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Design and Feasibility Analysis of Visual Monitoring Scheme for Tri-Fold Logistics Box

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Abstract: Our project team has developed the tri-fold logistics box which can employ multi-level folding to adjust the height and expand the capacity with dual-box splicing. This study proposes a monitoring framework with machine vision to track the cargo status in the box during transportation. The monitoring unit is designed to integrate a three-camera system with a rotatable brackets to fulfill the requirement of the multi folding status. The lightweight YOLOv8-nano network combined with spatial attention mechanisms is proposed to detect the cargo status. We propose to use an STM32 + NPU embedded hardware which has compact size and low power consumption. It will not interfere with the normal operation of the box. The study proposes a monitoring plan for the tri-fold logistics box to serve as a reference for research on foldable logistics equipment.

Keywords: Tri-fold Logistics Box; Machine Vision; Cargo Status Monitoring; YOLOv8-nano; Spatial Attention Mechanism.

1. Introduction

With the intelligent and green development of logistics industry, the containers are changing into foldable and recyclable types. Foldable logistics containers can improve space utilization with flexible operation [1]. Lee S et al. [2] showed that foldable containers can reduce the cost of empty container return. This type of container has many folding states. The cargo may shift and get damaged during transport[4]. The current methods still have disadvantages in solving these problems. Traditional manual detection fails to keep up with modern logistics. The visual monitor with fixed point has obvious blind spots because of fixed viewing angles[5]. Existing IoT sensing schemes can detect temperature, humidity and position, but most only focus on environmental data collection [6]. In addition, Zeissler K [7] pointed out that rigid sensors cannot adapt well to the repeated folding motions of containers. This study proposes a monitoring method to adapt the tri-fold logistics container developed by our project team.

Domestic research on foldable logistics containers mainly focuses on structure[8]. There is little research on intelligent vision systems for monitoring tri-fold containers. In logistics monitoring, deep learning methods like YOLO and Faster R-CNN are widely used in fixed scenes. Redmon J [9] proposed YOLOv3, which is accurate and fast enough for industrial use. Naumann A et al. [10] found that these detection systems are usually designed for stable environments, such as warehouses and conveyor belts. Domestic visual monitoring research is mostly used in fixed scenes, such as warehouse storage and express sorting. Current systems have obvious drawbacks. Fixed cameras cannot change their shooting angles adaptively. Hardware modules may easily crash into moving parts. Common detection algorithms are not specially optimized for folding containers. Sun et al. [11] proved that embedded systems based on STM32 chips can work well in logistics monitoring. Lightweight models such as YOLOv8-nano and MobileNet can satisfy the needs of low power consumption and small size in real applications. Zan et al. [12] pointed out that current lightweight algorithms are not specially optimized for folding containers.

Aiming at the tri-fold logistics container designed by our project team, this study proposes the cargo status monitoring method based on machine vision. This paper designs an adaptive visual layout with three coordinated cameras and rotatable bracketss. An improved version of the lightweight YOLOv8-nano detection algorithm is proposed. An embedded hardware platform is designed with STM32H743 and NPU. Through these steps, this study analyzes the theoretical feasibility of the proposed scheme.

2. Monitoring Requirements and Overall Scheme of Tri-fold Logistics Box

The monitoring scheme of this study is customized based on the structural characteristics of the tri-fold logistics container designed by our project team. The Structure of Tri-fold Logistics Box is shown in Fig.1. The main goal of this study is to match the container's features, such as multi-stage folding, height adjustment and dual-container splicing. The installation and movement design of monitoring parts will not change the container's original structure and affect its basic functions. The monitoring range can cover all four working states: fully unfolded, semi-folded, fully folded and spliced.

The working process of the system is as follows. After the system is powered on and initialized, Hall sensors would collect real-time signals, which include the height of the folding top plate, the rotation position of the front plate, and the locking state of the spring locks. The system would judge the current working state of the container accurately .The main control unit would adjust the rotation angle of the camera brackets automatically. At the same time, it would also control three cameras to collect images inside the container. The image data would be sent to the processing module. The NPU would accelerate the algorithm calculation to identify cargo status quickly. If the result is normal, the status indicator stays on. If an abnormality is detected, the system would send out an alarm at once.

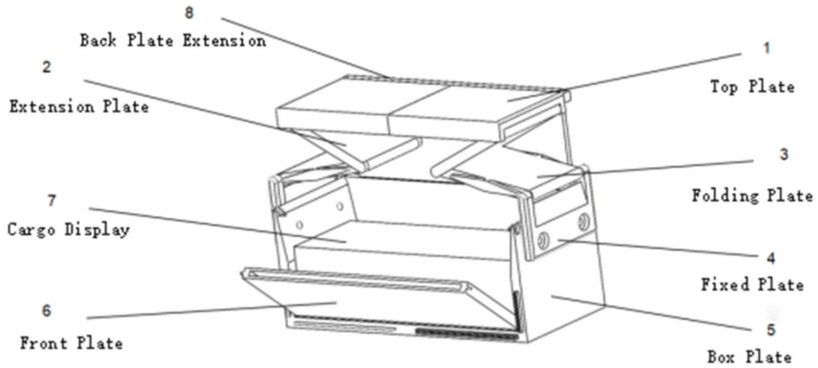

Fig 1. Structure of Tri-fold Logistics Box

The monitoring unit uses a hierarchical modular design. It is designed to include four functional modules: perception acquisition, data processing, algorithm inference and status output. All modules work together to complete automatic closed-loop monitoring. The perception acquisition layer integrates three small wide-angle cameras, a rotatable brackets and Hall sensors. It is designed to be responsible for collecting images inside the container and sensing the container state. The data processing layer uses STM32 as the main control chip and is equipped with an NPU acceleration unit. It would be able to transmit monitoring data and speed up algorithm calculation. The algorithm inference layer uses an improved YOLOv8-nano model, which can recognize cargo status and mechanical abnormalities. The status output layer includes acousto-optic alarms and indicator lights. It would show normal working status and send out early warnings when abnormalities appear. The overall architecture of the monitoring system is shown in Fig. 2.

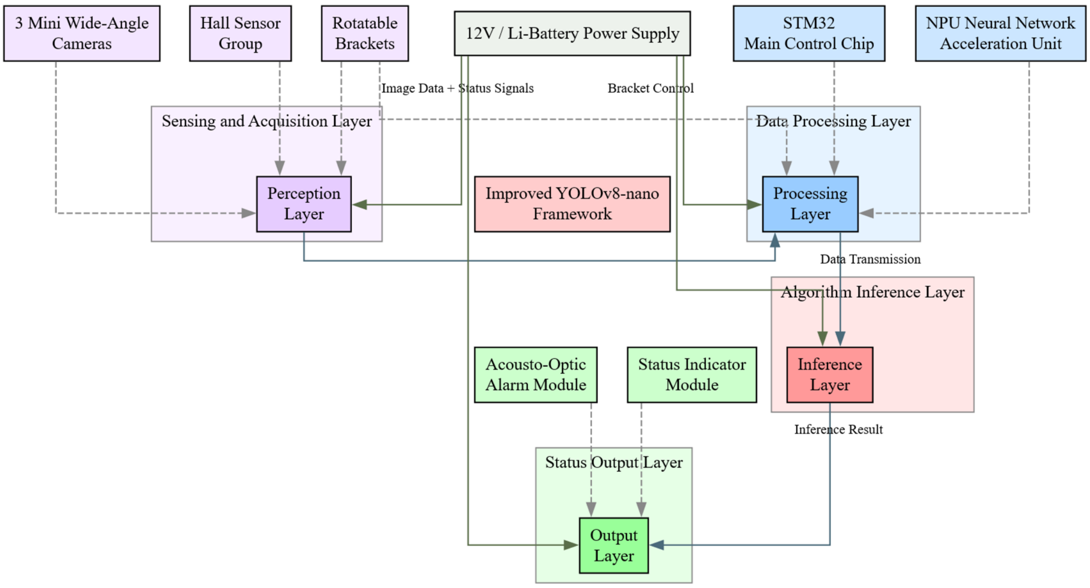

Fig 2. The Overall Architecture of the Monitoring System

3. Visual Monitoring Layout Design for Tri-fold Logistics Box

3.1. Box Working States and Spatial Characteristics

Table 1. Spatial Characteristics and Monitoring Challenges of Tri-fold Logistics Boxes in Different Operational States

Working State	Spatial Variation Features	Key Monitoring Challenges
Fully expanded	Top plate rises to the highest position, with the maximum internal volume of the box	Monitoring blind spots are prone to appear at the box edges
Semi-Folded	Top plate drops to the cargo height, and the folding plate compresses the cargo	Incomplete compression and cargo displacement are likely to occur
Fully Folded	Folding component is folded into the box, with the minimum internal volume of the box	Rotation interference of the folding mechanism is easy to happen
Spliced	Two boxes are clamped by slots, with the volume doubled	Need to monitor the slot clamping status and cargo at the splicing position

Tri-fold logistics containers have four different working states. Each state has different space features and different occlusion levels, so a single fixed camera cannot cover the whole monitoring area. As a result, an adaptive layout is required to match the dynamic changes of the container. The spatial features and monitoring challenges of each state are listed in Table 1.

3.2. Three-Camera Coordinated Layout

A three-camera system is designed three cameras on the top, side wall and front side to form a complementary layout. These cameras and brackets are designed to be installed without touching the core structure of the container.The layout and main functions of the three cameras are shown in Table 2 and Fig. 3.

Table 2. Three-Camera Arrangement Modes and Core Functions

Camera Position	Installation Method	Adapted Structure	Core Monitoring Function
Top Center	Fixed at the top of the rear inner wall of the box	Avoid the lifting trajectory of the top plate	Detection of cargo posture, displacement and compression status
Side Wall	Fixed on the inner side of the fixed plate of the folding component	Slight linkage with the folding component	Detection of cargo damage, extrusion and spring lock status
Front Wall	Fixed on the front inner wall of the box	Avoid the rotation axis and slots of the front plate	Detection of mechanism interference, slot clamping and front cargo status

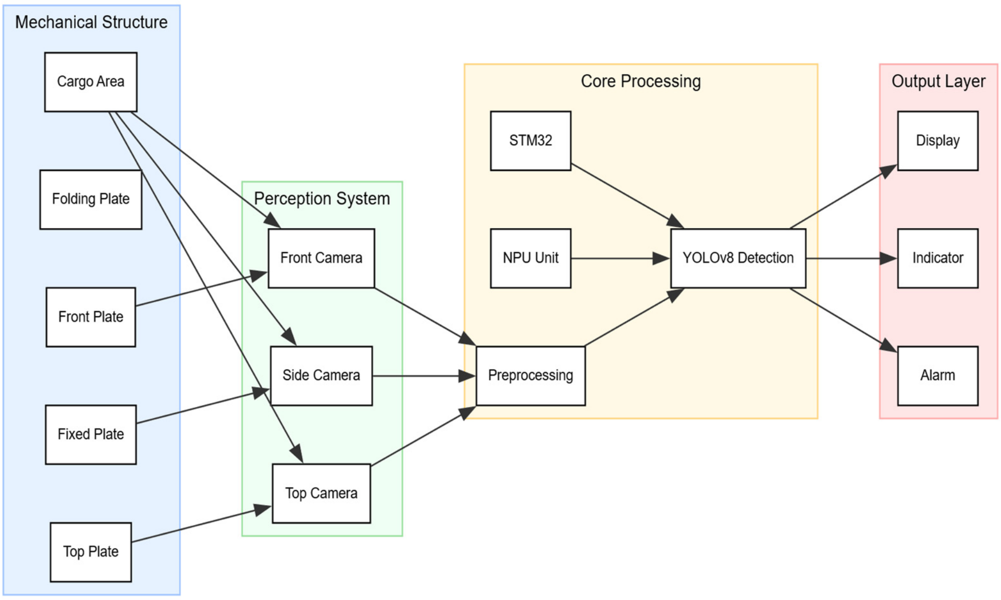

Fig 3. Schematic Diagram of Three-Camera Coordinated Layout

The central top camera is designed to be installed at the top of the rear inner wall of the container so that it does not affect the lifting movement of the top plate. This camera would monitor the whole container from top to bottom. It would mainly identify the overall posture of the cargo, large-range displacement and the compression state of the folding plate. The single side wall camera would be installed on either the left or right side. It is fixed inside the fixed plate of the folding component and moves slightly with it. It would monitor the damage and extrusion of side cargo, as well as the locking state of the spring lock. The front side wall camera is designed to be installed on the front inner wall of the container, which avoids the rotation axis and slot position of the front plate. It would adjust its shooting angle with the rotation of the front plate. This would make up for blind spots at the splicing position and in narrow spaces.The three cameras have a clear division of labor and complement each other. They would realize full-coverage monitoring of the whole container interior.

3.3. Linkage Control between Box Movement and Image Acquisition

The monitoring layout needs to match the container motion precisely, and the Hall sensor is critical for this purpose. It would collect real-time signals such as the height of the folding top plate, the position of the front plate, and the locking state of the spring lock. With these data, the system would judge the current working state of the container. The state signals would be sent to the main control unit in real time, which would generate control commands immediately. These commands would adjust the rotation angles of the camera brackets on the side and front walls automatically. In this way, clear and stable images would be obtained during container folding, compression and splicing. The linkage control flow of container motion and image acquisition is shown in Fig. 4.

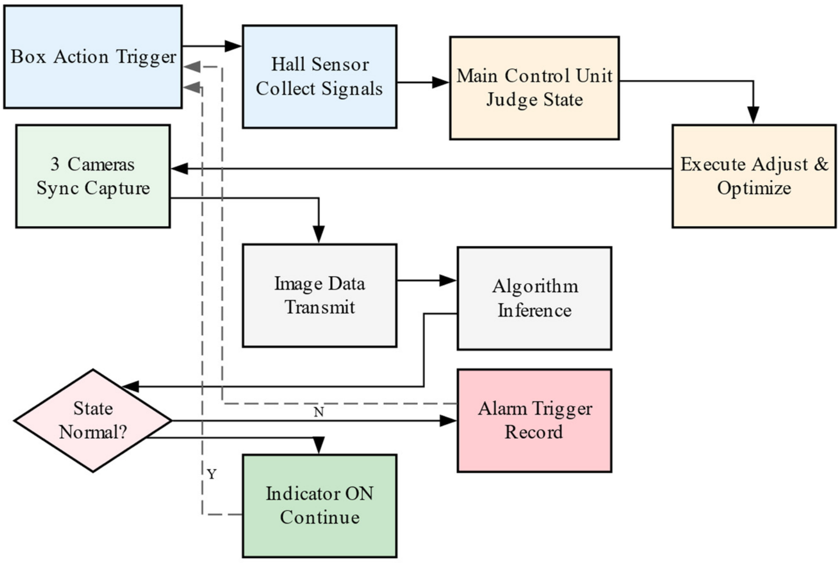

Fig 4. Flow Chart of Linkage Control Between box Action and Image Acquisition

4. Cargo Status Detection and Hardware Design

4.1. Lightweight Detection Algorithm for Folding Box

To meet the actual monitoring needs of tri-fold logistics containers, this paper proposes to use the lightweight YOLOv8-nano model. It has a simple structure, fewer parameters, and fast inference speed, which makes it suitable for hardware with limited computing resources. The spatial attention and channel attention mechanisms can be introduced into the model to improve detection robustness. This would help the system better identify occluded and small targets. In addition, prior information about container working states may be integrated into the detection process. Combined with Hall sensor signals, the system could adjust its detection strategy according to the four working states. Such optimization would help reduce the computational burden and improve the stability of the model on resource-limited hardware.

4.2. Construction of Embedded Hardware Platform

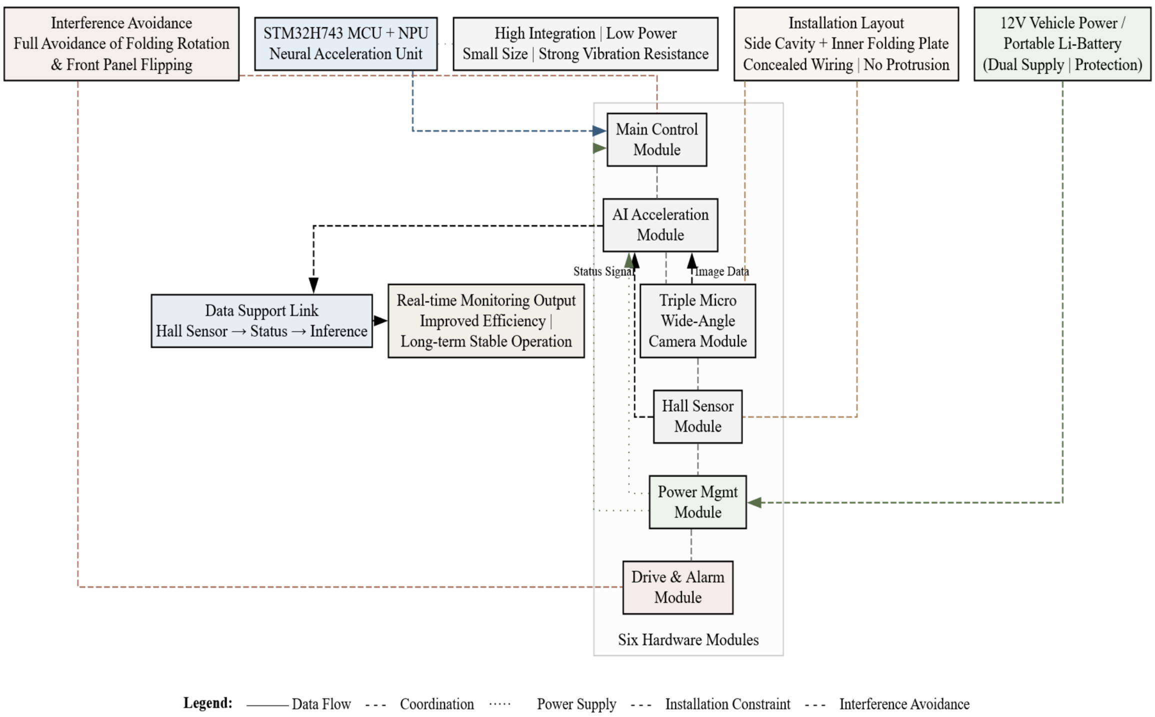

Fig 5. Architecture of embedded hardware platform

The hardware platform is designed based on the STM32H743 controller and an NPU to support the lightweight detection algorithm from Section 4.1. This design allows hidden installation, with low power and small size. All hardware parts would be placed so they do not disturb the normal movement of the container. The system includes six parts: main control unit, AI acceleration unit, three small wide-angle cameras, Hall sensor, power management unit and alarm unit. All parts would be fitted inside the empty space on the container's side wall and the inner folding plate.Wires would be hidden and organized well, with nothing sticking out. This would avoid the folding mechanism and front plate from being blocked or disturbed. The power unit can use both 12V vehicle power and portable lithium batteries. It has overvoltage and overcurrent protection and low power use, so it can run steadily for a long time in tough logistics environments. The AI acceleration unit is designed to provide computing support for algorithm inference, improving recognition speed and supporting real-time monitoring. The Hall sensor is designed to be attached directly to the surface to match the container and folding structure. It would collect different state signals correctly and supply data for monitoring and algorithm processing. The structure of the embedded hardware platform is shown in Fig. 5.

5. Feasibility Analysis

The proposed visual monitoring system for tri-fold logistics boxes is feasible in structural design, visual monitoring, algorithm-hardware matching and engineering use. All monitoring parts are designed to be installed inside the box, away from its key moving parts. In this way, the system would not affect the box's original structure or basic functions. These parts can be hidden in the box's reserved spaces and fixed plates, which would keep the box's appearance and strength unchanged. The assembly process is designed to be simple and reliable, so it can be used for mass production. The three-camera layout with rotatable bracketss is designed to adjust viewing angles freely under four working states. It would cover the whole inside of the box and reduce blind spots from fixed cameras. Small wide-angle cameras with adjustable parameters would take clear pictures when the space changes, targets are blocked or light changes. This would provide stable data for later target recognition and state judgment. The lightweight YOLOv8-nano algorithm, improved with attention mechanisms and working state information, can run fast and pick out key features well. It would be suitable for the narrow and blocked inside of the box. The STM32+NPU embedded hardware is designed to meet the needs of computing power, power consumption and size. It would work stably for a long time in vehicle logistics scenarios. The hardware uses a modular design with mature industrial parts, which can control cost, be used widely and be easy to assemble. The system can be well integrated with the box structure and installed on the production line without extra changes. It has low power consumption, good anti-vibration performance and hidden installation, so it would adapt to complex logistics transportation environments and have great potential for practical use and promotion.

6. Conclusion and Prospect

This study provides a machine vision monitoring system for the self-designed tri-fold logistics box, to solve its structural features and monitoring problems. We use three cameras with rotating supports to monitor the whole box under all working states. Hall sensors would connect box status sensing with image collection. We improve the lightweight YOLOv8-nano model with better feature extraction and scene information, so it can recognize cargo status and mechanical problems in complex environments. An STM32+NPU embedded hardware platform is designed to meet the needs of small size, low power use and strong shock resistance. Feasibility analysis shows this system is reasonable, logical and suitable for the box structure. It can be used as a reference for intelligent monitoring of foldable logistics equipment.

In future work, we plan to make a prototype and carry out real tests. We will build a test platform and create a special data set, to further improve the algorithm and hardware design. We also want to make the system more stable and more accurate in complex transport environments.

Acknowledgments

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