HomeEnv-Link: A Smart Home System for Environmental Monitoring and Household Appliance Feedback Control

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Abstract

To address the limitations of traditional smart home devices, including scattered functional modules, single interaction modes, poor device interconnection compatibility, and insufficient local automatic feedback capability, this paper designs and implements a smart home environmental monitoring and household appliance feedback control system. The system is based on the STMicroelectronics 32-bit (STM32) microcontroller. Centering on the technical framework of multi-sensor environmental perception and multi-modal human-machine interaction, the system integrates six core functional modules. These include multi-parameter environmental monitoring, offline voice recognition, local Organic Light-Emitting Diode (OLED) visual display, Pulse Width Modulation (PWM) drive control, key parameter configuration, and ESP8266 cloud remote communication. The system adopts the STMicroelectronics 32-bit F1 series (STM32F103C8T6) chip as the underlying main control core. It collects indoor environmental data through Digital Humidity and Temperature sensor 11 (DHT11), MQ-2, and BH1750 sensors. Offline voice parsing is realized via Universal Asynchronous Receiver/Transmitter (UART) serial communication with the Automatic Speech Recognition PRO (ASR-PRO) module. The ESP8266 Wireless Fidelity (Wi-Fi) module establishes bidirectional Message Queuing Telemetry Transport (MQTT) data interaction with the Internet of Things (IoT) cloud platform. This constructs a closed-loop operation mechanism of “environmental sensing - logical judgment - equipment execution - multi-terminal feedback”. Experimental test results demonstrate that the system meets the real-time and stability requirements of household application scenarios. This is shown in sensor measurement error, voice recognition accuracy, wireless communication response delay, and other key performance indicators. The proposed system achieves a low-cost and lightweight smart home solution. It supports both manual control mode and threshold-triggered automatic operation mode. This provides a feasible technical reference for the multi-modal interaction and intelligent linkage of civil smart home terminals.

Keywords

Smart home system, STMicroelectronics 32-bit microcontroller, Off line voice interaction, Environmental monitoring, Internet of Things cloud communication

Introduction

Driven by the rapid development of the IoT and embedded technology, smart home terminals greatly improve residential comfort and safety. However, traditional smart home control systems suffer from fragmented functions, single interaction modes, and poor hardware compatibility. They also lack sufficient local automatic feedback. Most existing solutions rely excessively on cloud servers. Network failures thereby disable core monitoring and control functions, failing to meet user demands. These demands include local autonomous operation, voice hands-free control, and remote mobile management. With low power consumption, high integration, and flexible secondary development, low-cost 32-bit Microcontroller Unit (MCU)-based embedded smart home solutions have become a popular research direction [1].

Current studies have explored MCU-based home environment monitoring. Indoor temperature and humidity acquisition and local display were realized via STM32 and Digital Humidity and Temperature (DHT)

sensors. This verified the feasibility of embedded multi-sensor data collection. An indoor gas detection system was developed with metal oxide (MQ-series) sensors and ESP8266 modules. It pushed cloud-based alarm notifications to mobile terminals. A light-driven automatic curtain control system was designed to achieve ambient light linkage. Nevertheless, these studies only support single-dimensional monitoring or partial actuator control. They lack integrated functions of offline voice interaction, local display, threshold configuration, and cloud access. They are unable to form a complete closed-loop feedback control system [2].

Progress has also been made in smart home human-computer interaction and IoT communication. Relevant studies have proven that offline voice interaction effectively reduces manual operation workload. It also improves household control efficiency. ESP8266-based IoT gateways are widely adopted for MQTT-based sensor data transmission and remote command forwarding. However, most existing voice-control smart home devices adopt cloud speech recognition. This approach is highly network-dependent and prone to recognition errors under unstable network conditions [3].

Against this backdrop, this paper proposes the HomeEnv-Link system with three core innovations. First, it establishes an integrated closed-loop framework covering multi-source environmental perception, offline voice parsing, local automatic feedback, and cloud remote management. The system integrates sensor sampling, voice recognition, OLED display, PWM adjustment, and IoT interaction on a single hardware platform. This solves functional fragmentation problems. Second, it adopts the ASR-PRO offline voice recognition chip to complete local voice parsing without cloud computing. This avoids performance fluctuations caused by poor network conditions. Third, dual manual and automatic threshold-triggered operation modes are realized. The system can automatically activate fans, humidifiers, and buzzers according to user-defined thresholds, with adjustable parameters via onboard keys or a mobile application (APP). Featuring low cost and high integration, the proposed multi-modal interactive system provides a reliable technical reference for the development of lightweight civil smart home terminals.

System overall architecture

This paper designs a household environment monitoring and smart appliance feedback control system. The system adopts a layered architecture consisting of perception, control, communication, and application layers. Taking the STM32F103C8T6 microcontroller as the core control unit, the system collects environmental data through a temperature-humidity sensor, a smoke sensor, a light intensity sensor, and a voice sensor. It also receives manual input from keys. The STM32 chip completes logical judgement and drives actuators, including a stepper motor, a humidifier, a fan, and a light-emitting diode (LED). An OLED screen displays real-time environmental parameters, and a buzzer gives an alarm for abnormal conditions. The ESP8266 Wi-Fi module establishes bidirectional data transmission with the Internet of Things (IoT) cloud platform. The system forms a closed-loop feedback mechanism of environmental monitoring and smart appliance control. The overall functional block diagram of the proposed system is illustrated in Figure 1.

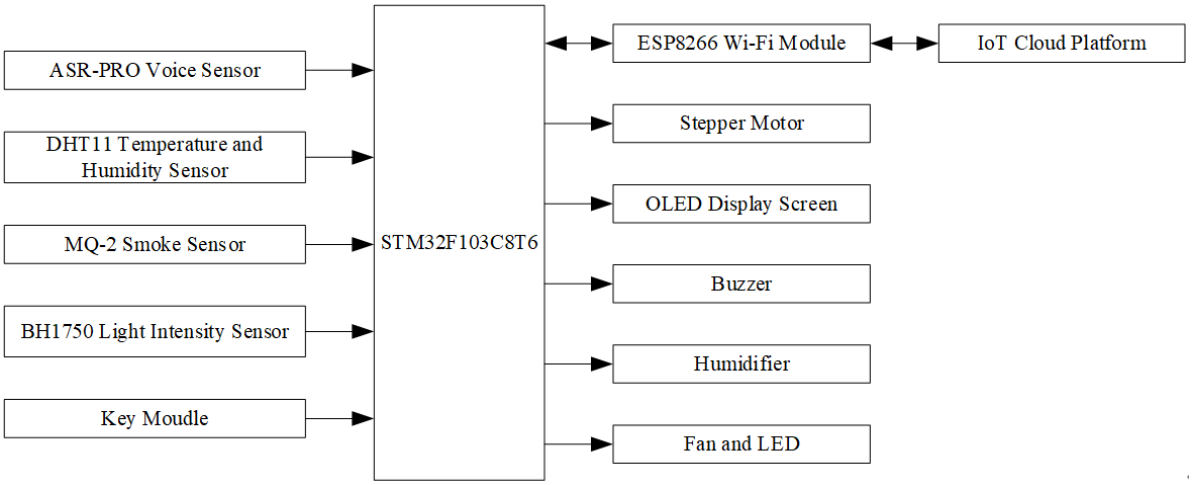


Figure 1. Overall system functional block diagram.

The system functions are divided into three core modules.

(1) Multi-source environmental perception module

This module is responsible for the real-time collection of indoor environmental parameters. The DHT11 sensor acquires indoor temperature and humidity. The MQ-2 sensor detects smoke and combustible gas concentration. The BH1750 (GY-302) module collects ambient light intensity. To eliminate random sampling noise, the STM32 microcontroller adopts a multi-sampling averaging algorithm to filter the original sensor data. The processed effective environmental parameters support local OLED display, automatic threshold judgment, and cloud data uploading [4,5].

(2) Multi-modal human-machine interaction module

This module integrates three interaction modes: offline voice recognition, local key operation, and cloud-based mobile APP remote control. The ASR-PRO module captures and parses preset voice commands locally, and transmits the resolved instruction codes to the STM32 via UART serial communication. The physical keys support system mode switching and threshold parameter modification, while the OLED screen dynamically displays real-time environmental data and system operating status. Meanwhile, the mobile APP acquires sensor data from the cloud platform and delivers remote control commands to the system.

(3) Intelligent feedback control execution module

This module implements dual control logic, including threshold-triggered automatic operation and manual intervention control. In automatic mode, the STM32 compares the collected environmental data with user-defined thresholds. It then drives the PWM-adjustable fan and LED lamp, stepper-motor-driven simulated curtain, relay-controlled humidifier, and buzzer alarm according to the comparison results. In manual mode, the system directly executes control commands from voice input, physical keys, or a mobile app without automatic judgment logic. It synchronously feeds back the operating status to the OLED screen and cloud platform in real time.

The three functional modules operate collaboratively to realize local autonomous operation, offline voice control, remote cloud monitoring, and intelligent environmental adjustment. This fully meets the lightweight and multi-functional design requirements of the smart home system.

Hardware system design

Main-control unit and peripheral interface

The system adopts the STM32F103C8T6 micro-controller as the lower-computer main control chip. Based on the Cortex-M3 architecture, the chip supports a maximum operating frequency of 72 MHz, with built-in Flash and SRAM resources. It integrates abundant peripheral interfaces, including ADC, USART, I2C, GPIO, and timers. These fully meet the system requirements for multi-channel sensor sampling, serial communication, and PWM signal generation. The MCU minimum system consists of a crystal oscillator circuit, a reset circuit, and a power filter circuit. These guarantee stable system clock operation and reliable power-on initialization.

All peripheral modules are connected to the STM32 chip through standard interfaces. The DHT11 sensor communicates via a single-bus GPIO interface. The BH1750 illuminance sensor adopts the I2C bus. The MQ-2 smoke sensor transmits analogue signals to the STM32 ADC channel. The ASR-PRO voice module realises data interaction through the USART3 serial port. The ESP8266 Wi-Fi module is connected via the USART interface. The OLED display works based on I2C communication. The internal timers of STM32 generate PWM waveforms to realise fan speed regulation and LED brightness adjustment.

Environmental sensing unit

The system adopts three types of sensors to realize multi-dimensional household environment monitoring.

(1) DHT11 temperature and humidity sensor

As a digital single-bus sensor, the DHT11 collects indoor temperature and relative humidity. It transmits 40-bit data frames to the STM32 microcontroller and adopts checksum verification to ensure data transmission integrity.

(2) MQ-2 gas and smoke sensor

The MQ-2 is an analog sensor sensitive to smoke and various combustible gases. Its output analog voltage signal is sampled by the internal ADC module of STM32. A multi-sample averaging filtering algorithm is adopted to suppress data fluctuations, and the original

ADC values are further converted into standard smoke concentration values in parts per million (ppm).

(3) BH1750 (GY-302) illuminance sensor

This is a high-precision digital light sensor based on the I2C communication protocol. It outputs ambient illuminance data in lux and supports continuous high-resolution measurement.

The main control chip periodically collects data from all sensors. After digital filtering and unit conversion, the processed environmental data provide reliable basis for system automatic control logic and real-time visual display [6].

Human machine interaction hardware unit

(1) ASR-PRO offline voice recognition module

The ASR-PRO is a standalone offline voice processing module that operates independently of cloud servers. The onboard microphone captures ambient voice signals and completes local feature extraction and matching with the built-in command vocabulary. Once a valid preset voice instruction is recognized, the module transmits the corresponding command code to the STM32 microcontroller via the UART serial port. It supports common household voice commands, including turning the fan on and off, opening and closing the curtain, and switching system operating modes [7].

(2) 0.96-inch OLED display module

The 128 × 64 dot-matrix OLED screen adopts the I2C bus for data communication and displays real-time system information, including indoor temperature, humidity, light intensity, smoke concentration, operating mode, and threshold parameters. Two display interfaces, namely the main monitoring interface and the parameter configuration interface, are designed and can be switched through key triggering.

(3) Independent key module

Four mechanical keys are connected to the GPIO pins of the STM32 chip to realize system mode switching, display page toggling, and threshold value adjustment. All modified threshold parameters are stored in the on-chip Flash to achieve persistent data saving after power off.

(4) Buzzer alarm module

The buzzer is driven by STM32 GPIO level signals. In the automatic operating mode, when the detected smoke concentration exceeds the preset safety threshold, the buzzer is activated to issue an audible alarm to realize a safety warning [8].

Actuator drive unit

This module is responsible for the physical execution of control commands and integrates four types of simulated household appliance loads. Its specific functional implementation is as follows:

(1) PWM-controlled fan and LED lamp

The internal timer of the STM32 microcontroller generates PWM signals with adjustable duty cycles. These signals are amplified via an S8050 triode drive circuit to regulate the fan speed and LED brightness, enabling smooth, stepless parameter adjustment through duty cycle variation.

(2) 28BYJ-48 stepper motor curtain simulation

Adopting a ULN2003 driver chip for drive control, the STM32 outputs sequential pulse signals to govern the forward and reverse rotation of the 28BYJ-48 stepper motor, which simulates the opening and closing actions of household curtains.

(3) Relay-controlled humidifier

An SRD-05VDC-SL-C normally open relay module is driven by STM32 GPIO level signals. The switching of relay contacts realizes the start and stop control of the simulated humidifier.

(4) Power supply circuit

A regulated 5 V and 3.3 V power supply provides stable power for all functional modules. Meanwhile, power isolation design is adopted to eliminate mutual interference between different functional units and ensure stable system operation.

ESP8266 wireless communication unit

The ESP8266 Wi-Fi module serves as the data interaction gateway between the local hardware system and the IoT cloud platform. It communicates with the STM32 microcontroller via UART serial ports and is configured through AT commands. Operating in STA mode, the module connects to a domestic Wi-Fi router and establishes an MQTT communication link with the cloud server. The sensor data acquired by STM32 is uploaded to the cloud platform through the ESP8266. Meanwhile, remote control commands sent from the mobile application are forwarded by the cloud server and transmitted to STM32 via serial communication, implementing bidirectional transparent data trans-

mission. In the event of a Wi-Fi disconnection, the local monitoring and control logic continues to operate normally, ensuring the system does not crash or stop working.

Software system design

Overall software architecture

The overall software workflow follows a fixed execution sequence. When the system is powered on, it first completes hardware peripheral initialization, system parameter restoration, and network module configuration. After entering the main loop, the system continuously collects and processes sensor data, monitors key triggers and voice instructions, and executes corresponding control logic according to preset thresholds and operating modes.

The system synchronously updates the local display interface and uploads valid data to the IoT cloud platform. All external data from the voice module and Wi-Fi module are received through interrupt service programs to ensure real-time interaction. The above cycle runs continuously after system startup, forming a stable and closed-loop software operation process. The overall system flow chart is shown in Figure 2.

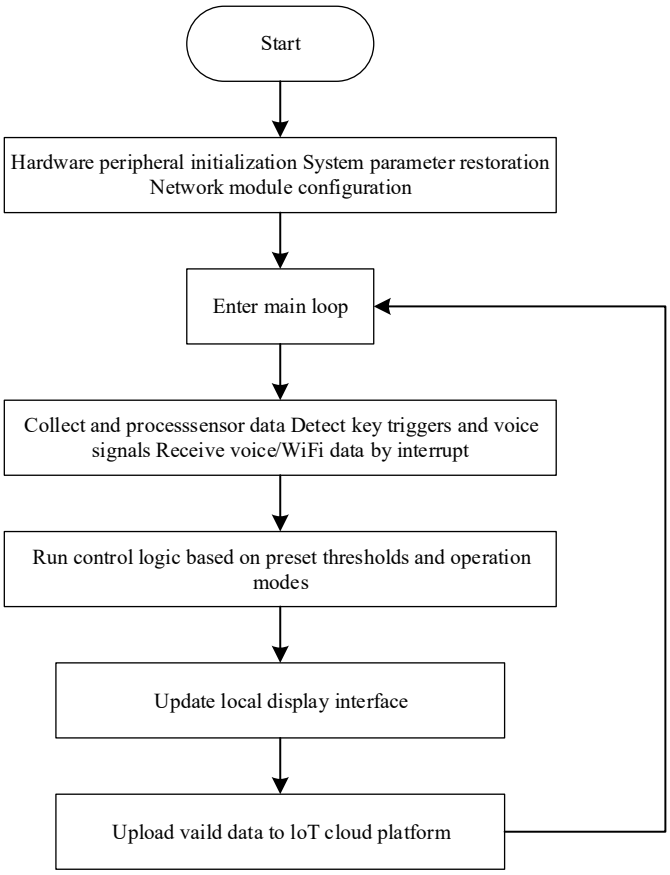


Figure 2. Overall system flow chart.

Core functional module software realization

(1) Multi sensor data acquisition program

For the DHT11 sensor, the MCU transmits a start signal and receives a 40-bit data frame. A checksum validation is carried out; temperature and humidity values are extracted only if the validation succeeds.

For the MQ-2 smoke sensor, multi-point ADC sampling is implemented, followed by averaging to suppress data jitter. The raw ADC readings are then converted to smoke concentration in ppm.

For the BH1750 light intensity sensor, 16-bit raw data is acquired via I2C read operations and converted into illuminance in lux using the formula specified in the chip datasheet.

All valid sensor data is stored in global structure variables for subsequent logic invocation, local display and cloud uploading. This modular scheme ensures each sensor is polled independently, while the unified storage structure allows the main program to access all environmental parameters synchronously [9]. The process runs periodically in the main loop, maintaining real-time responsiveness without blocking other tasks. The flowchart of the multi-sensor data acquisition program is shown in Figure 3.

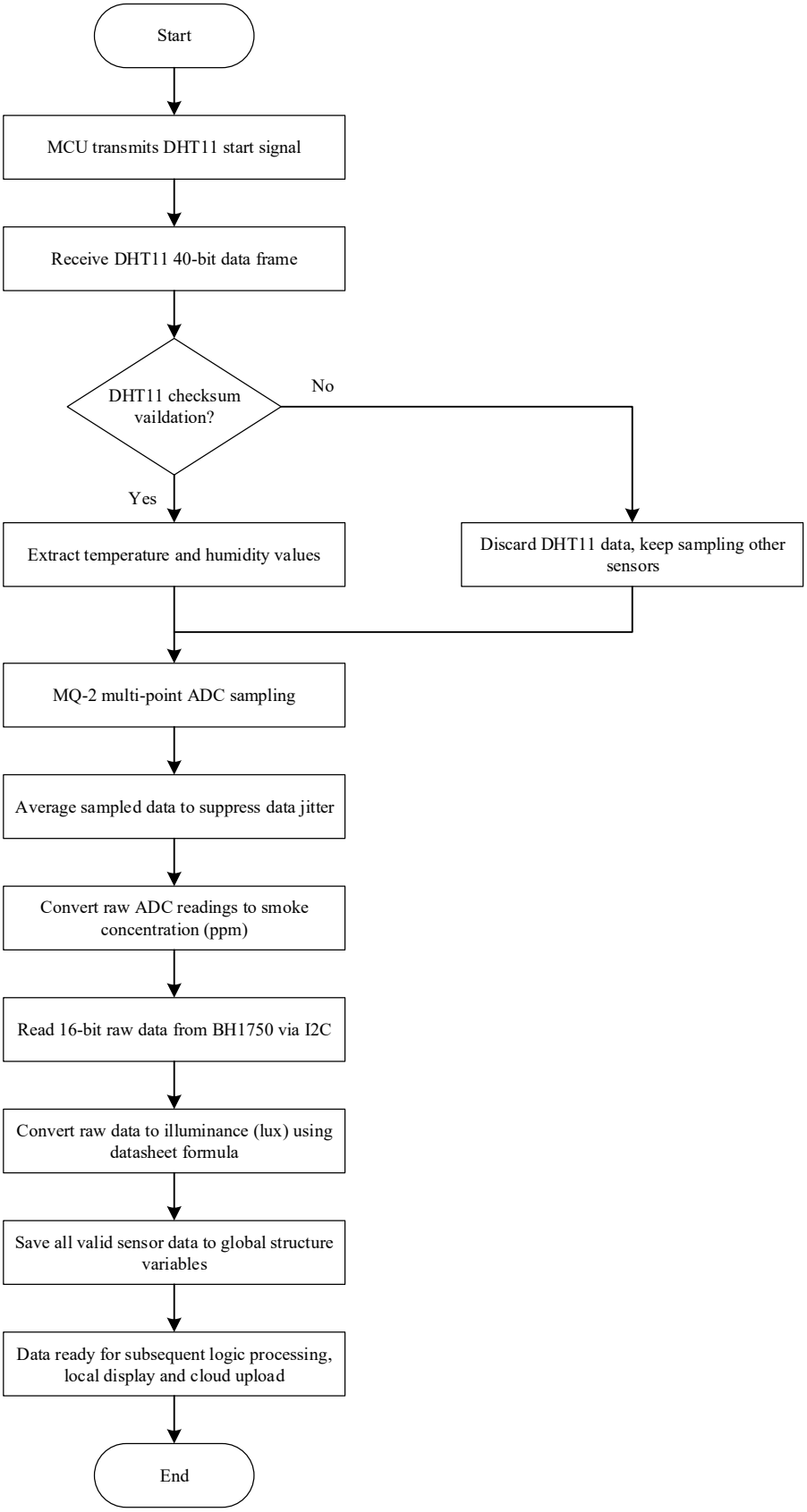


Figure 3. Flowchart of Multi-sensor Data Acquisition Program

(2) Off line voice command parsing program

The UART3 serial port interrupt receives data packets transmitted by the ASR-PRO voice module. Once a complete instruction frame is received, the corresponding interrupt flag bit is asserted. In the main loop, the program detects this flag bit, extracts the command type byte and parameter byte from the data packet, and maps them to the corresponding control operations. Under manual mode, voice commands can control fan on/off, LED brightness adjustment, curtain

opening and closing, humidifier switching, and system mode switching. In automatic mode, direct voice-triggered device control is masked to prevent conflicts with the automatic control logic. Invalid or unrecognized voice instructions will not alter the system operating state. The flowchart of the complete offline voice command parsing program is clearly shown in Figure 4.

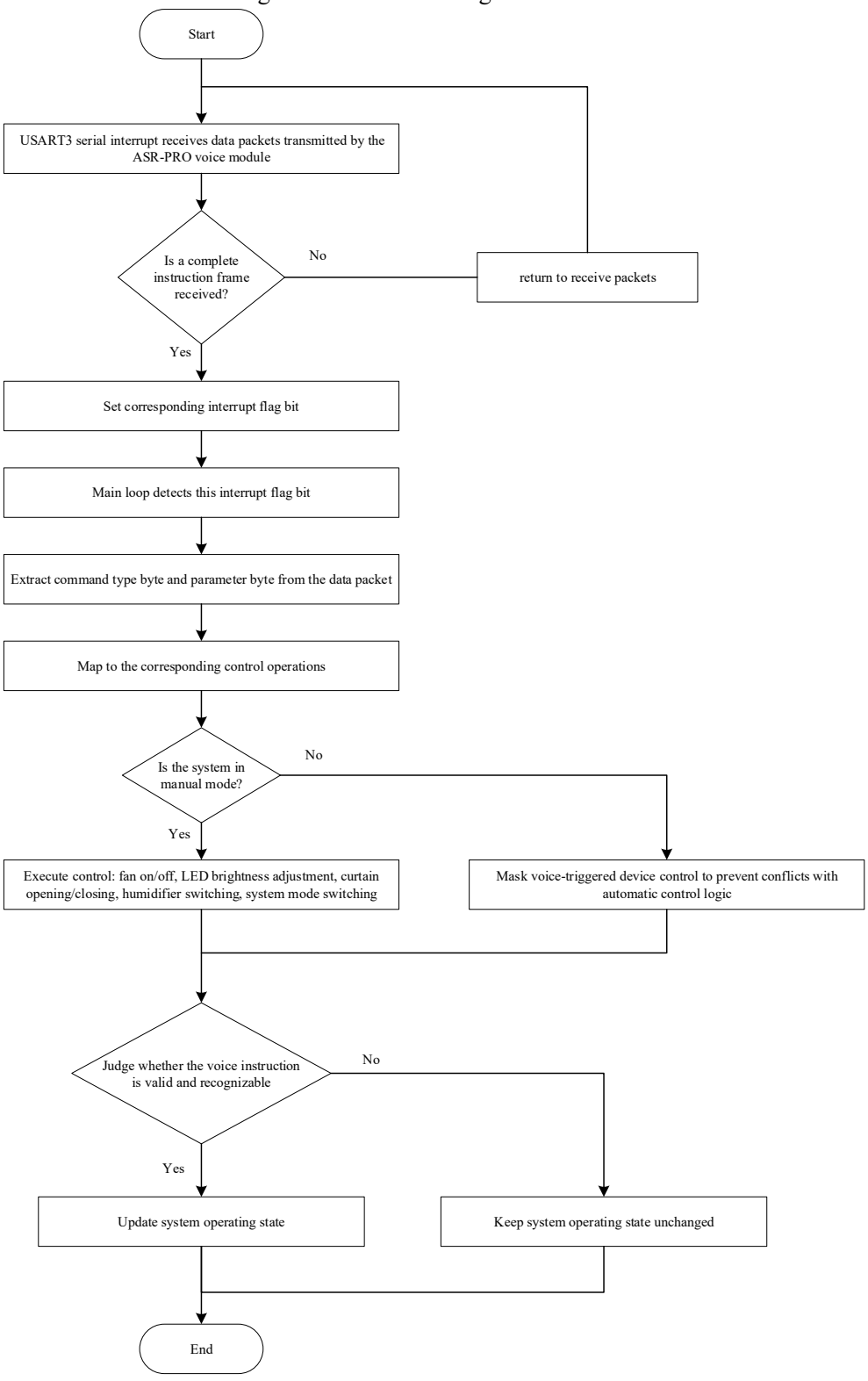


Figure 4. Flowchart of offline voice command parsing program.

(3) OLED display and key processing program

The system implements two distinct and user-friendly OLED display interfaces. The main monitoring page presents clear real-time environmental parameters and the current system operating mode, while the parameter setting page displays the threshold values of temperature, humidity, smoke concentration and light intensity. Physical keys support convenient page

switching and threshold value adjustment. After parameter modification, users can easily save the updated thresholds to the STM32 on-chip Flash through the save key, realizing power-off data persistence. The OLED screen automatically refreshes synchronously once data or threshold parameters change. The program flowchart of OLED display and key processing is shown in Figure 5.

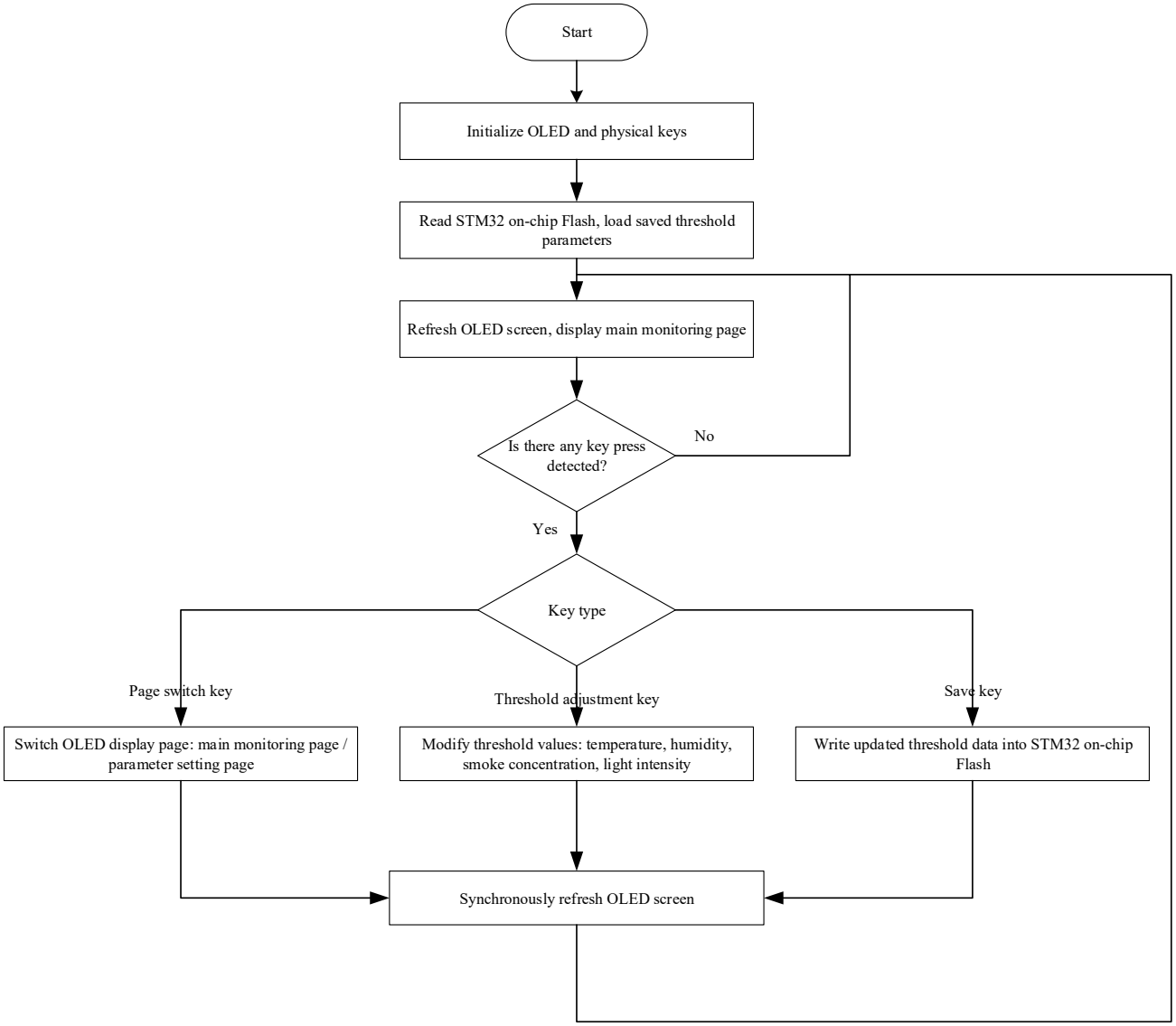


Figure 5. Flowchart of OLED display and key processing program.

(4) Automatic feedback control logic program

When the system operates in automatic mode, the program compares real-time sampled environmental data with user-stored threshold parameters:

a) If the temperature exceeds the predefined upper threshold, the humidifier is activated via the relay.

b) If the smoke concentration surpasses the alarm threshold, the buzzer alarm is triggered.

c) The opening and closing state of the curtain is adjusted according to the ambient light intensity threshold.

Once environmental parameters return to the normal range, the corresponding actuators and alarm devices stop operation. When switched to manual mode, all automatic trigger logic is disabled, and devices can only be controlled by voice commands, physical keys or remote APP instructions [10].

(5) ESP8266 Cloud communication program

The STM32 transmits sensor data packets to the ESP8266 over the serial port. The ESP8266 then uploads these packets to the IoT cloud platform via the MQTT protocol. The mobile application retrieves environmental data from the cloud and presents the data visually. Remote control commands sent by the APP are forwarded through the cloud platform and delivered to the STM32 via the ESP8266 serial port for parsing and execution. This module adopts a lightweight Wi-Fi reconnection strategy upon wireless disconnection, and

all local functions of the system remain operational during network outages.

System test and verification

The test environment is built based on the STM32F103C8T6 hardware prototype, which integrates various sensor and actuator modules, an ASR-PRO voice recognition unit, an ESP8266 Wi-Fi module, an OLED display screen, and a supporting mobile APP client. Sub-module tests and overall system tests are conducted to verify the performance of hardware circuits and software programs. The test evaluation covers system measurement accuracy, functional integrity and operational stability.

Sensor module accuracy test

A comparative test is carried out under indoor static conditions. Calibrated commercial environmental measuring instruments are used to acquire reference values, which are then compared with the measurement data obtained by the developed system (Table 1).

Table 1. Sensor measurement test results.

Test item	Reference actual value	System measured value	Relative error	Evaluation result
Temperature	25.59 ℃	26 ℃	1.6%	Acceptable
Humidity	45.5% RH	47% RH	3.3%	Acceptable
Light Intensity	1670.87 lux	1721 lux	3.0%	Acceptable
Smoke Concentration	375.60 ppm	388 ppm	3.3%	Acceptable

Test results show that relative errors of each sensor are within acceptable scope for household scenarios, which fully satisfies the environmental monitoring requirements in practical applications.

Voice control function test

Common household control voice commands are tested under normal indoor noise environment to evaluate their recognition accuracy and response reliability (Table 2).

Table 2. Voice recognition test results.

Voice command	Recognition result	Execution outcome	Evaluation
Turn on fan	Correctly recognized	Fan starts normally	Pass
Turn off fan	Correctly recognized	Fan stops normally	Pass
Open curtain	Correctly recognized	Curtain simulation motor opens	Pass
Close curtain	Correctly recognized	Curtain simulation motor closes	Pass

In low noise indoor environment, the offline voice module achieves high recognition rate and fast response speed, and can complete expected control operations in manual mode.

Actuator execution test

Test equipment responses under three control sources: local key, offline voice and APP to compare response speed and stability (Table 3).

Table 3. Actuator execution test.

Controlled object	Control source	Execution status	Response speed	Result
Fan	Key / Voice / APP	Start-Stop works normally	Fast	Pass
LED lamp	Key / Voice / APP	Brightness adjustable via PWM	Fast	Pass
Curtain simulation	Key / Voice / APP	Open-Close action reliable	Relatively fast	Pass
Humidifier relay	Key / Voice / APP	Relay switch reliable	Fast	Pass

Each actuator can respond correctly to multi source control instructions. PWM brightness speed adjustment output is smooth without obvious mutation.

Remote communication and automatic mode test

After ESP8266 connects to Wi-Fi, environmental data can be stably uploaded to cloud platform, and mobile APP can real time display temperature, humidity, light intensity and smoke concentration. Remote control commands sent by APP can be correctly parsed and executed by hardware terminal. Under automatic mode, when environmental parameters exceed user defined threshold, corresponding actuators and buzzer alarm are

triggered automatically; after parameters return to normal, devices automatically stop action. When Wi-Fi network is disconnected, local monitoring, voice control and automatic feedback control functions still run stably.

Comprehensive test conclusion

Multiple rounds of continuous operation testing prove that the hardware connection is reliable; each software module runs stably; multi modal control channels work normally; sensor measurement error meets household application requirements; automatic threshold triggered feedback control and cloud remote monitoring functions are realized. The system achieves all preset design targets [11].

Conclusion

This paper designs and implements HomeEnv Link, a smart home environmental monitoring and household appliance feedback control system based on STM32F103C8T6 microcontroller. Taking STM32 as main control core, the system deploys multi type sensors to collect indoor temperature, humidity, smoke concentration and light intensity data. It adopts ASR PRO offline voice recognition module to realize network independent voice command parsing. Combined with OLED local display, key based parameter configuration and ESP8266 IoT communication, it supports manual intervention mode and automatic threshold triggered feedback control mode. The system constructs a complete closed loop of "environmental perception command resolution logical judgment actuator execution multi terminal feedback presentation".

Experimental tests verify that the system features low cost, complete functions and stable operation, which can satisfy basic intelligent monitoring and automatic control demands for civilian household environments. For future improvement, more sensor types can be expanded, such as human body infrared detection. Speech recognition robustness can be optimized for complex noise environments. More household appliance simulation interfaces can also be expanded. Lightweight local edge computing algorithms can be introduced to further enhance system intelligence level and practical promotion value.

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Conflicts of Interest

The author declares no conflict of interest.

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