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DESIGN AND IMPLEMENTATION OF AN INTELLIGENT CHILD FALL PREVENTION SYSTEM FOR PARALLEL-PUSH WINDOWS

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Abstract: Traditional parallel-push windows employ simple handle-locking mechanisms that young children can easily unlock, whereas permanently locking these windows restricts ventilation and obstructs emergency egress. To address these issues, a dual-controller intelligent parallel-push window system based on the STM32F407ZGT6 microcontroller and the K230 visual AI module is designed and implemented. The K230 module runs a YOLO-based object detection model to recognize children approaching the window frame and estimate their distance, transmitting a window-closing command to the STM32 microcontroller upon detecting a potential hazard. Serving as the central hub, the STM32 manages multi-source environmental sensor data acquisition and actuation mechanism control, forming a closed-loop control system in conjunction with limit switches. The software architecture adopts a hybrid approach, combining external interrupts for immediate response to emergency events with dynamic polling within the main loop for routine monitoring. Furthermore, the system supports dual-channel operation via 4G remote control and a local touchscreen interface; in the event of a network outage, the STM32 can execute safety protocols independently. Performance tests demonstrate that the system automatically closes and locks the window when a child approaches, and responds similarly to environmental anomalies such as strong winds, heavy rain, or combustible gas leaks. The system effectively meets domestic fall-prevention requirements, exhibiting significant practical value and potential for widespread application.

Keywords: Intelligent parallel-push window; Child fall prevention; STM32F407; K230 visual module; YOLO object detection

1 INTRODUCTION

1.1 Research Status

In recent years, preventing children from falling from heights has emerged as a critical research direction in public and residential safety. Early foreign studies extensively analyzed fall characteristics, risk factors, and the efficacy of policy interventions, demonstrating that the institutionalized configuration of passive protective devices, such as window guards, can significantly reduce fall incidents [1-5]. However, these studies predominantly rely on passive protection and policy mandates, lacking active recognition and intelligent control integrated into the window itself. Conversely, domestic research has focused heavily on the development of smart windows and smart home systems, yielding substantial achievements in environmental sensing, remote control, and energy-saving regulation [6-10]. Nevertheless, existing smart windows are primarily designed to optimize indoor comfort or energy efficiency, rarely targeting high-security scenarios like child fall prevention, and they lack active recognition and closed-loop control mechanisms for hazardous behaviors such as approaching, climbing, or leaning out of windows.

In terms of visual perception, object detection algorithms like the YOLO series and Faster R-CNN, along with lightweight backbone networks such as MobileNetV2, have laid a solid theoretical foundation for edge-side real-time deployment [11-15]. Nonetheless, current visual detection research is mostly tailored for generic object recognition, traffic monitoring, or industrial inspection. Dataset construction, model optimization, and embedded deployment validation specifically for the composite safety scenario of "child-window-hazardous action" remain insufficient. Consequently, integrating object detection algorithms with smart window control systems to achieve active perception, rapid judgment, and automated protection for children's hazardous behaviors warrants further investigation.

1.2 Limitations of Existing Research

Based on the current research status at home and abroad, existing smart window protection systems exhibit several critical limitations. Specifically, there is a distinct absence of active protection mechanisms; traditional child fall prevention relies heavily on post-accident statistics and passive physical barriers, whereas current smart windows focus primarily on environmental regulation, leaving a technological gap in active perception and automated interception triggered by hazardous behaviors. Furthermore, the interactive redundancy and autonomous survival capabilities of these systems remain poor, as control modalities overly depend on cloud networks, smartphone apps, or remote controllers, lacking local multi-modal interaction and independent safety execution during network outages to cope with complex household environments. Moreover, edge-intelligent linkage is still insufficient; deploying visual algorithms on low-power edge devices faces a severe trade-off between real-time performance and false/missed detection rates, and the closed-loop coupling between edge visual perception and mechanical actuation mechanisms remains inadequately explored.

1.3 Key Work and Innovations

To address these limitations, this paper designs and implements a dual-controller intelligent parallel-push window system based on the STM32F407ZGT6 microcontroller and the K230 visual AI module. The STM32F407 serves as the central control hub responsible for multi-source perception data synergy and actuation mechanism control, while the K230 acts as the edge perception unit, running a deployed YOLO model to actively recognize children approaching the window. The core innovations of this paper are outlined as follows:

1)Heterogeneous Dual-Controller Synergy and High-Redundancy Interaction Architecture: A heterogeneous dual-processor architecture utilizing the STM32 and K230 is proposed, establishing a multi-channel interaction system encompassing "cloud platform + local touch control + edge vision". Independent safety execution protocols during network outages are designed to guarantee high safety redundancy under extreme scenarios.

2)Multi-Modal Active Safety Protection and Conflict Arbitration Mechanism: Based on edge-side real-time object detection, hazardous behavior determination for children near the window (within 50 cm) is achieved. By integrating multi-source environmental sensors covering wind/rain intrusion and gas leaks, an active safety control and multi-perception conflict arbitration mechanism is introduced, shifting the smart window from "passive physical defense" to "active intelligent protection."

3)High-Real-Time Hybrid Software Architecture: To meet the demands of multi-sensor synergy and mechanical linkage, a hybrid software architecture combining "external interrupts for immediate response" and "main-loop dynamic polling" is developed. This architecture successfully balances the instantaneous real-time requirement of emergency safety events with the long-term stability of routine environmental monitoring.

2 HARDWARE DESIGN OF THE SYSTEM

2.1 Overall System Architecture

As illustrated in Figure 1, the system adopts a hierarchical architecture with the STM32 microcontroller at its core, establishing an integrated intelligent window control platform that features perception, execution, and interaction. This architecture comprises four cooperative layers: the perception, control, communication, and application layers. Specifically, the perception layer integrates environmental sensors, the K230 visual AI module, and a touchscreen interface. The control layer executes multi-source data fusion and logical decision-making, driving the actuators for window deployment and achieving closed-loop position control. The communication layer connects to the IoT platform via a 4G module to facilitate real-time data uploading and remote command reception. Additionally, the application layer supports real-time monitoring, data visualization, and remote operations on a mobile app. All layers seamlessly interoperate through standardized interfaces.

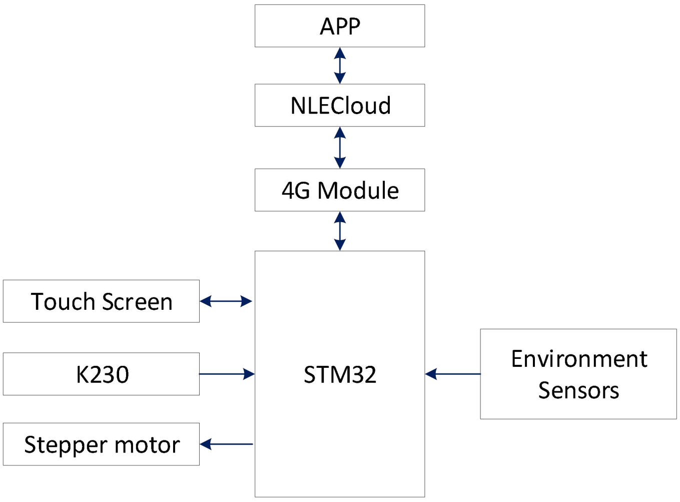


Figure 1 Overall System Architecture

2.2 Main Controller Circuit

The main controller circuit utilizes an STM32F407ZGT6 microcontroller. An external high-speed crystal oscillator is configured to provide the primary system clock, while interfaces for a low-speed crystal oscillator are reserved for real-time clock (RTC) calibration. General-purpose input/output (GPIO) pins are assigned in a functionally modular manner, and sufficient expansion pins are reserved to support the concurrent connection of multiple peripheral devices.

2.3 Power Management Circuit

The power supply system adopts a two-stage architecture combining a DC-DC step-down converter and a low-dropout (LDO) linear regulator, as shown in Figure 2. A reverse polarity protection circuit and a filter network are deployed at the input terminal. In the first stage, a switching voltage regulator chip steps down the 12 V input to 5 V to independently power high-power loads such as stepper motors, thereby isolating logic circuits from the interference caused by motor start-up surges. In the second stage, the LDO linear regulator converts 5 V to 3.3 V, providing clean power for the main control chip, K230 visual module, sensors, and communication modules. Filter capacitor networks are symmetrically arranged at both the input and output terminals to suppress voltage ripple.

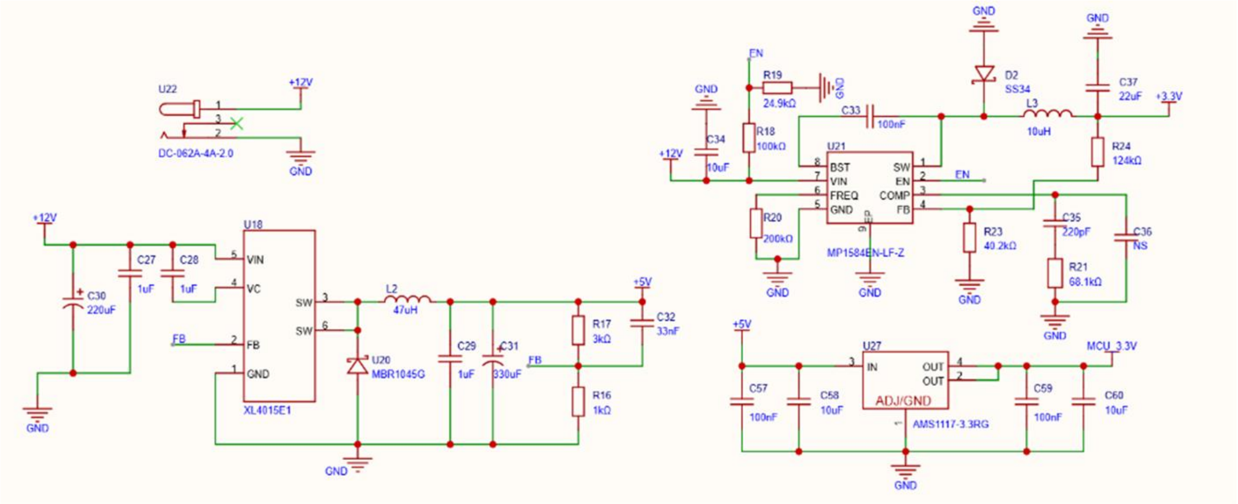


Figure 2 Power Management Circuit

2.4 Drive and Actuator Circuit

The stepper motor is driven by the ULN2003A Darlington array chip. Featuring high withstand voltage and large current capacity, this chip integrates freewheeling diodes internally, which can effectively absorb the back electromotive force generated when the stepper motor coils are de-energized, so as to protect the circuit. For closed-loop control, mechanical limit switches are installed at the extreme moving positions of the window. When the window touches the switch, the feedback signal is transmitted to the STM32 microcontroller, which immediately disables the motor drive. Thus, dual closed-loop control combining physical position limiting and software counting is realized.

2.5 Environmental Perception Module

The system is equipped with multi-dimensional sensing units to achieve comprehensive acquisition of environmental and target status information. In terms of visual perception, a K230 vision AI module is connected via the Universal Asynchronous Receiver/Transmitter (UART). It realizes detection of approaching children and distance measurement, providing core sensing support for the active safety protection of the system.

For environmental monitoring, a DHT11 sensor is adopted to collect ambient temperature and humidity. MQ series sensors and SGP30 sensors are used to monitor combustible gas concentration and air quality respectively. A rain sensor is deployed to detect rainfall and trigger the automatic window-closing logic. Meanwhile, infrared correlation modules are mounted on the window frame to detect obstacles on the window closing path, enabling the anti-pinch protection function.

2.6 Communication and Human-Computer Interaction Circuit

For local interaction, an interface for serial port screen is configured to build a graphical user interface, which displays environmental data and system operating status. A buzzer circuit is designed for fault alarm and operation prompt. The remote 4G communication module communicates with the main controller through UART. Supporting MQTT and TCP protocols, this module realizes cloud upload of environmental data and real-time reception of remote control commands.

The main parameters of system hardware modules are listed in Table 1.

Table 1 Main Hardware Module Parameters of the System

Module Name	Model/Device	Key Parameters	Function Description
Main Controller	STM32F407ZGT6	Main frequency: 168 MHz; Flash: 1 MB	Core system control, data acquisition and logic decision-making
Vision AI Module	K230	Dual-core RISC-V architecture; TOPS computing power	Pedestrian detection (for children), gesture recognition and distance estimation
4G Communication Module	Air780ep (Luat)	TD-LTE (China Mobile 4G)	Remote data transmission based on MQTT protocol
Motor Driver	ULN2003A	500 mA per channel	Stepper motor driving and freewheeling protection
Temperature & Humidity Sensor	DHT11	Temperature accuracy: ±2 °C; Humidity accuracy: ±5% RH	Indoor ambient temperature and humidity acquisition
Gas Sensor	MQ-6 / SGP30	Combustible gas detection / TVOC detection	Gas leakage monitoring and air quality detection
Infrared Photoelectric Sensor	HX1838	—	Obstacle detection for window anti-pinch protection
Raindrop Sensor	Digital output	—	Rainfall detection, automatic window closing trigger
Touch Display Screen	TJC T1 Serial Screen	—	Local human-machine interaction and status display

3 SYSTEM SOFTWARE DESIGN

3.1 Communication Protocol

This system adopts a layered communication architecture. Data interaction between the client and the IoT platform is implemented via the HTTP protocol, while data reporting and command delivery between the device terminal and the platform rely on the MQTT protocol. Featuring lightweight design, configurable QoS levels and automatic reconnection after disconnection, MQTT is well suited for IoT communication scenarios. The QoS 1 mechanism is adopted in this system to enhance the transmission reliability of control commands.

The 4G communication module embeds an MQTT client and communicates with the STM32 microcontroller through UART. The STM32 packages environmental sensor data and device status information into JSON format, which is then uploaded to the Newland IoT platform via the 4G module. The platform receives device data and issues control commands through corresponding topics. Once abnormal environmental conditions or hazards such as approaching children are detected, the STM32 promptly uploads alarm messages, which are subsequently pushed to the user APP by the platform.

3.2 System Control Strategy

As illustrated in Figure 3, the system performs initialization and self-check procedures immediately after power-on. It verifies the connection status of each sensor and the 4G module item by item, and enters the main loop only after normal operation is confirmed. The system supports two operating modes: automatic mode and manual mode.

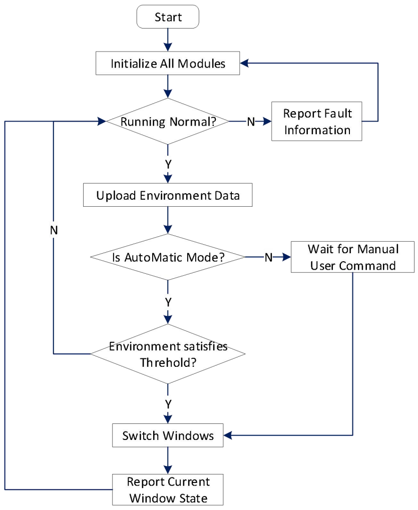


Figure 3 Program Flow of the Intelligent Control System

When the following environmental conditions are detected, the system will automatically close the windows, as shown in Table 2.

Table 2 System Control Logic and Response Strategies

Trigger Conditions	System Response Actions	Priority
K230 detects children approaching (distance < 50 cm)	Close the window immediately to prevent falling accidents	High
Indoor combustible gas concentration exceeds the threshold	Open the window for ventilation immediately and push alarm messages to the mobile APP	High
Anti-pinch and limit detection	Automatically stop window movement once obstacles are detected during operation	High
Indoor formaldehyde/CO_2 concentration exceeds the standard with better outdoor air quality	Open the window automatically for ventilation, and adjust the opening range according to outdoor temperature and humidity	Medium
Excessively large indoor-outdoor temperature/humidity difference (8 °C / 20% RH)	Automatically adjust the window opening range to balance ventilation and energy consumption	Medium
Triggered by remote gesture commands	Open or close the window	Medium
User-defined strategies via APP	Execute corresponding actions as configured	Low

After the automatic opening or closing of the window is completed, the system immediately initiates the status feedback process. It uploads the window opening degree and trigger cause to the cloud platform via the 4G communication module, and sends notifications to the user APP.

In practical complex and variable environments, the system may encounter extreme operating conditions where data from multiple sensors are inconsistent. For instance, if the indoor air quality monitored by the SGP30 exceeds the standard severely and requires immediate window ventilation, while the raindrop sensor simultaneously detects rainfall and requests window closure, a logical conflict between opening and closing commands will occur. To prevent indoor air quality deterioration or rain ingress caused by a single priority strategy, a compromise arbitration strategy is adopted in this design. When mutually exclusive control commands are detected, the actuator drives the window to stay at a 50% opening (half-open state). This state maintains partial ventilation to improve air quality and meanwhile reduces the risk of rain or strong wind entering the room. In addition, the system marks the current status as "environmental abnormal conflict", and immediately pushes a high-priority alarm to the user terminal. Subsequent automatic adjustment logic is suspended, and the system waits for remote manual commands from users, who are granted the final decision-making authority.

3.3 Vision AI Module

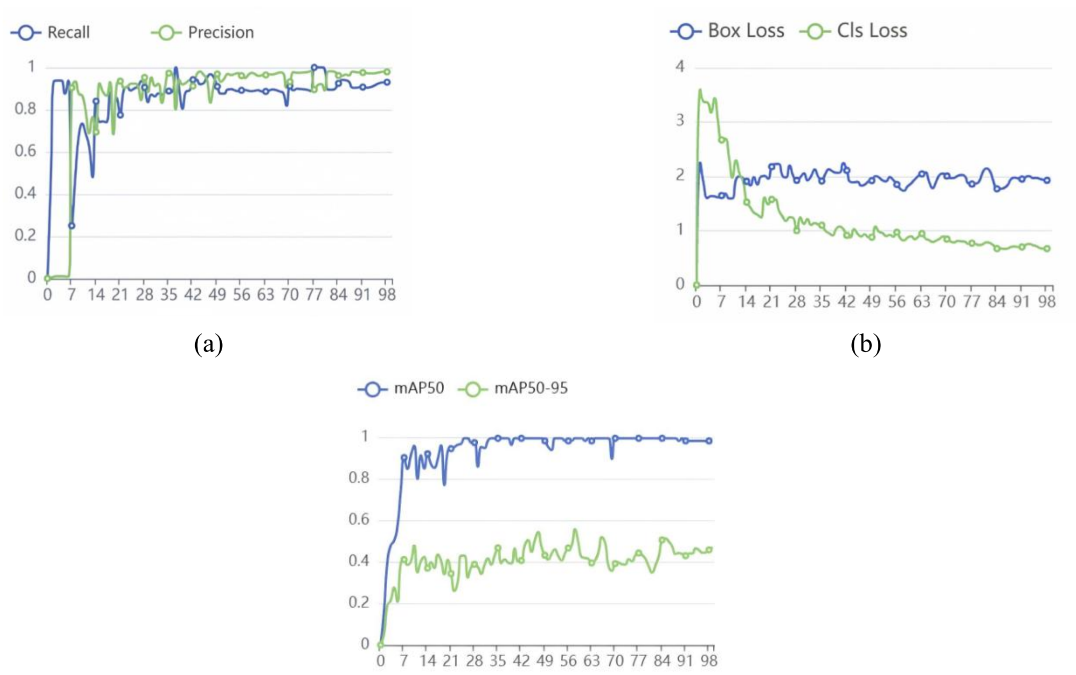
The K230 vision AI module performs two core tasks: child proximity detection and gesture recognition for control. The YOLOv11n model is trained on a custom dataset, optimized via model quantization and deployed on the module to support real-time edge inference.

The dataset is established by combining self-collected data and public datasets, covering categories of children approaching, children moving away, adults and various gestures. The initial dataset comprises roughly 200 annotated images, which is expanded to over 800 samples through data augmentation techniques, including random flipping, brightness alteration, and Mosaic augmentation. Built upon the YOLOv11n architecture, the model converges after 100 training epochs, with mAP@0.5 reaching 98.25%.

According to the training results, all evaluation metrics fluctuate significantly during the early stage of training. As the number of epochs increases, the Precision and Recall on the validation set gradually rise and eventually stabilize, as illustrated in Figure 4(a). Concurrently, the classification loss decreases continuously, demonstrating the progressively enhanced classification capability of the model. Although the bounding box regression loss exhibits minor fluctuations, it remains generally stable (Figure 4(b)). The mAP@0.5 plateaus during the middle and late training stages, thereby verifying the satisfactory detection performance of the model. Nevertheless, the relatively low mAP@0.5:0.95 indicates that the bounding box localization accuracy under strict IoU thresholds warrants further improvement (Figure 4(c)). Overall, the model achieves favorable convergence and fully satisfies the real-time requirements for deployment on the K230 edge device.

After training, the model is converted into the required format and optimized via quantization, then deployed on the K230 platform. The K230 performs image acquisition, object detection, result analysis and risk assessment, and communicates with the STM32 via serial port to realize window closing control.

The system estimates distance based on the object category, confidence score and bounding box information. A window closing command will be triggered once a child target is detected within the dangerous range. For the gesture control function, a face authentication mechanism is adopted. Only registered users are granted access to operate the system, so as to enhance overall security.



(a)

(b)

(c)

Figure 4 K230 Training Results

4 SYSTEM TEST AND ANALYSIS

4.1 Functional Test and Verification

During normal operation, data collected by various environmental sensors is uploaded to the Newland IoT cloud platform through the 4G communication module. Users can check device status and environmental parameters in real time via the mobile APP. To verify the system’s capabilities of environmental perception, risk judgment, execution control and remote alarm in automatic mode, functional tests are conducted under typical scenarios including combustible gas leakage, excessive indoor humidity, excessive indoor temperature and strong outdoor wind.

In the combustible gas leakage test, standard butane gas is released approximately 10 cm away from the MQ-6 sensor to simulate indoor gas leakage. When the combustible gas concentration exceeds the preset threshold, the system activates audible and visual alarms and adopts a graded ventilation strategy according to concentration levels. For low concentration, early warning messages are pushed to the APP. In the case of high concentration, the window is partially opened for ventilation, and gas leakage alarms are sent to users.

In the temperature and humidity anomaly tests, water vapor and external heat sources are used respectively to simulate the rise of indoor humidity and temperature. Once the measured values exceed the thresholds, the system automatically opens the window for ventilation and sends corresponding notifications of excessive humidity or temperature to the user terminal.

In the outdoor strong wind test, when the wind speed sensor detects that the wind speed reaches or exceeds the preset threshold (i.e., wind force grade no less than Grade 4), the system automatically closes the window and reports the window status to the APP. The test results prove that the system can realize automatic response, control execution and remote alarm under various abnormal environmental conditions, which satisfies the safety control requirements of the intelligent horizontal sliding window.

4.2 Performance Test and Analysis

To further evaluate the practical performance of the system, quantitative tests are carried out on key indicators. The test results are presented in Table 3.

Table 3 System Performance Test Results

Test Item	Test Conditions	Design Index	Measured Result
Child detection response time	Indoor normal illumination, distance of 50 cm	≤ 800 ms	Approximately 500 ms
Child detection accuracy	100 tests at multiple angles and distances	≥ 90%	93%
Distance detection accuracy	Measuring range: 30 ~ 80 cm	± 10 cm	± 5 cm

Test Item	Test Conditions	Design Index	Measured Result
Window closing execution time	Full stroke (open to closed)	≤ 10 s	Approximately 8 s
Sensor response delay	DHT11 / MQ-6 / Raindrop sensor	≤ 500 ms	Approximately 200 ms
4G communication delay	Stable 4G network environment	≤ 5 s	Approximately 1.5 s
System standby power consumption	All sensors in operating state	≤ 500 mA	Approximately 180 mA
Offline independent operation	4G module disconnected	Operate normally	All safety strategies work properly
Continuous operation stability	24-hour continuous operation	No faults	No abnormalities, all functions work normally

As shown in Table 3, all key performance indicators of the system meet or exceed the design requirements. The child detection response time of the K230 vision module is approximately 500 ms with an accuracy of 93%, which satisfies the real-time requirements for child anti-falling protection. The STM32 can independently execute all safety strategies when the network is disconnected. No malfunctions occur during 24-hour continuous operation, which verifies the basic stability of the system for engineering deployment.

5 CONCLUSION AND PROSPECT

5.1 Research Conclusions

Aiming at the deficiencies of traditional horizontal sliding windows in child anti-falling protection, this paper designs and implements a dual-main-controller intelligent horizontal sliding window system based on STM32F407ZGT6 and K230 vision AI module. The main work and achievements are summarized as follows:

(1) A layered and modular system architecture with STM32F407 and K230 as the core is constructed, realizing the collaborative operation of vision perception, multi-source environmental sensing, actuator control and remote communication. A dual-channel safety strategy and environmental conflict arbitration mechanism are proposed for multiple scenarios including children approaching, wind and rain intrusion, and gas leakage. The system can still perform all safety strategies offline.

(2) The YOLOv11n model is deployed and quantized on the edge side of K230. The response time for detecting approaching children is about 500 ms and the recognition accuracy reaches 93%. The system runs stably for 24 consecutive hours, proving its reliability for practical engineering application.

5.2 Limitations and Future Work

(1) The distance estimation based on monocular vision suffers from reduced accuracy under complex lighting conditions. Infrared supplementary lighting or binocular vision will be adopted in follow-up research to improve system robustness.

(2) Currently, the gesture recognition and face authentication functions only support single-user access. Multi-user management will be expanded, and a liveness detection mechanism will be introduced to prevent photo spoofing.

(3) The system currently controls only a single window. In the future, it will be upgraded to a multi-window linkage solution and connected to the whole-house smart home system to achieve comprehensive safety protection.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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