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Research Article

Development and Implementation of an FPGA-Embedded Multimedia Remote Monitoring System for Information Technology Server Room Management

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Conventional data acquisition systems face challenges in achieving high acquisition speeds and rapid storage of large data volumes using microcontrollers. In contrast, field-programmable gate arrays (FPGAs) offer numerous advantages, including high clock frequencies, minimal internal delays, fast operational speeds, abundant internal RAM resources, and simplified control of complex peripheral circuits. This study presents the design of an FPGA-based multimedia remote monitoring system for information technology server rooms. The proposed system utilizes an FPGA as the primary controller and incorporates environmental sensors, electrical energy sensors, carbon monoxide sensors, smoke sensors, and A/D converter modules to monitor multiple locations within the server room. Simultaneously, the FPGA transmits the collected data from each monitoring point via a serial port to an LCD serial screen for display. An alarm is triggered if any environmental anomalies are detected, indicating abnormal statuses. Additionally, the system employs the fast Fourier transform algorithm and butterfly operations to derive voltage and current AC quantities, while utilizing relative temperature differences to identify equipment faults within the server room. The system is evaluated in terms of functionality, user-friendliness, and reliability. Experimental results demonstrate that all performance measures align with expectations, fulfilling the initial design objectives and highlighting the potential applicability and relevance of FPGA technology in the monitoring field. In addition, a comparison between FPGA and traditional microcontroller systems is performed, showcasing the superior processing speed and performance of the FPGA-based system. This comparative analysis further validates the advantages of using FPGA technology in high-speed data acquisition and monitoring applications.

1. Introduction

With the rapid development of technology and economy in the information age, monitoring systems have been widely used in various industries [1]. Multimedia remote monitoring system in the server room monitoring application can assist the server room technicians at any time to monitor the multifaceted dynamic observation of the point, to prevent the emergence of monitoring dead spots. And timely discovery of which there are security risks or technical problems, for rapid processing, prevents greater security accidents. The multimedia remote monitoring system is upgraded to establish an independent multimedia database, and the relevant information data and various dynamic images can be collected and accurately organized and stored at any time [2]. Their automatic storage time is up to one month, and the operating status of each work in the server room can be obtained in real time. Additionally, the multimedia remote monitoring system enables real-time monitoring of the operational status and timely digital compression of equipment-related images and videos [3–5]. The digital coding system alarm sensor can also implement the transmission of data information and related video images, so that the monitoring center can grasp all the data status in a timely manner and carry out multilevel processing, for example, decompression for different levels of multimedia data information, decoding processing, and then playback of audio and video for real-time monitoring [6]. Meanwhile, the rapid development of TCP technology, IP technology, and video decoding technology and the scope of application have been expanding [7]. As a result, multimedia remote monitoring systems are widely used in various industrial fields of monitoring, such as traffic monitoring, telecommunication rooms, power distribution system development aspects, and banking system digitization and networking [8].

Meanwhile, the challenge of monitoring a vast number of server room environments has grown. Consequently, achieving cost-effective and real-time monitoring of these environments, along with efficient automatic control of the equipment within them, has emerged as a pressing issue in today's society. Addressing this problem constitutes the primary focus of this research endeavor. Scholars at home and abroad have conducted in-depth research on this topic. Gogate and Bakal [9] designed a remote monitoring system based on WSNs. The system design includes two parts, sensor control and remote control, which combines dynamic adjustment of window data and message period to improve the network delay and overall packet loss rate to achieve remote monitoring of equipment operation status. However, the system needs to consider both sensor control and remote control parts, and the design scheme is cumbersome. Yan et al. [10] designed a remote monitoring system based on a software development kit (SDK). Configure the .NET platform and set access rights to remotely monitor the operational status of industrial robots. However, the system requires more controllers, and the monitoring process is more complicated. Rana et al. [11] used .net framework and C# language to build a C/S architecture power environmental monitoring information management system, which provides a good platform for the staff and can meet the daily monitoring needs. Fotouhi et al. [12] introduced a mobile communication base station dynamic loop monitoring system. The system adopts C#, which can realize the functions of power environmental monitoring and image acquisition; can take regular inspection, maintenance, and overhaul for the equipment; and has a self-management function. Rahman and Wahid [13] introduced a dynamic loop monitoring system based on an on-site ZigBee wireless network and 3G network to transmit the data collected in the field. The software was developed based on J2EE platform, and the implementation of topology management, temperature, and humidity management was proposed for the system. Zhang et al. [14] provided a set of intelligent monitoring design schemes developed on J2EE platform. The focus is on the study of the system to provide reliability, and by studying clustering and load balancing techniques, the system stability and reliability are significantly improved. Kolesnikov et al. [15] used STM32 microcontroller with W5500 hardware Ethernet protocol stack to transfer multimedia data collected by sensors to the upper computer monitoring through 100 Gigabit Ethernet. Prasojo et al. [16] employed the AT89S52 microcontroller to transmit multipoint temperature data from the server room to a remote host computer through the RS232 bus on the serial port. This data was then displayed and recorded for monitoring purposes. In a similar vein, Weng and Geng [17] utilized the AT89C52 microcontroller to achieve temperature monitoring and implement a high-temperature alarm system within a network room housing a significant amount of precision equipment. Behera et al. proposed a power environmental monitoring system for power communication rooms [18]. The design principle of this monitoring system is based on fieldbus, and each device is connected through the bus, which is more suitable for systems of small scale. Idrees et al. proposed a machine room management system based on C/S architecture [19]. At present, the monitoring technology based on C/S architecture is relatively mature and has been successfully used in various types of server room power distribution systems. However, its upper computer interface is overly dependent on the configuration software, and the network communication method still uses the traditional socket and FTP technology, which is not suitable for the construction of large-scale informationized server rooms. Zhao et al. proposed a design scheme for power distribution monitoring system based on BS mode [20]. The scheme adopts improved TCP/IP transmission technology, and the design vendor only needs to debug the IP and basic network protocol settings to realize real-time monitoring of the power distribution system directly through a common browser (e.g., IE). However, the design only focuses on the network layer for research and exploration and does not involve the hardware layer.

Along with the continuous development of multimedia technology, integrated data analysis and processing has gradually become the mainstream development trend. Therefore, when developing the corresponding algorithm, we should not only consider the capital, time, and labor cost of research and development but also pay attention to its later update and upgrade with applicability and portability. In the current landscape of information technology server room monitoring, traditional data acquisition systems primarily rely on microcontrollers. While widely used, microcontrollers encounter formidable challenges in reconciling the escalating demands for accelerated acquisition speeds and expeditious storage of voluminous data. This discrepancy becomes more pronounced in the context of the burgeoning requirements for real-time monitoring and automated control within server room environments. FPGA technology has been widely used due to its high integration, low cost, flexibility, and easy modification [21]. Although high-end microcontrollers excel in many applications, FPGAs show relative strengths in certain specific high-performance, real-time data processing and hardware customization needs. FPGAs offer unique and compelling advantages over microcontrollers. FPGAs, characterized by high clock frequencies, minimal internal delays, rapid operational speeds, ample internal RAM resources, and the capacity to intricately control complex peripheral circuits, present an opportune technological avenue. Recognizing these attributes, this research aspires to harness the latent potential of FPGA technology to architect a cutting-edge multimedia remote monitoring system explicitly tailored for the nuanced requirements of information technology server rooms.

To address the challenges of low-cost, real-time monitoring and efficient automatic control in the information technology server room environment, this research proposes an FPGA-based multimedia remote monitoring system for IT server rooms. The system employs an FPGA as the central controller, integrating environmental sensors, power sensors, carbon monoxide sensors, smoke sensors, and an A/D conversion module to monitor multiple locations within the server room. Simultaneously, the FPGA transfers the data collected from various monitoring points to an LCD display through a serial port for visualization. In the event of any environmental anomalies, an alarm is triggered, and the abnormal status is displayed. Furthermore, the system utilizes the fast Fourier transform algorithm and butterfly operations to derive the alternating current quantities of voltage and current, and it identifies equipment faults in the server room using relative temperature differences.

This research presents significant contributions in the field of information technology server room monitoring, encompassing the following key aspects: (1) proposal of an FPGA-based multimedia remote monitoring system: this study introduces a pioneering monitoring system that leverages FPGA technology as the core controller. This approach effectively addresses the challenges associated with low-cost, real-time monitoring and efficient automatic control within server room environments. (2) Integration of diverse sensors: the system seamlessly integrates a range of sensors, including environmental, power, carbon monoxide, and smoke sensors and A/D conversion modules. This comprehensive integration enables extensive monitoring of multiple locations within the server room, ensuring prompt detection of environmental abnormalities. (3) Real-time display of collected data: by harnessing the capabilities of FPGA and serial ports, the system facilitates the real-time transfer of collected data from each monitoring point to an LCD serial screen. This feature empowers users to visualize the monitored parameters and promptly identify any anomalous conditions. (4) Advanced fault detection techniques: the system employs sophisticated fault detection techniques, such as the fast Fourier transform algorithm and butterfly operations, to derive precise measurements of voltage and current fluctuations. Additionally, it utilizes the relative temperature difference to identify equipment faults within the server room. (5) Comprehensive evaluation of system performance: the functionality, user-friendliness, and reliability of the proposed system are meticulously evaluated. Through extensive experimentation, the results validate that the system achieves the anticipated performance indicators, effectively fulfilling the initial design goals.

In order to increase the readability and clarity of this paper and to ensure that the reader can easily refer to the abbreviations used, all the abbreviations mentioned are listed in Table 1.

Table 1: The abbreviations of this paper.

Abbreviations	Explanation
FPGA	Field-programmable gate array
RAM	Random access memory
C/S	Client server
A/D	Analog to digital
SDK	Software development kit
BS	Browser-based software
LCD	Liquid crystal display
ADC	Analog-to-digital converter

2. State of the Art

FPGAs are highly integrated, reliable, and programmable semicustom chips that offer several advantages over traditional digital circuits. Compared to ASICs, FPGAs provide abundant internal resources, a shorter design cycle, high flexibility, and lower costs [21, 22]. These advantages have led to the widespread utilization of FPGA in various research fields, including multimedia database query processing, autonomous driving, embedded systems, artificial intelligence, communication, and electrical engineering [23–28].

In the context of multimedia remote monitoring systems, FPGA offers significant benefits due to their parallel execution capability, high integration, rich logic resources, and programmability features. These features greatly facilitate the design and development of hardware circuits, reducing development and debugging time and lowering costs. Consequently, FPGA technology has gained popularity among developers in this field.

To provide a comprehensive overview of the state of the art, we conducted an extensive review of relevant literature published in the past five years (2017-2022) by searching for references using the keyword “FPGA” on Google Scholar. As shown in Figure 1, the analysis of search results and statistical data revealed the discipline distribution of FPGA-related papers during this period. Notably, FPGA has found applications in various disciplines, including radio electronics (23.85%), telecommunication technology (19.62%), computer software and applications (18.58%), automation technology (18.45%), and multimedia technology (7.50%) [29–32]. These five subject areas collectively represent 88% of the FPGA applications. Automation technology and multimedia technology, in particular, have emerged as the main support disciplines in the monitoring field, accounting for a total of 25.95% of FPGA applications. This indicates the wide adoption of FPGA in monitoring systems and provides a solid basis for selecting FPGA as the hardware implementation platform for designing the data concentrator in our proposed multimedia remote monitoring system for information technology server rooms.

FPGA technology has gained significant attention and usage across various research fields. Its advantages, including parallel execution capability, high integration, rich logic resources, and programmability, make it an ideal choice for the design and development of hardware circuits in monitoring systems. The extensive research conducted in recent years, as evidenced by the referenced literature, highlights the applicability and relevance of FPGA technology, specifically in the context of server room monitoring. These insights and findings serve as a solid foundation for our

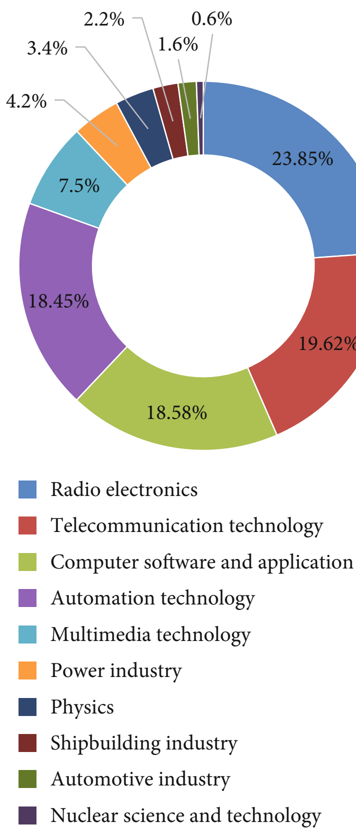

Figure 1: Discipline distribution of FPGA-related papers in 2017-2022.

design and implementation of the multimedia remote monitoring system presented in this paper.

State-of-the-art research in the field of monitoring systems has witnessed the significant utilization of FPGA due to their remarkable features and capabilities. FPGAs offer a flexible and reconfigurable platform for implementing complex logic circuits, making them ideal for various applications, including multimedia remote monitoring systems. Numerous studies have explored the advantages of using FPGA in monitoring systems. For instance, Ahmed et al. [33] propose a reconfigurable framework for an automated secure home system, incorporating features such as password-protected door lock control, monitoring of electronic devices, fire safety with temperature monitoring, and an antitheft system. It utilizes an FPGA board to integrate different sensors, enabling cost-effective integration of multiple analog sensor inputs and efficient processing. In another study, Xiong et al. [34] develop a real-time field-programmable gate array-digital twin technique for monitoring and diagnostics of power electronic transformers. They propose a novel method based on FPGA-DT to analyze and detect open-circuit faults in PETs by comparing fault characteristics between actual and DT systems. The effectiveness of the proposed method is validated by testing various O/C faults on different sides of the PET. Additionally, the work of Teodoro et al. [35] provided the implementation of a tree parity machine neural network architecture for efficient key exchange in resource-constrained devices. FPGA-based implementations of TPM were tested and analyzed, demonstrating improved performance compared to software implementation, making it a useful reference for cryptography applications in FPGA. In summary, the utilization of FPGAs in monitoring systems has gained considerable attention in the literature. The discussed studies above have emphasized the capabilities of FPGAs in terms of high-speed data processing, parallelism, real-time monitoring, and efficient handling of sensor and video data. These works serve as valuable references in understanding the significance and potential of FPGA-based approaches in the context of monitoring systems.

3. Methodology

In this section, we provide an overview of the methods employed to design and implement the multimedia remote monitoring system for information technology server rooms. The overall structure of the monitoring system is illustrated in Figure 2.

The focal point of the overall structural design is to create a comprehensive framework for the monitoring system. Each equipment within the server room is equipped with a monitoring terminal, which serves as an embedded FPGA server. These terminals collect environmental information and transmit it wirelessly or through Ethernet. The hardware design phase involves the selection of various components and their integration into the system. The Spartan-6 series FPGA, produced by Xilinx, was chosen as the main controller due to its stability, abundant logic resources, and support for complex logic control. Furthermore, sensors such as environmental sensors, power sensors, carbon monoxide sensors, and smoke sensors are integrated to monitor various aspects of the server room environment. The software design focuses on enhancing real-time operations and system management. The μC/OS-III software operating system is employed to enable modular programming and efficient task scheduling. Specific program designs include programs related to power measurement, serial communication, and abnormal state alarms. Figure 2 illustrates the interaction among key components of the multimedia remote monitoring system. This simplified diagram facilitates a concise and clear depiction of our approach. In the following sections, we will delve into various aspects of the methodology, providing detailed explanations of the hardware components, software modules, and program designs employed in the development of this innovative monitoring system.

The internal design architecture of the remote monitoring system on the FPGA comprises several key components that work together to achieve the desired monitoring functionalities. These components are shown in Figure 3.

(1) Data acquisition block: this block is responsible for interfacing with external sensor devices, such as temperature sensors, humidity sensors, dust sensors, and carbon monoxide sensors. It collects data from these sensors and converts it into a suitable format for processing

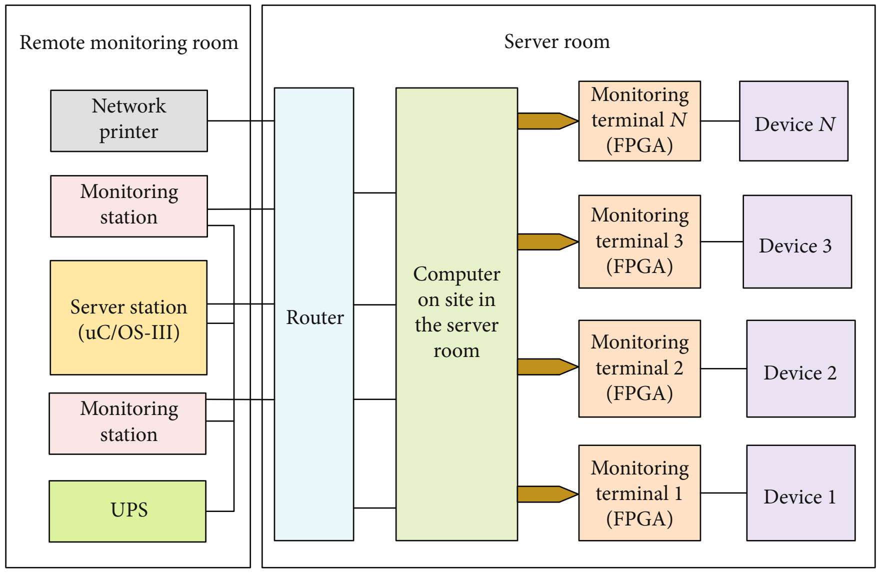

Figure 2: Overall structure of the monitoring system.

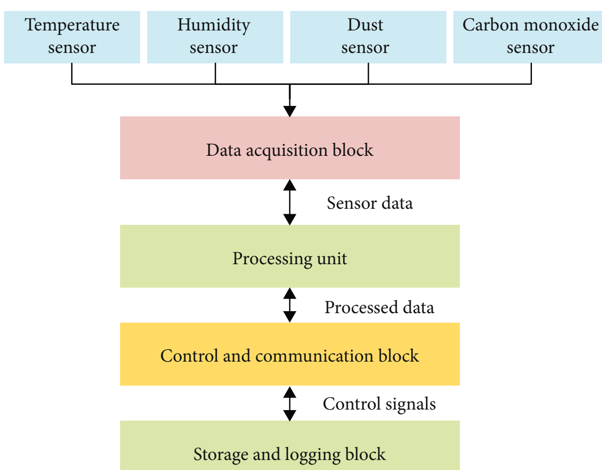

Figure 3: Internal design architecture diagram.

(2) Processing unit: the processing unit performs data processing and analysis tasks. It receives the sensor data from the data acquisition block and applies various algorithms and logic to perform real-time monitoring and analysis. It may include functions such as data filtering, threshold detection, and anomaly detection

(3) Control and communication block: this block handles the control and communication aspects of the monitoring system. It manages the communication protocols with external peripherals, such as display units, alarm systems, and network interfaces. It also coordinates the overall operation of the monitoring system, including data transmission, system configuration, and user interaction

(4) Storage and logging block: this block is responsible for storing and logging the monitored data. It may include memory components or external storage devices to store the collected sensor data for further analysis or future reference

By integrating these internal blocks, the FPGA-based monitoring system can effectively acquire, process, and monitor the sensor data in real time. The specific functions of each internal block are closely related to the corresponding peripheral devices, ensuring seamless communication and efficient operation of the monitoring system.

3.1. Hardware Design. In this study, the main controller in the system is implemented using the Spartan-6 series FPGA manufactured by Xilinx, with a typical operating frequency of 50 MHz, replacing the conventional microcontroller commonly used in similar applications. The choice of FPGA as the main controller is attributed to its excellent operational stability, ample gate array resources, suitability for handling complex logic control, and capability to accommodate multiple communication interfaces.

The electricity sensor is used to detect the power data in the measurement modes of three-phase fundamental, harmonic, and full wave for multiple incoming as well as outgoing lines. The AS02HT-K84NW sensor is used to detect the dust, temperature, and humidity conditions in the server room environment. The AD7606 analog-to-digital conversion module converts the analog voltage value output from the MQ-7 into a digital quantity and then calibrates the carbon monoxide concentration value according to the MQ-7 module. The FPGA stores the collected environmental information and carbon monoxide concentration at each monitoring point in RAM. The data is transmitted to the switch through the RTL8211EG Ethernet PHY chip according to the UDP transmission protocol format and then forwarded to the control center PC and the host PC. The host computer is written in the MFC framework. At the same time, the FPGA will also send the monitoring data to the LCD serial

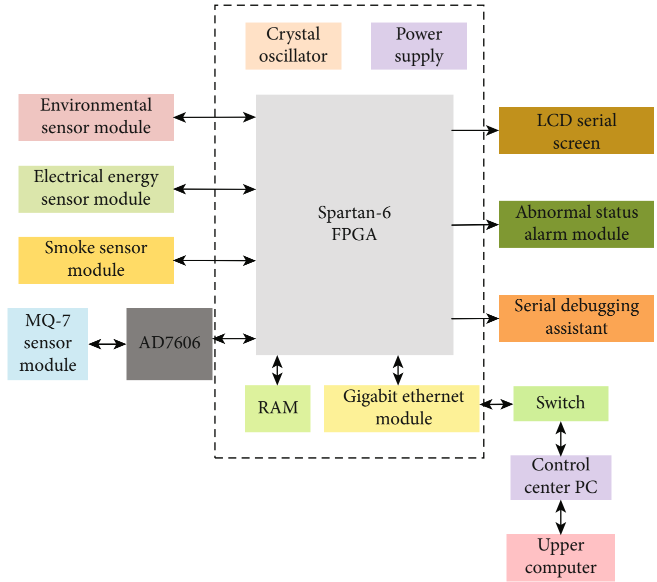

FIGURE 4: FPGA-based hardware system architecture.

screen for display according to the serial transmission protocol. If the data is abnormal, the abnormal status alarm will be triggered. The hardware system of monitoring terminal is shown in Figure 4.

3.1.1. Environmental Sensor Module. Due to the large variety of physical parameters to be collected in this design, if a single physical parameter sensor is used for environmental data information collection, it will cause the serial port resources of the lower computer control circuit to be congested. Moreover, the processing of the collected environmental data by the lower computer operating system will be more cumbersome, which limits the overall performance of the monitoring system. Intelligent environmental sensors can detect a variety of environmental condition parameters, commonly used in smart homes, server room monitoring, health care, and other industries in the use of the environment [36–38]. Based on a comprehensive analysis, the AS02HT-K84NW three-in-one integrated environmental sensor from Arsend is used in this design based on the functional requirements of the environmental monitoring system in the server room and the requirements of the national standard specifications for each condition parameter. It integrates three environmental condition parameters of dust, temperature, and humidity, which can maximize the monitoring of environmental information in large area information technology rooms. The control flow of the FPGA accessing the AS02HT-K84NW for environmental information data via the control interface DQ is shown in Figure 5.

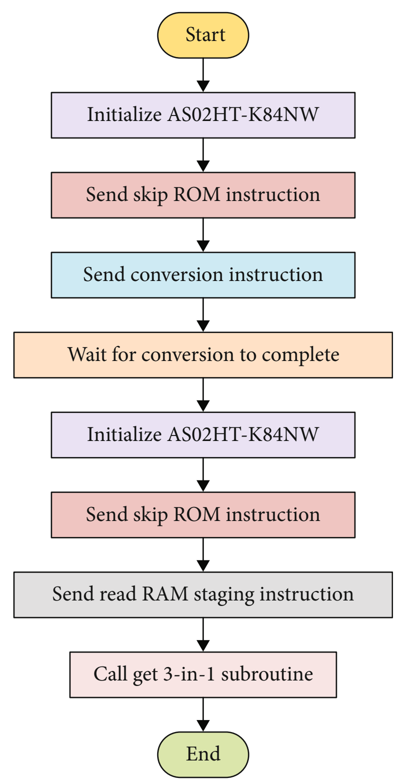

FIGURE 5: Environmental data information acquisition process.

3.1.2. Electricity Sensor Module. The main function of the power sensor module is to detect the power, voltage, current, and other information of the equipment in the server room, to calculate the power consumption, and to provide a basis for power management. The design uses the multifunctional power metering chip RN8302B produced by Shenzhen Ruineng Micro Technology, which has the functions of power parameter measurement, power metering, power theft prevention, and software meter calibration. The chip provides seven 24-bit high-precision ADC sampling channels for full-wave and fundamental-wave active and reactive power measurement, with nonlinear error < 0.1% in the dynamic range of 5000 : 1 and 0.5S and 0.2S accuracy for active power measurement.

The hardware design of the power sensor module mainly includes the metering chip driving the minimum system circuit, voltage sampling circuit, and current sampling circuit. The hardware connection structure of FPGA and RN8302B is shown in Figure 6.

3.1.3. MQ-7 Sensor Module. The MQ-7 sensor operates with three voltages applied: high heating voltage VH, low heating voltage VL, and test voltage VC, where VH and VL provide a specific operating temperature for the sensor and VC is used to determine the voltage across the load resistor RL in series with the sensor. The MQ-7 uses a high- and low-temperature cycle to detect carbon monoxide gas when heated at low-temperature VL, and the conductivity of the sensor increases as the concentration of carbon monoxide gas in the air increases; when the high-temperature VH is heated, it cleans the stray gas adsorbed during the low-temperature heating. Therefore, the change in conductivity can be converted into an analog voltage output signal corresponding to the concentration of this gas by circuit design.

Since the MQ-7 output is an analog voltage value, analog-to-digital conversion into the corresponding digital quantity is required before the FPGA can calculate the detected CO gas concentration value based on the MQ-7 concentration calibration curve. AD7606 is an integrated 8-channel data synchronization acquisition system. It is powered by a single +5 V supply and can handle ±5 and ±10 V bipolar input signals to achieve 16-bit analog-to-digital conversion performance, which can be maintained under high noise conditions. The AD7606 supports both SPI communication and parallel mode data transfer methods. The system in this paper uses the parallel mode with faster processing speed.

The AD7606 can perform simultaneous sampling of 8 analog input channels. To ensure the real-time and synchronous acquisition of multimedia data, two CONVST pins can be connected in parallel to start the sampling of all channels synchronously at the falling edge, and setting AAD7606 to the no-oversampling mode can improve the conversion rate. The hardware connection of FPGA with AD7606 and MQ-7 is shown in Figure 7.

3.1.4. Smoke Sensor Module. The design of this paper uses smoke sensor devices to monitor and alarm the smoke concentration in the server room environment. It is connected to the lower computer central control system through an RS232 serial communication interface. The lower computer of the server room unit constantly queries the working status of the smoke sensor through the serial port, and once a fire occurs to produce smoke, the smoke sensor will issue an alarm and trigger the lower computer buzzer at the same time. Based on the above functional requirements, the photoelectric smoke detection sensor is selected for this design. Compared with other smoke monitoring sensors, photoelectric-type monitoring has the characteristics of high stability and sensitive sensing and can adapt to various working environments. Shown in Figure 8 is the physical diagram of the smoke sensor device of this design.

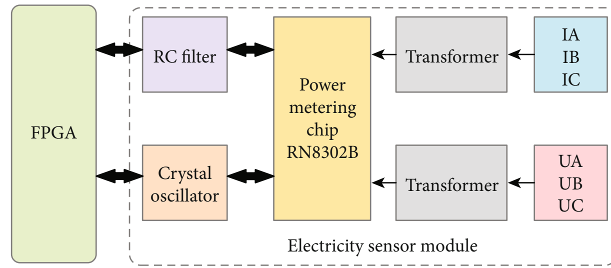

Figure 6: Schematic of the hardware connection between FPGA and RN8302B.

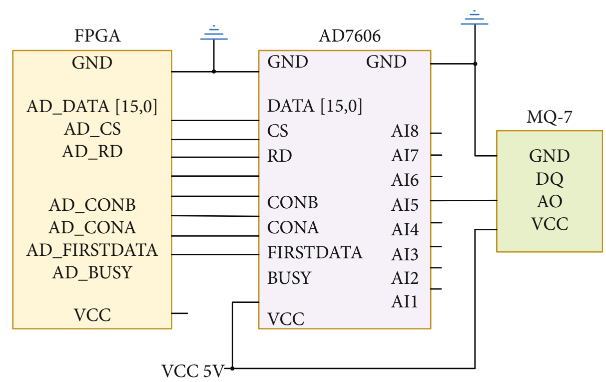

Figure 7: Hardware connection of FPGA to AD7606 and MQ-7.

Figure 8: Physical representation of smoke sensor.

3.1.5. Ethernet Module. This system incorporates the RTL8211EG Ethernet PHY chip, which is a highly integrated component capable of supporting adaptive network rates of 10, 100, and 1000 Mb/s. In the case of Gigabit Ethernet connectivity, multimedia data transmission between the FPGA and RTL8211EG is facilitated through the GMII bus. The transmit clock, operating at a frequency of 125 MHz, is supplied by the FPGA, while the receive clock is provided by the PHY chip. The multimedia data is sampled on the rising

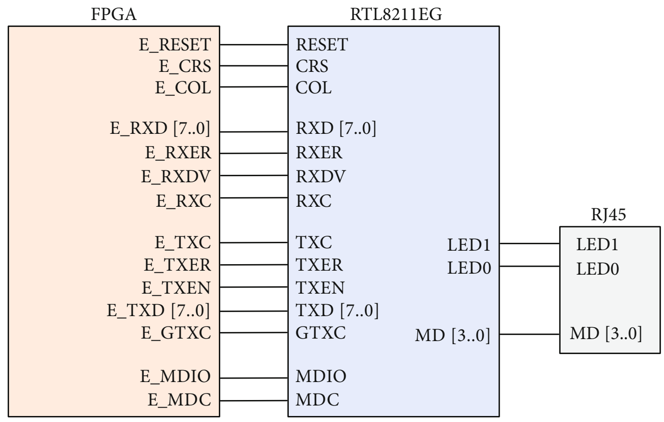

Figure 9: Schematic diagram of hardware connection between FPGA and RTL8211EG.

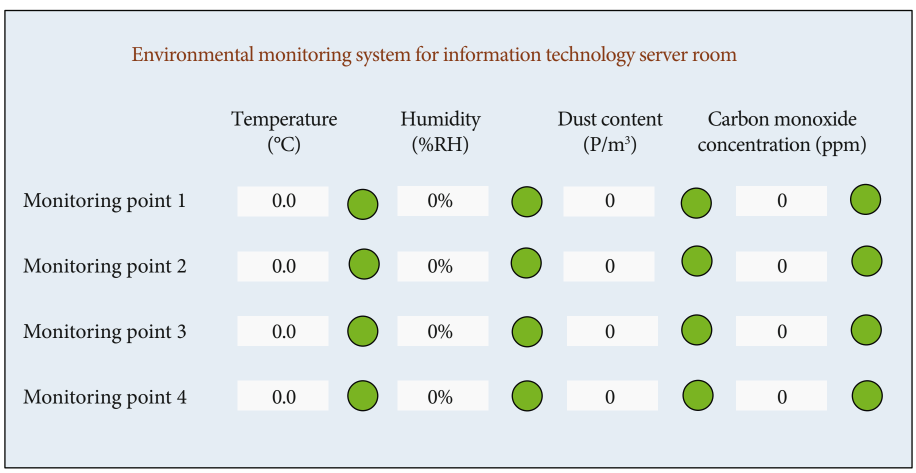

Figure 10: LCD serial screen initial interface design.

edge of the clock. When the network is connected to 100 Gigabit Ethernet, multimedia data transmission between FPGA and RTL8211EG is communicated via MII bus with a transmission clock of 25 MHz, and both the receive clock and transmit clock are provided by the PHY chip. The multimedia data is sampled at the rising edge of the clock.

The hardware connection between FPGA and RTL8211EG is shown in Figure 9. In this paper, the system adopts the gigabit communication method, and the multimedia data transmission is through GMII bus. When the FPGA sends multimedia data, the transmit clock is 125 MHz GTXC signal, multimedia data is transmitted from TXD0 to TXD7, multimedia data valid signal is TXEN, and TXC signal is not used. When receiving multimedia data, the receive clock is the RXC signal provided by RTL8211EG, multimedia data is transmitted from RXD0 to RXD7, and the valid signal for multimedia data is RXDV.

3.1.6. LCD Serial Screen Module. LCD serial screen adopts F series serial screen produced by Guangzhou Dachai Company. It has industrial standards, supports RS232/TTL serial communication mode, supports various baud rate settings, and is widely used in the fields of intelligent home appliances and security monitoring. The initial interface design of the serial screen is shown in Figure 10, which mainly shows the temperature and carbon monoxide concentration values of each monitoring point, and the green icon will switch to red if the value exceeds the set value.

3.2. Software Design. To improve the effectiveness of real-time operation of the terminal, the μC/OS-III software operating system is ported in this paper. The program is modularized, tasks are created separately, and the size of the stack and priority is set according to the actual situation. Each module of the monitoring terminal automatically schedules tasks to occupy CPU in turn with high efficiency to realize parallel management.

3.2.1. Power Metering-Related Program Design. The system adopts FPGA chip that can realize the organic combination of assembly and C language and combine it with the parallel operation function of FPGA chip, so that the calculation result is closer to the actual value. AC sampling is an important part of the whole system software, and this system uses the frequency change tracking sampling technique to collect information on constant change points. The AC volume calculation part uses the fast Fourier transform algorithm based on time extraction, and the calculation equation is as follows.

$$i(n) = \sum_{n=0}^{t} \delta_n^t i(2n), \tag{1}$$

where δ_n^t denotes the multimedia remote monitoring sequence coefficient and n denotes the monitoring time. The $t/2$ butterfly modules present at t points are calculated by Equation (1), and the process is shown below.

Firstly, i_1 and i_2 as the inputs, the corresponding outputs are

$$i_1' = i_1 + i_2\delta_n^t, \tag{2}$$

$$i_2' = i_1 - i_2\delta_n^t. \tag{3}$$

The butterfly operation, one multiplication operation, and two addition and subtraction operations are executed according to Equations (2) and (3), and the input of the inverse sequence is converted into a natural sequence using the inverse property of the FFT algorithm. The FFT method is used to find out the real and imaginary parts of each subharmonic, and a series of voltage and current data are obtained using vector calculations to ensure data synchronization.

The monitoring of nonelectrical signal temperatures allows early warning of faults in equipment in the server room. Based on specific temperature values, the relative temperature difference can be used to determine the type of fault of the equipment in the server room, and the corresponding maintenance plan can also be formulated for different fault conditions. Relative temperature difference refers to a temperature rise ratio of the corresponding measurement point temperature and hotter temperature of the equipment in the server room under the same conditions. The calculation equation is

$$\varepsilon_n = \frac{N_1 - N_2}{N_1 - N_0}, \tag{4}$$

where N_0 indicates the ambient reference temperature, N_1 indicates the hot spot temperature, and N_2 indicates the normal point temperature. According to the calculation results, the causes of heat generation are classified into three types: current generation, voltage generation, and integrated generation. For these three types, the detailed analysis is as follows.

For the power loss of equipment in the server room of the current-caused heat type, the calculation equation can be expressed as follows.

$$P_1 = I_1^2 R_1, \tag{5}$$

where I_1 indicates the output current and R_1 indicates the circuit resistance. For the voltage-caused thermal type of equipment loss power in the machine room, the calculation equation can be expressed as

$$P_2 = U_1 I_2, \tag{6}$$

where U_1 indicates the voltage difference and I_2 indicates the leakage current.

For the comprehensive thermogenic type of equipment that loss power in the server room, the calculation equation can be expressed as follows.

$$\gamma\alpha S_1 N_1^3 + \beta S_2 N_1 + \lambda S_3 d = X_1^2 r_1 + \beta S_2 N_0 + \gamma\alpha S_1 N_0^3, \tag{7}$$

where α denotes the equipment heat generation coefficient, β denotes the heat conduction coefficient, λ denotes the heat transfer coefficient, γ denotes the Fourier heat transfer constant, S_1 denotes the equipment heat generation area, S_2 denotes the heat conduction area, S_3 denotes the convective heat transfer area, and d denotes the temperature gradient on the heat conduction surface.

In a certain temperature range, the temperature rise of the equipment in the server room is related to the effective value of the conductive current. And on the same line, the two equations corresponding to the temperature rise are as follows.

$$\begin{aligned} \phi_1 &= \eta_1 R_3 I_3^w, \\ \phi_2 &= \eta_2 R_4 I_4^w, \end{aligned} \tag{8}$$

where η_1, R_3, and I_3 denote the heat dissipation coefficient, resistance value, and current value of the measurement point, respectively; η_2, R_4, and I_4 denote the heat dissipation coefficient, resistance value, and current value of the heat dissipation point, respectively; and w denotes the power of the subdivision. Based on this, the relative temperature difference is calculated as

$$N' = \frac{\eta_1 R_3 I_3^w - \eta_2 R_4 I_4^w}{\eta_1 R_3 I_3^w}. \tag{9}$$

The operating status of equipment in the server room is judged according to the change in relative temperature, and the form of equipment failure can be determined.

3.2.2. Serial Communication Program Design. The serial communication module is mainly for setting the parameters of the serial port and opening the operation of the serial port. After the interactive platform control system is powered on and the GUI application is started, it should first obtain the available serial ports, query the serial ports connected to the interactive platform control system, and write the corresponding code to realize this function. Querying the current free serial ports can be achieved by using the QT-integrated QSerialPortInfo class. Use the available Ports() function of the QSerialPortInfo class to return all the serial port data, and use for each to traverse to get the serial port name. The flow of the machine room parameter setting module is shown in Figure 11. The obtained serial

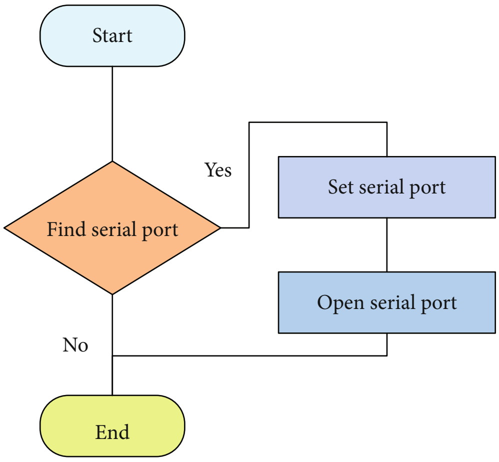

Figure 11: Serial port setup flow chart.

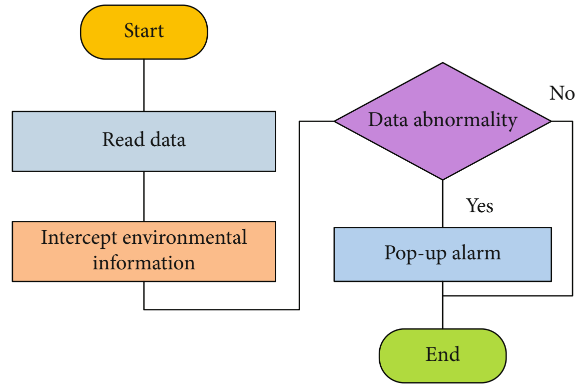

Figure 12: Flow chart of abnormal status alarm.

port name information data is displayed to the combo box control by the add item (info.portName ()) method, which can be selected by the user. The following is the definition of the serial port information: to use QT to operate on the serial port, you need to use the QSerialPort class. After referencing the header file, first, create the serial port object, then set the parameters, and you can read and write to the serial port.

3.2.3. Abnormal State Alarm Program Design. The abnormal states monitored by the alarm module mainly include abnormal temperature, abnormal humidity, abnormal dust concentration, abnormal UPS status, flooding alarm, and smoke alarm. The alarm pop-up window is designed using the message dialog box QMessageBox, the dialog box title parameter is set to "Alarm," and the warning content parameter is set for different abnormal states. The module is only used to alert the abnormal state alarm, so there is no need to use the return value of the dialog box button and no need to assign values to the confirm and cancel button parameters and just exit. The abnormal status alarm module intercepts the environmental information and compares it with the normal status threshold. When the environmental data is in the abnormal value range, the monitoring host software system will pop up an alarm pop-up window to indicate the abnormal environmental status of the server room. Figure 12 shows the flow chart of the abnormal state alarm module.

4. Result Analysis and Discussion

This chapter tests each main function of the FPGA-embedded server room remote monitoring system separately and describes the test work to verify the practicality and stability of the whole monitoring system.

4.1. Test Content and Purpose. This test is for the FPGA-embedded server room multimedia remote monitoring system to carry out functional, performance, and quality testing. The test content mainly includes functionality test, ease of use test, and reliability test. The purpose is to determine whether the monitoring system meets the functional and performance objectives of the expected design. Through the testing process, the logic errors and design defects in the software program were found, the correctness and accuracy of the hardware design were ensured, and the reliability of the stable operation of the whole monitoring system was ensured.

4.2. Functional Test

4.2.1. Data Acquisition Functional Test. The multimedia data acquisition function of the environmental parameter acquisition equipment in the server room is one of the most basic functions of the whole monitoring system. The testing of this part of the function is mainly focused on the multimedia data sending and receiving process between each submodule device and the control system. First, each submodule device is disconnected from the control system, and the control system is connected to the PC through the RS232 serial communication interface of each submodule device. At this time, the PC establishes communication between the serial port and the control system through the serial debugging assistant, and each serial port can continuously receive status query commands from the control system, and all the data of the query commands received are correct. As shown in Figure 13, the serial port of the lower computer queries the serial port data of the three-in-one environmental sensor device.

4.2.2. Information Display Functional Test. The information of the environmental conditions of the server room is displayed in the graphical interface of the platform control system and the interface of the multimedia remote monitoring host software system. When the monitoring system is in normal operation, the interactive platform program interface is observed at this time, and there are multimedia data displays of temperature, humidity, dust content, and UPS equipment working status in the environmental information display area. The current environmental information data is constantly updated, and the system displays more accurate conditions by comparing it with the parameters measured in the current laboratory. Checking the display information on the remote network monitoring host side, the multimedia data information is more accurate and the environmental

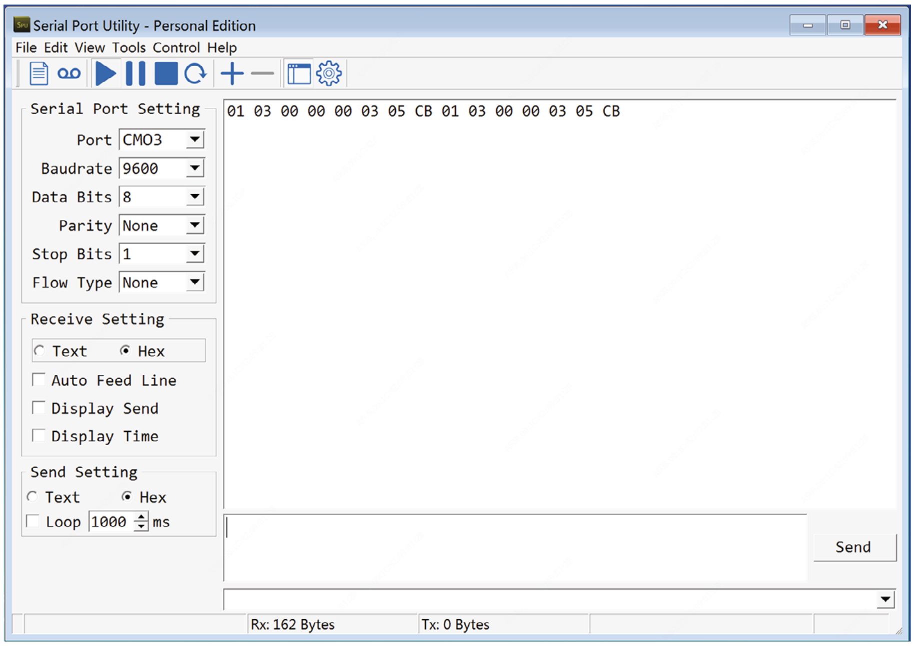

Figure 13: Query data test results.

condition parameters of the server room are normal. After working continuously for more than 12 hours and conducting several tests, the information display function of the whole monitoring system is normal, and the multimedia data query delay is low, which meets the software design index. Figure 14 shows the functional test results of monitoring host software system information.

4.2.3. Alarm Prompt Functional Test. For the testing of the alarm prompting function of the abnormal state in the server room environment, it is mainly divided into the following aspects: abnormal temperature in the server room environment, abnormal humidity in the server room environment, abnormal dust concentration in the server room environment, smoke, abnormal UPS working status, and other alarm prompts. Test process in the experimental environment simulated 40°C high-temperature environment and 0°C low-temperature environment, and the room control system triggered high-temperature and low-temperature alarm prompts. When simulating a fire and smoke environment, smoke sensor equipment triggers sound and light alarm prompts. At the same time, the multimedia remote monitoring host software system interface information shows abnormal status, prompting staff to investigate the security risks of the abnormal state of the server room environment. The test results show that all abnormal state alarm functions can be achieved, and the alarm prompt response time is short to meet the expected software design indicators. Figure 15 shows the abnormal message of multimedia remote monitoring host smoke status.

4.3. Usability Test

4.3.1. Ease of Understanding. Ease of understanding refers to the degree of difficulty for users to understand the structure, function, logic, and application scope of the server room environmental monitoring system software. After repeated operation tests of the system, the design of the software system function names, control buttons, and information display is simple and clear, so that the staff in the server room can know the meaning of the operation at a glance, indicating that the design of the software system has a good comprehensibility. The success of this usability aspect underscores the effective design principles applied in crafting the software system.

4.3.2. Ease of Operation. The usability tests also evaluated the ease of operation, emphasizing a user-friendly interface and sound design. The interactive platform control system and remote network monitoring host software designed in this paper are highly easy to operate. The user interface design is not only friendly but also scientific and reasonable. The ease of operation is reflected in the direct usability of the interface, which minimizes the need for extensive reference to software usage documentation. This intuitive operation is a key factor in ensuring efficient control and management of the monitoring system.

4.4. Reliability Test

4.4.1. Stress Test. Stress test refers to the reliability and stability of the whole system hardware and software by performing repeated operations before the monitoring system is put into use. For the stress test of the monitoring system in this paper, it is mainly carried out by long-time operation test. After a long period of operation, simulating various situations that occur in the server room environment, the monitoring system in this paper can achieve the corresponding functions and run normally and stably. This test ensures

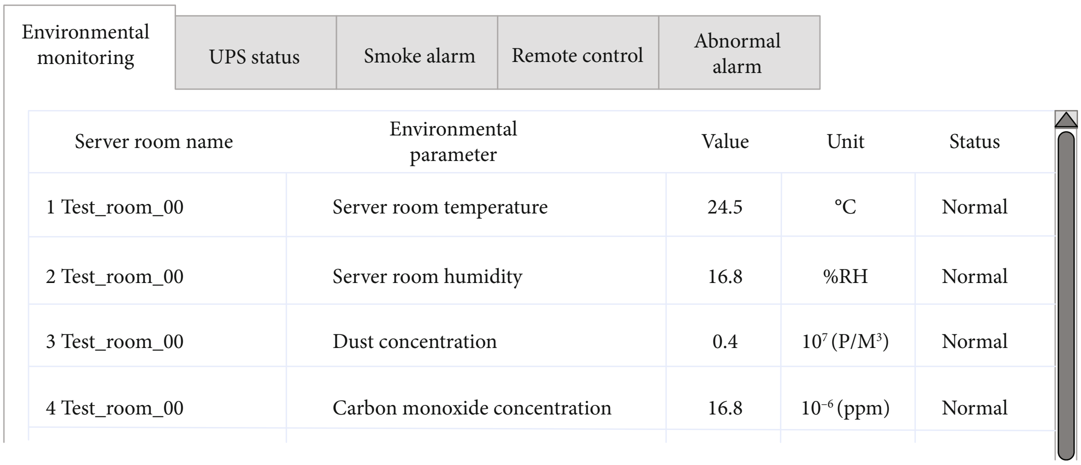

Figure 14: Monitoring host information display test.

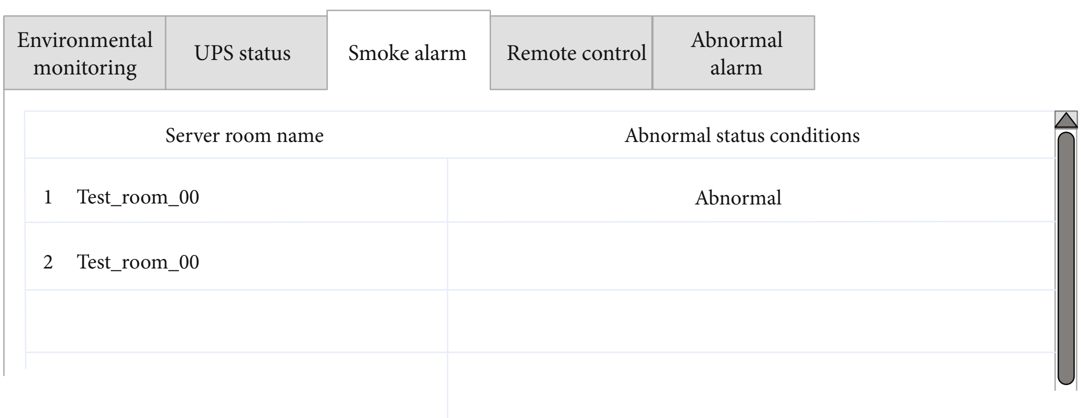

Figure 15: Monitoring host status abnormal display.

that the system can withstand the demanding conditions it might encounter in real-world server room scenarios.

4.4.2. Fault Tolerance Test. The fault tolerance test of the monitoring system in this paper refers to the test that the whole system can operate normally under abnormal conditions. During the test, the equipment of the machine room submodule is powered off or removed while the system is running to simulate the situation such as equipment damage. The proposed monitoring system not only continued to operate normally but also provided relevant prompts and error reporting information. This robust fault tolerance is indicative of the system's capacity to handle unexpected disruptions and maintain operational integrity, aligning with high standards of reliability.

4.5. Analysis of Test Results. After the above tests, it can be seen that the main functions of the monitoring system are all normal, the operation interface is simple and easy to use, and the working condition is very stable, which fully meets the expected design index of the system. Test items and results are shown in Table 2.

As shown in Table 2, a comprehensive analysis of the test results shows the normality observed in the functionality, usability, and reliability test categories, further demonstrating that the proposed system is well designed and fully meets the expected design specifications. The success of the data collection function, message display, alarm prompts, availability, stress, and fault tolerance tests collectively demonstrate the robustness and effectiveness of the system in this paper.

Table 2: Experimental test results.

Test item	Test content	Results
Functional test	Data acquisition functional testing	Normal
	Information display functional test	Normal
	Alarm prompt functional test	Normal
Usability test	Understandability test	Normal
	Operability test	Normal
Reliability test	Stress test	Normal
	Fault tolerance test	Normal

4.6. Timing Diagram Simulation Results. To validate the data processing speed of the FPGA by observing the sensor data

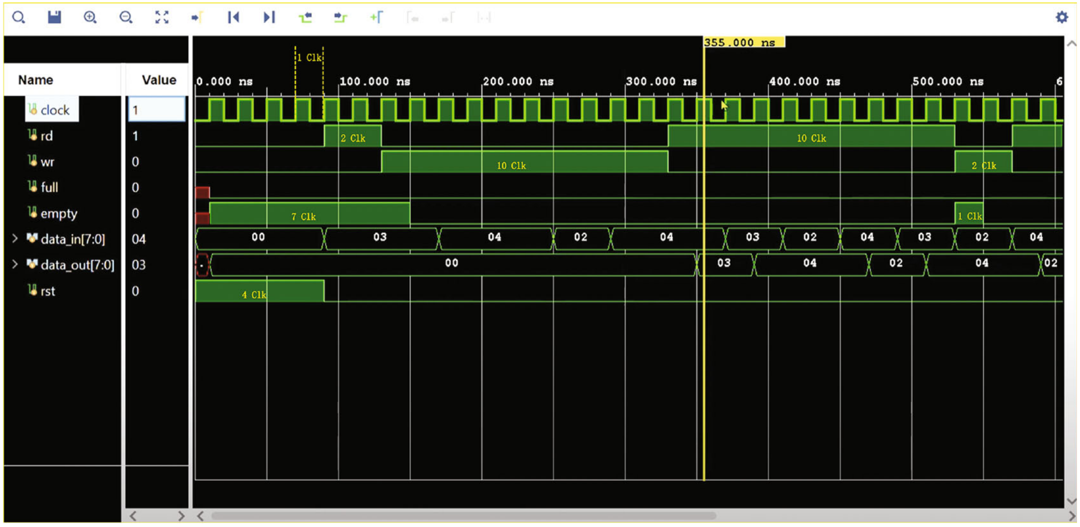

Figure 16: Timing diagram simulation results.

input and FPGA processing, we conducted a timing diagram simulation using SystemVerilog in Vivado Xilinx. During the simulation, the clock cycle "clock" was set to 20 ns, corresponding to a frequency of 50 MHz. The sensor input data was simulated as "data_in[7:0]", and the FPGA output data was represented as "data_out[7:0]." The simulation results are shown in Figure 16. To enhance the clarity of the timing diagram in Figure 16, we have meticulously annotated the diagram, clearly indicating the count of clock cycles needed for each processing step.

By carefully observing the timing diagram simulation results, we draw the following conclusions: the system requires 13 clock cycles, equivalent to 260 ns, for processing. This highlights the efficiency of the system. This swift processing time is paramount, especially in real-time applications where responsiveness is pivotal. Furthermore, we note that the order of input and output data throughout the processing remains consistent, further validating the correctness of the system during the processing.

Through this timing diagram simulation, we further verify the performance and accuracy of the system. The achieved 260 ns processing time signifies the FPGA-based system's adeptness at rapid and accurate sensor data processing. This is particularly significant in real-time scenarios, where timely responses to dynamic data inputs are imperative. The system's ability to maintain consistency in processing across various phases further solidifies its applicability in dynamic and time-sensitive environments.

4.7. Comparative Experiment. In this section, we conduct a series of experiments to compare the performance differences in sensor data processing between the FPGA system and the microcontroller system. The objective is to evaluate the advantages of the FPGA system in real-time data processing applications. For the experiments, we prepare a Xilinx Spartan-6 FPGA development board and an ATmega328P microcontroller development board and connect temperature sensors, humidity sensors, dust concentration sensors, and carbon monoxide concentration sensors. The Spartan-6 series is renowned for its reliability and suitability for applications demanding high-speed data processing. The board's capabilities align well with the requirements of real-time multimedia data processing in the server room monitoring system. The ATmega328P is an 8-bit AVR microcontroller. It is widely used in embedded systems. Its maximum clock frequency is 20 MHz; the typical clock frequency (under standard operating conditions) is 16 MHz. The processing times for the FPGA system and the microcontroller system are measured and compared, as shown in Table 3.

Table 3: Comparison of system processing times.

Sensor type	FPGA (ms)	Microcontroller (ms)	Percentage of improvement (%)
Temperature	0.25	2.10	88.09
Humidity	0.30	2.25	86.67
Dust concentration	0.32	2.50	87.20
Carbon monoxide concentration	0.35	2.90	87.93

Analyzing the data in the table, we draw the following conclusions. First, we observe that the FPGA system exhibits significantly faster processing speed compared to the microcontroller system. Whether it is temperature sensors, humidity sensors, dust concentration sensors, or carbon monoxide concentration sensors, the FPGA system's processing time is much lower than that of the microcontroller system. The percentage of improvement, as shown in Table 3, is derived from the computation utilizing the formula "(processing time with microcontroller – processing time with FPGA)/processing time with microcontroller." This resulting value converges at approximately 87%. This empirical evidence serves to reinforce the proposition that the FPGA system possesses inherent efficiency and expedited processing prowess, particularly in the realm of sensor data management.

Second, we notice that the FPGA system demonstrates consistent processing times for different types of sensors. Regardless of the sensor type, the FPGA system's processing time remains consistent. This demonstrates the stability and consistent performance of the FPGA system in processing sensor data. Finally, we observe that the microcontroller system has relatively longer processing times. Compared to the FPGA system, the microcontroller system exhibits noticeable delays in processing time. This may be attributed to the computational capability and processing speed limitations of the microcontroller system.

Therefore, through comparative experiments, we discover clear advantages of using the FPGA system for sensor data processing, including faster processing speed and better stability. This indicates the potential advantages and application value of FPGA systems in real-time data processing and applications with high response requirements.

5. Conclusion

This paper designs a multimedia remote monitoring system for server room with FPGA as the core technology. The hardware part and software part of the FPGA-embedded server room multimedia remote monitoring system are studied and designed in depth. The hardware part first studied and designed the overall architecture of the monitoring system. Then, each submodule is studied and designed in depth. The software part is divided into three parts: the program design related to energy metering, the serial communication program design, and the abnormal status alarm program design. After conducting thorough experiments, it has been conclusively demonstrated that all functionalities of the multimedia remote monitoring system proposed in this paper effectively achieve the intended goals set during the initial design phase. Furthermore, to emphasize the advantages of our FPGA system, we conducted a comparative analysis with traditional microcontrollers. The results clearly indicate that our FPGA-based system outperforms traditional microcontrollers in terms of processing speed, enabling faster and more efficient data acquisition and analysis. Beyond the evident enhancement in latency, our FPGA system excels in facilitating advanced data analysis and processing, exemplified by its capability to perform rapid Fourier transforms. This functionality proves crucial for ensuring precise monitoring of server room conditions. Furthermore, we delve into the extensive sensor integration capabilities of our system, made possible by the abundant I/O resources inherent in FPGA technology. This holistic approach ensures a comprehensive monitoring of various parameters within server room environments.

However, it must be acknowledged that our approach has its limitations. The scalability of our system and its compatibility with different server room environments require further investigation. In our future work, we plan to enhance the environmental monitoring capabilities by integrating additional sensing sensors. Additionally, we will continue to monitor and compare advancements in other research works to add more value and depth to our study. Lastly, we would like to offer recommendations to other researchers and practitioners in this field. It is crucial to consider the specific requirements and constraints of the server room environment when designing monitoring systems. Careful evaluation of hardware components, communication protocols, and software algorithms is essential for achieving optimal performance and reliability.

Data Availability

The labeled dataset used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no competing interests.

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