks parcels exceeding the storage period. Staff can filter and export the list of stranded parcels, and the system will prompt relevant disposal actions.

Using the simple background query interface of this module, station managers can conduct data query and statistics and export business records on local terminals. Selective external data synchronization is available under network connectivity, and local management functions remain fully functional when the network is disconnected.

4.5 Design of Intelligent Navigation Module

As the core functional module of the AI algorithm decision-making layer, the intelligent navigation module consists of the multi-dimensional bin allocation sub-algorithm, indoor positioning solution

sub-module and dynamic path planning sub-module. It provides algorithmic support for the shelving operations of embodied intelligent robots and delivers positioning guidance for parcel pick-up users.

The multi-dimensional bin allocation sub-algorithm allocates bins based on three indicators: courier company, actual parcel size and tracking number suffix. Bin matching prioritizes parcel volume: large parcels are assigned to large-size bins while small parcels are stored in concentrated areas. Zoning is further refined by courier company and tracking number suffix to avoid mixing parcels from the same batch and reduce the risk of mis-taking. If the preset target bin is occupied or abnormal, the algorithm can quickly provide available alternative bins to ensure continuous warehousing operations.

The positioning algorithm running on the local embedded terminal supports the indoor positioning solution sub-module. Without relying on cloud computing power, it calculates the position information of robots and bins inside the station and outputs precise coordinates to provide position input for path planning.

The dynamic path planning sub-module has two sets of operation logic. The first set is designed for embodied intelligent robots. Combined with obstacle information returned by the perception unit, it dynamically generates robot movement paths for shelving. When pedestrians or obstacles are encountered during travel, partial route adjustment can be performed. The second set serves user parcel pickup scenarios. It generates and outputs positioning information of target bins and cooperates with the shelf positioning and identification module to realize label guidance for parcel pickup. In high-concurrency business scenarios, this module supports parallel multi-task processing and responds simultaneously to navigation and positioning requests from multiple robots and users to meet the business load demand during station peak hours.

4.6 Data Interaction Logic between Modules

The embedded system support layer provides operational support for the five modules and realizes data and instruction interaction among them. All interactions of core businesses are completed locally without external cloud servers. After the embodied intelligent robot module collects parcel information, it submits the data to the intelligent navigation module for bin calculation. The calculated bin results are sent back to the robot for shelving execution and pushed to the information management module for data binding. When a user submits a pickup request through the embedded query module, the request is transferred to the intelligent navigation module for positioning calculation, and light control instructions are issued to the shelf positioning and identification module. After the user completes parcel pickup, status change information is written back to the information management module to generate an outbound log. During business interactions among modules, a complete "perception-decision-execution" closed loop is formed, ensuring normal offline operation of the whole system.

5. Conclusion

Small and medium-sized courier stations generally face three types of problems: heavy manual workload, low parcel-searching efficiency for users, and high cost of existing intelligent transformation

schemes with excessive reliance on cloud networks. In accordance with current development policies of smart logistics, this paper carries out demand analysis based on literature review and field investigation, constructs the three-layer architecture of embodied intelligence execution layer, AI algorithm decision-making layer and embedded system support layer, and completes detailed design of five business modules covering the whole chain of parcel warehousing, shelving, pickup and outbound to form a complete offline business closed loop. Integrating embodied intelligence perception capability and AI navigation algorithms, adopting three-level pickup guidance and the multi-dimensional bin allocation algorithm, and following the philosophy of embedded offline priority and lightweight transformation, the system can be applied to small and medium-sized stations in campuses, communities and towns. It serves as a feasible design scheme for intelligent transformation of last-mile courier stations.

This paper has basically finished the scheme design of the prototype system. Restricted by existing conditions, long-term field deployment in high-traffic commercial courier stations has not yet been implemented, and further improvement is required in multi-robot collaboration and robustness under complex environments. Future research can further optimize algorithms, explore feasible multi-robot operation modes, and realize connection with external courier business systems while guaranteeing offline operation of the system. The research expands the application ideas of embodied intelligence in last-mile logistics scenarios and possesses certain theoretical reference and practical value for improving the quality and efficiency of courier last-mile services.

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