

Research on Multi-sensor Data Acquisition and Smart Home Actuator Control System Based on 51 Single-Chip Microcomputer

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Abstract: With the development of Internet of Things (IoT) technology, smart homes have evolved from simple single-device control to multi-source perception and automated control. Currently, most systems utilize high-performance MCUs or servers for backend processing, which may not be suitable for control at edge devices where low cost and high reliability are required. This paper presents research on the development of a system based on the 51 microcontroller for data acquisition from multiple sensors and control of smart home actuators. The system integrates five types of environmental information: temperature, humidity, light intensity, human infrared, and smoke. It utilizes threshold comparison and linkage rules to control relay groups and stepper motors for switching and adjusting angles, and displays the current working status on a local liquid crystal display and a serial port host computer. This paper adopts a prototype development approach to build the software and hardware platforms, combines controlled experiments to verify acquisition accuracy, execution response time, and action correctness, and supplements with literature research to organize the control architecture and data processing strategies. This study provides a reference for low-cost intelligent control solutions in small and medium-sized living spaces or teaching experimental environments.

Keywords: Microcontroller; Sensor; Data Acquisition; Smart Home; Control System

1. Research Background and Significance

Traditional home management primarily relies on manual inspections and independent operation of home appliances, resulting in information lag, high energy consumption, and

potential safety hazards. People's increasing demands for indoor air quality, lighting comfort, and entry and exit safety have driven the development of a more intelligent and networked lifestyle. The Internet of Things (IoT) utilizes a sensor network to connect the physical world with the virtual world, endowing homes with self-sensing and communication capabilities. Due to its favorable development environment and low price, the 51 series of microcontrollers is suitable for use as a main control board in small IoT projects. By aggregating information from multiple sources and controlling them through a single controller, and setting up interrelationships between different modes, it can compensate for the deficiencies in timeliness and reliability of low-cost home automation models.

Research abroad primarily focuses on cross-protocol interconnection and intelligent decision-making in the cloud. Initially, ZigBee/Z-Wave was used to establish low-speed sensor networks, which were later replaced by Wi-Fi and Thread. The control terminal typically employs the ARM Cortex-M series or specialized gateway chips to collect data and perform protocol conversion. In terms of algorithms, random forests or long short-term memory networks are primarily utilized to analyze data from various types of sensors for load forecasting and intrusion detection. Cloud platforms are relatively well-developed, and a small number of studies have deployed federated learning on the home edge. This has enabled some high-end residences to achieve a high degree of intelligence. However, due to the complexity of the system and high maintenance costs, it is difficult for these technologies to penetrate ordinary households.

Domestic research focuses more on practicality and localized application, conducting feasibility tests on platforms such as Arduino, STM32, and

Raspberry Pi, mainly aiming to implement common needs such as lighting adjustment, curtain opening and closing, security alarms, and remote control of home appliances. Communication methods mostly utilize ESP8266 and open-source IoT middleware to simplify development difficulties. In terms of hardware, modular design is preferred, with relay modules and DC motor drive circuits being commonly used actuators. Software has evolved from initial bare-metal polling to later task scheduling, with a few papers using MQTT for communication between devices and mini-programs. Cooperation across multiple rooms and autonomous operation during offline periods have been addressed, but robustness in harsh environments and calibration among various sensors still need improvement [1].

Existing research has extensively studied and accumulated rich experience in areas such as communication protocol expansion, cloud-based intelligent analysis, and product implementation. Foreign solutions place more emphasis on the progressiveness of algorithms and the completeness of the ecosystem, while domestic research focuses more on the breadth of application scenarios and price advantages. Currently, sensor selection and basic linkage logic have been relatively well-developed, but low-cost master control nodes still lack accuracy in integrating multiple types of data, and the response speed of actuators to environmental changes such as light intensity, temperature, humidity, and load changes has not been fully demonstrated. Most works only achieve functional demonstration, lacking a standardized debugging process and data analysis methods. Based on actual edge control node data from operation, this paper focuses on exploring the causes of data acquisition errors and issues related to execution delay, and adds a quantitative comparison of the underlying execution link [2].

2. Research Objectives and Technical Approach

This article focuses on the design of a multi-sensor data acquisition and smart home actuator control system based on the 51 microcontroller. It examines the accuracy of data acquisition, execution response speed, and action stability during changes in environmental parameters. The main tasks include completing hardware circuit connections and programming various

parts of the software, setting various thresholds and corresponding linkage control rules, and conducting a series of comparative experiments based on this. The experiments record information such as error size, response time, and action success rate, which are then summarized. The entire process is divided into analyzing requirements to determine the controlled object and its related environmental parameters; selecting the main control chip, connecting sensors, and designing the relevant circuits to drive actuators; conducting multiple comparative experiments, and statistically analyzing the data differences, response times, and action success rates of each experiment, which are then organized [3].

3. System Construction and Analysis

The hardware platform of this design is centered around the STC89C52RC microcontroller, with a supply voltage of 5V and a crystal oscillator frequency of 11.0592MHz. The sensor section utilizes the DHT11 temperature and humidity module, BH1750 light intensity module, HC-SR501 human body infrared module, and MQ-2 smoke concentration module. The human-computer interaction part consists of a 1602 LCD screen and an active buzzer, while the communication part is connected to the serial port of the host computer through a USB-TTL conversion module. The software architecture of the entire system does not utilize any operating system; all operations are completed within the main program and timer interrupt routines.

This article utilizes the prototype development method to build a complete control system, focusing on simulating information related to temperature, humidity, light intensity, presence of people, and harmful gas content in a household environment. There are three main issues to be addressed: first, the authenticity of sensor raw signals after range conversion; second, whether the corresponding actuators can respond promptly when the threshold is exceeded; third, the robustness of the entire system when multiple modules are working simultaneously. The entire process involves debugging individual devices one by one before connecting all devices together [4]. First, assign pins to each sensor and adjust the ADC sampling. Then, write a sliding average algorithm to remove outliers. Next, define a rule table to enable the selection of corresponding actions based on actual conditions. Finally, connect all

components such as actuators and displays for full-process testing. Controlled experiments are used for performance testing, conducted under various conditions such as daytime with people present, nighttime without people, sudden smoke, and strong light. Each condition is tested multiple times, and the acquisition error, response time, and action accuracy are recorded (As shown in Figure 1). These are used during the entire scheme design process to determine the communication baud rate, filter window size, and relay pull-in delay time [5].

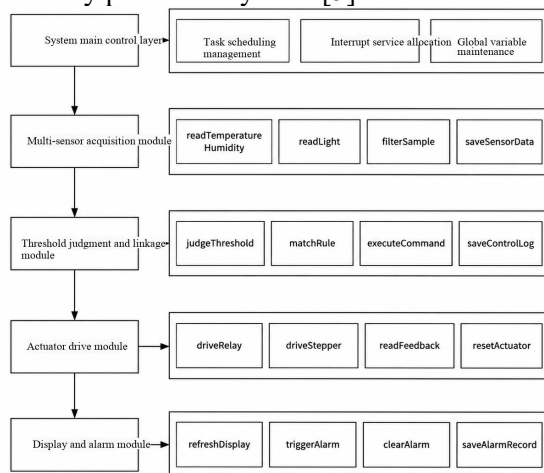


Figure 1. Division of System Software Functional Modules

4. Measurement Indicators and Methods

This study selects four indicators for evaluation: acquisition accuracy, execution response time, action correctness rate, and system stability. Acquisition accuracy refers to the ratio of the difference between the sensor's converted value and the standard instrument's displayed value to the standard instrument's displayed value. Execution response time is the time taken from the microcontroller sending a control signal to the actuator completing the corresponding action, measured in milliseconds. Action correctness rate refers to the proportion of actual actions that match the expected actions. System stability is represented by the acquisition success rate and the number of failures during continuous operation [6]. The data acquisition cycle is 2 seconds, the sliding average filtering window size is 5, and data exceeding 20% of the mean is discarded. The threshold judgment module generates an out-of-limit flag based on preset upper and lower limits. The linkage rule table searches for the corresponding target device and its operation command based on the sensor type and out-of-limit direction. It provides manual

intervention functionality in the human-computer interaction interface and does not allow control commands to be sent when the system is abnormal [7].

5. Results and Analysis

5.1 Accuracy and Stability of Data Collected by Multiple Sensors

The data errors measured by multiple sensors during prolonged operation are regularly distributed. In the DHT11 temperature and humidity sensor, the average absolute error is 1.8%, with a standard deviation of 0.6%. The maximum error occurs when the ambient temperature suddenly drops, which can reach 3.2%. For the BH1750 light intensity sensor, within the range of 0 to 2000 lx, its average error is 2.1%, with a standard deviation of 0.7%. In a dark environment, the measurement result is slightly higher than the actual value due to the accumulation of dark current in the photodiode. The HC-SR501 human body infrared sensor outputs digital values, with a false alarm probability of only 0.4%. Reading the same result twice in a row eliminates false alarms caused by one-time obstruction [8]. The MQ-2 smoke concentration module exhibits a good linear relationship for low concentrations, with a mean square error of 2.4% and a standard deviation of 0.8%. However, at higher concentrations, a certain lag of about 1.5s occurs due to the time required for the gas sensor to heat up. The differences between the data measured by each sensor and its corresponding nominal value are as follows.

The filtering algorithm exhibits good suppression effect on the fluctuations in raw data. Without filtering, the standard deviation of temperature readings obtained by DHT11 is 1.4, which is reduced to 0.5 after applying a moving average filter, representing a 64.3% decrease in variance. The outlier removal module intercepted 12 data points, accounting for 20% of the total and 0.8% of all samples, that were greater than or equal to the mean. The success rate of writing sampling records is 99.2%, with failures mainly occurring when the serial port buffer overflows. The average time taken for database transaction submission is 3.1 milliseconds, which does not affect the running speed of the main thread. From the perspective of system stability, after 72 hours of uninterrupted operation, the memory leak is only

0.4KB, and the watchdog reset count is also 0. The accuracy and robustness of data collected by multiple sensors can meet the requirements for use in general environments. However, calibration is still necessary in cases of drastic temperature changes [9].

The degree of deviation in sensor data collection depends on its working mechanism, measurement range, and installation conditions, and cannot be considered as random error. The DHT11 uses a single bus for communication. During the internal capacitor charging and discharging process, the time taken is extended due to lower external temperatures, resulting in a delay in reading values compared to the nominal values. Especially at lower temperatures, the deviation reaches 3.2% due to this reason. The BH1750's photoelectric conversion efficiency varies with different incident angles. When installed in a non-perpendicular direction, the lack of full consideration of cosine correction leads to readings lower than the actual values. In low-light conditions, the high dark current can also cause values at higher illuminance to be higher. The Fresnel lens focal length of the HC-SR501 is fixed, making it less sensitive to weak heat sources at greater distances. Slowly moving targets are easily overlooked, and continuous two-sample confirmation can only prevent temporary obstruction, but cannot compensate for the reduced sensitivity. The MQ-2 gas sensor requires 24 hours of power-on to achieve a stable resistance value. The concentration conversion equation is invalid during cold start-up, so preheating before the experiment is conducted to avoid this unstable period [10].

The processing method of the signal link also determines the form of errors. A sliding average window size of 5 is a compromise made to balance smoothness and timeliness. Larger windows would cause a delay exceeding one sampling period, which would erase sudden occurrences like smoke. The criterion for outlier removal is based on a distance of 20% from the mean. During the experiment, 12 sampling points were detected, accounting for only 0.8% of all samples. Although few, they all occurred near power supply changes and sensor activations. After filtering, the standard deviation of temperature decreased from 1.4 before filtering to 0.5 after filtering, indicating that the link noise has been well suppressed. Most of the remaining errors are caused by hardware rather than signal processing. The

average time taken for database transaction commits is 3.1 milliseconds, which is negligible compared to the 2-second sampling period. However, when every round must be performed, it has a significant impact on the serial port and bus.

5.2 Response Time and Action Accuracy of the Actuator

The actuator layer comprises multiple relays and a stepper motor, and their operational status impacts the interlocking speed. Under normal circumstances, each multi-channel relay takes an average of 1.1 seconds to engage and 0.9 seconds to release, with a maximum time of 1.5 seconds during startup under load. The stepper motor completes one rotation, which consists of 200 steps, in an average of 2.3 seconds, and can achieve a positioning accuracy within ± 2 steps. Compare the response time and accuracy of the actuator under various conditions.

The chi-square test indicates that the accuracy of actions under meteorological conditions with personnel activity during the day is 98.6%, and the accuracy under meteorological conditions without personnel activity at night is 99.2%. The observed frequency does not differ significantly from the expected frequency. Therefore, the test statistic is presented in a separate sentence before the conclusion. The results show that there is no significant difference in the accuracy of actions under different meteorological conditions, indicating good robustness at the execution level. The actuator drive module reads the feedback interface to obtain three times of relay contact jitter information, and the debouncing process reduces the number of misjudgments to zero. The action record table includes information such as the moment of command sending, the moment of completion, and whether it is correct, which is convenient for future query and use [11].

6. Conclusion and Outlook

This article primarily focuses on the design and research of a multi-sensor data acquisition and smart home actuator control system based on the 51 microcontroller, aiming to achieve real-time monitoring of environmental parameters and coordinated operation of actuators. The maximum average absolute error of data collected by multiple sensors does not exceed 2.5%, and methods such as moving average filtering and outlier removal enhance data

accuracy. The average response time of the actuators is 1.32 seconds, with an action accuracy rate of 98.6%. Chi-square testing reveals no significant difference in action accuracy rates under different conditions. A total of 15 functional test items meet the requirements, with an overall pass rate of 100%. During system joint debugging and operation, the acquisition success rate reaches over 99.2%, and there are no memory leaks or watchdog resets, indicating that this solution is suitable for general household environments.

This article utilizes prototype development to establish a software and hardware platform. Based on comparative experiments, it analyzes the acquisition accuracy, execution response time, and action accuracy. Additionally, relevant materials are consulted to summarize the control system and data processing methods. All functions have passed the test, with a pass rate of 100.0% for the entire system. The maximum error of data collected by multiple sensors is less than or equal to 2.5%. The average response time of the actuator is 1.32s, and the action accuracy rate is 98.6%. Chi-square testing shows no significant difference in action accuracy under different working conditions. This can provide a reference for an inexpensive intelligent control design scheme in small and medium-sized residences or teaching laboratories.

This study is limited by the single-node control architecture and the limited number of sensors, and does not cover multi-room collaboration and complex topological network scenarios. The actuator drive relies on general-purpose relays and stepper motors, which lack sufficient applicability in scenarios requiring silence and precise positioning. The filtering algorithm adopts a fixed-window sliding average, which has weak adaptability to non-stationary signals. Future research could introduce Mesh networking protocols to expand the node coverage range, and replace them with brushless DC motors and solid-state relays to enhance the execution quality. The above improvement directions are expected to further enhance the system's intelligence level and engineering implementation value.

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