Design and Implementation of Embedded Environmental Control Terminal Based on Multimodal Interaction

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Abstract: *This paper designs and implements a multi-modal environmental interaction and intelligent control terminal based on embedded technology. With STM32U5 as the core, the terminal integrates multi-dimensional environmental perception, intelligent human-computer interaction and edge-cloud data synchronization, enabling real-time monitoring of indoor environmental parameters and adaptive regulation of scene-based modes. It supports local touch control, voice control and remote management via WeChat Mini Program, and is applicable to various scenarios such as home and office. The terminal realizes the intelligentization and convenience of indoor environmental management, reduces manual operation costs, provides a practical scheme for the research and development of intelligent environmental equipment, and also offers a reference for the application of the Internet of Things in the field of indoor health.*

Keywords: *Multimodal Human-Computer Interaction; Environmental Regulation; Offline Control*

1. Introduction

The deep integration of the Internet of Things and embedded technologies promotes the of indoor environmental equipment toward intelligence and interactivity. Traditional environmental control devices feature single interaction modes, high misoperation rates, and lack scenario-based customization and local offline control capabilities, which can hardly meet diversified application demands[1]. Therefore, this paper designs a STM32-based environmental control terminal with multimodal human-computer interaction, integrating touch, voice and light feedback interaction, equipped with anti-misoperation and other functions, supporting local offline operation and peripheral linkage, and accurately connecting with environmental perception, disinfection and purification modules. The design achieves a good balance between convenience and stability, providing a practical solution for the research and development of human-computer interaction systems for intelligent environmental equipment, and has good application prospects in smart home, medical treatment, office and other fields[2].

2. Overall System Architecture

As shown in Figure 1, the system adopts an overall hardware-software collaborative end-cloud integrated design scheme. The hardware side takes STM32U575 main control chip and iLTE9866 co-processor as the dual-core core, integrating multimodal perception sensors, human-computer interaction, 4G communication, disinfection and purification execution, and graded power supply modules. All modules cooperate to complete environmental data collection, instruction processing and other operations, forming a high-reliability and low-power embedded hardware architecture[3]. The software side adopts a layered modular design, which is divided into five layers: edge perception control, data transmission, cloud service, application interaction and local UI. Each layer realizes data intercommunication based on standardized protocols, forming an end-cloud collaborative closed loop of "perception-decision-execution-feedback", which provides core support for the intelligent operation of the system[4].

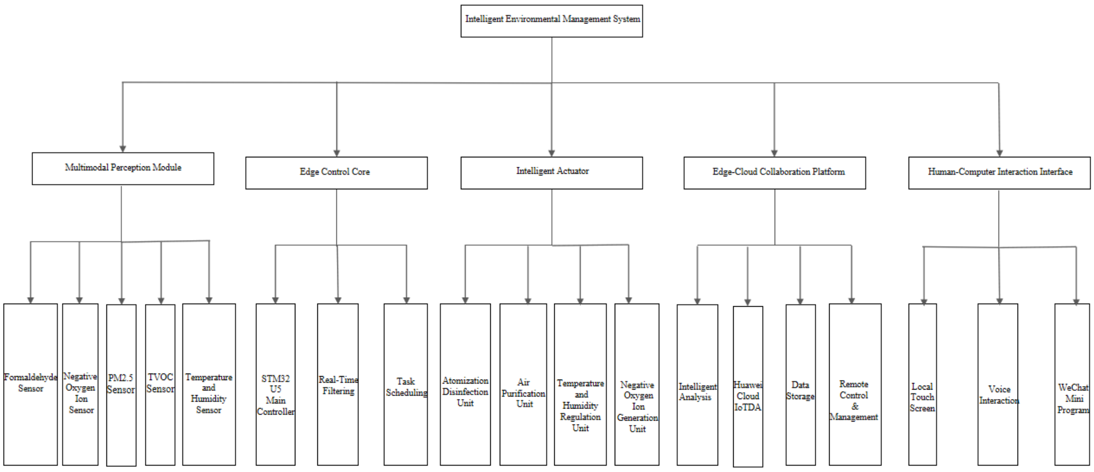

Figure 1: Functional structure diagram of the system

2.1. System Hardware Design

The finished hardware of the system is shown in Figure 2. Focusing on modularization, high reliability and low power consumption, the hardware architecture is built with a dual-core control module as the core, integrating five functional modules: perception, execution, interaction, communication and power supply, to meet the actual demands of multimodal environmental perception and dynamic disinfection and purification. Each module is functionally independent and cooperates efficiently, which can complete the whole process such as environmental data collection and disinfection execution, providing solid hardware support for the accurate and intelligent operation of the system.

Figure 2: Physical hardware prototype

2.1.1. Dual-Core Control Module

The control module adopts a dual-core architecture consisting of the STM32U575RI main control chip and the iLTE9866 co-processor. With ultra-low power consumption, high computing power and abundant peripheral interfaces, STM32U575 undertakes the core tasks including multi-source sensor data aggregation, filtering and calibration, scenario policy scheduling, peripheral driving and end-cloud communication coordination. The iLTE9866 focuses on high-voltage driving control and sensor data preprocessing, and cooperates with the main controller via the I2C protocol, which not only ensures the safe driving of high-voltage execution units but also reduces the computing load of the main controller and improves the system response speed, providing efficient hardware support for the access of various modules.

2.1.2. Multimodal Perception Module

The perception module integrates formaldehyde (detection limit 0.01 mg/m³), TVOC, PM2.5 (resolution 0.001 mg/m³), temperature/humidity (temperature control accuracy ±1°C) and negative oxygen ion (precision at pcs/cm³ level) sensors, all connected to the control module via standard I2C/UART interfaces[5]. With fast response and high data accuracy, it can collect key indoor environmental parameters in real time, providing reliable data support for intelligent system decision-making[6].

2.1.3. Intelligent Execution Module

The execution module integrates nano-silver atomization disinfection, air purification, temperature and humidity regulation, and negative oxygen ion generation units. The atomization disinfection unit generates 1–5μm droplets for full-space disinfection; the air purification unit adopts PWM speed regulation to match different purification intensities; the temperature and humidity regulation unit achieves precise control based on PID algorithm; the negative oxygen ion unit outputs forest-grade to medical-grade negative oxygen ions. All units work cooperatively under the scheduling of the control module to realize full-dimensional indoor air conditioning.

2.1.4. Human-Computer Interaction and Communication Module

The human-computer interaction module consists of a 7-inch IPS full-laminated touch screen, offline voice module, three-color early warning light and breathing light. The IPS screen displays environmental parameters and device status for local operation; the offline voice module recognizes more than 20 commands with a response time <0.5s and works without network; the light module provides status feedback and orange/red graded early warning, and multi-sensor fusion improves interaction convenience and reduces misoperation rate. The communication module uses the Fibocom ADP-L610-Arduino 4G module connected to the main controller via UART interface, realizes stable data interaction with Huawei Cloud IoTDA based on MQTT-SN protocol[7], completes data uploading to the cloud and remote command reception, supporting end-cloud collaboration and remote control.

2.1.5. Graded Power Supply and Drive Module

The power supply module adopts a 12V, 5V, 24V three-level isolated architecture with a pre-charge and soft-start circuit, limiting the atomizer impulse current within 8A. 12V supplies power to the 4G module, display screen and fans, 5V powers the main controller and voice module, and 24V is dedicated to the atomizer, ensuring stable operation of each module. The drive module uses hierarchical control: STM32U575 controls fan start-stop via GPIO and adjusts pump speed through PWM; the atomizer is driven by the three-level link of STM32U575→iLTE9866→MB9F, and MB9F provides hardware overcurrent protection to guarantee safe driving of execution units.

2.2. System Software Design

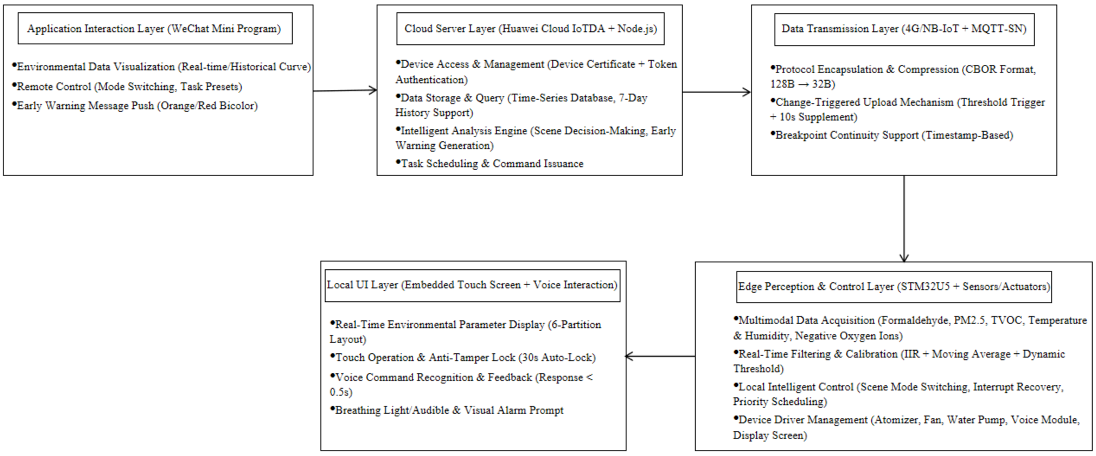

Figure 3: Layered modular software architecture diagram

As shown in Figure 3, the system software adopts a layered, decoupled and modular design. According to the core requirements of multimodal perception, dynamic disinfection and end-cloud collaboration, it is divided into five core layers. Data interaction between layers is realized based on standardized protocols, with clear division of labor and efficient cooperative scheduling, which can fully implement the whole-process software functions and provide core software support for the intelligent end-cloud collaborative operation of the system.

2.2.1. Edge Perception and Control Layer

Developed based on STM32U575 and FreeRTOS with C language programming, this layer is the core of the system's local software, including main program, data acquisition and filtering, hierarchical task scheduling, device driving, and local emergency response subroutines. The main program completes system power-on initialization and cyclic scheduling; the acquisition and filtering subroutine controls the collection error within ±0.5% FS via first-order IIR + moving average algorithm + dynamic threshold calibration; hierarchical scheduling adopts a three-level preemptive strategy to ensure low-latency response of core functions; the device driving subroutine precisely controls peripherals such as atomizers and fans; the emergency response subroutine triggers local disinfection within 0.2 seconds when parameters exceed the standard, enabling network-free emergency processing.

2.2.2. Data Transmission Layer

Developed based on the 4G module, the data transmission layer is centered on the communication subroutine, which completes MQTT-SN protocol configuration and CBOR data compression[8]. A "differential upload + exception trigger" mechanism is adopted to upload environmental data and device status to the cloud, supporting breakpoint resume and timestamp retransmission. On the premise of ensuring data integrity, the daily traffic is reduced to less than 8MB to lower transmission power consumption. Meanwhile, the layer receives remote control commands issued by the cloud to realize bidirectional data interaction between the terminal and the cloud.

2.2.3. Cloud Service Layer

The cloud service layer is developed based on Huawei Cloud IoTDA and Node.js, including device authentication management, data storage and query, intelligent analysis strategy, and early warning generation and push subroutines. Secure access is realized through device certificate and Token; environmental data is stored based on time-series database, supporting 7-day historical query; disinfection strategies are generated via scenario analysis and issued remotely; orange/red dual-color early warnings are triggered according to device status and environmental parameters and pushed to the application terminal timely to complete cloud intelligent analysis and control[9].

2.2.4. Application Interaction Layer

The application interaction layer is developed based on WeChat Mini Program with JavaScript, including five interfaces: real-time data, remote control, history curve, early warning prompt and device configuration. It calls Huawei Cloud API to obtain Token and connect to the cloud platform, synchronously displays environmental parameters and device status, supports remote start-stop, mode switching and task scheduling, allows viewing 7-day data trends, receives cloud early warnings, supports personalized parameter configuration, and provides hardware connection detection to ensure accurate remote control.

2.2.5. Local UI Layer

The local UI layer is developed based on the embedded touch screen, including parameter display, touch operation, voice recognition and analysis, and light feedback subroutines. The parameter display adopts a block layout to show key information such as negative oxygen ions, formaldehyde and disinfection progress in real time; the touch operation supports mode switching and task preset with a 30-second auto-lock anti-misoperation mechanism; the voice analysis subroutine communicates with the offline voice module via serial port and converts voice commands into control signals; the light feedback subroutine controls the breathing light and warning light according to the device status to realize operation feedback and status early warning, forming a visualized and convenient local interaction closed loop.

3. Conclusion

The multimodal human-computer interaction environmental control terminal designed in this project takes STM32U575 as the core, integrates touch, voice, light feedback and other multimodal interaction technologies, and builds a hardware-software collaborative local intelligent control system. The terminal can realize accurate collection and real-time feedback of multi-dimensional instructions, support scenario-based customization, anti-misoperation lock screen and other characteristic functions, and has both local offline operation and flexible peripheral linkage capabilities, which can adapt to the interaction needs of different environmental control devices and achieve convenient, personalized and safe environmental control operation. With reasonable design and stable operation, the terminal meets users' demands for upgraded interaction experience of intelligent environmental equipment, provides practical reference for the research and development of multimodal human-computer interaction systems of embedded devices, has good application and promotion value in smart home, medical treatment, office and other fields, and is of positive significance for the integration and implementation of embedded technology and interaction design[10].

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