A Reconfigurable Smart Sensor Interface for Industrial WSN in IoT Environment

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***Abstract*—A sensor interface device is essential for sensor data collection of industrial wireless sensor networks (WSN) in IoT environments. However, the current connect number, sampling rate, and signal types of sensors are generally restricted by the device. Meanwhile, in the Internet of Things (IoT) environment, each sensor connected to the device is required to write complicated and cumbersome data collection program code. In this paper, to solve these problems, a new method is proposed to design a reconfigurable smart sensor interface for industrial WSN in IoT environment, in which complex programmable logic device (CPLD) is adopted as the core controller. Thus, it can read data in parallel and in real time with high speed on multiple different sensor data. The standard of IEEE1451.2 intelligent sensor interface specification is adopted for this design. It comprehensively stipulates the smart sensor hardware and software design framework and relevant interface protocol to realize the intelligent acquisition for common sensors. A new solution is provided for the traditional sensor data acquisitions. The device is combined with the newest CPLD programmable technology and the standard of IEEE1451.2 intelligent sensor specification. Performance of the proposed system is verified and good effects are achieved in practical application of IoT to water environment monitoring.**

***Index Terms*—CPLD, IEEE1415 protocol, Internet of Things (IoT), sensor data acquisition.**

I. INTRODUCTION

WIRELESS SENSOR NETWORKS (WSN) have been employed to collect data about physical phenomena in various applications such as habitat monitoring, and ocean monitoring, and surveillance [1]–[3]. As an emerging technology brought about rapid advances in modern wireless telecommunication, Internet of Things (IoT) has attracted a lot of attention and is expected to bring benefits to numerous application areas including industrial WSN systems, and healthcare systems manufacturing [4], [5]. WSN systems are well-suited for long-term industrial environmental data acquisition for IoT representation [6]. Sensor interface device is essential for detecting various kinds of sensor data of industrial WSN in IoT environments [7]. It enables us to acquire sensor data. Thus, we can better understand the outside environment information. However, in order to meet the requirements of long-term industrial environmental data acquisition in the IoT, the acquisition interface device can collect multiple sensor data at the same time, so that more accurate and diverse data information can be collected from industrial WSN.

With rapid development of IoT, major manufacturers are dedicated to the research of multisensor acquisition interface equipment [8]. There are a lot of data acquisition multiple-interface equipments with mature technologies on the market. But these interface devices are very specialized in working style, so they are not individually adaptable to the changing IoT environment [9]. Meanwhile, these universal data acquisition interfaces are often restricted in physical properties of sensors (the connect number, sampling rate, and signal types). Now, micro control unit (MCU) is used as the core controller in mainstream data acquisition interface device. MCU has the advantage of low price and low power consumption, which makes it relatively easy to implement. But, it performs a task by way of interrupt, which makes these multisensor acquisition interfaces not really parallel in collecting multisensor data. On the other hand, FPGA/CPLD has unique hardware logic control, real-time performance, and synchronicity [10], [11], which enable it to achieve parallel acquisition of multisensor data and greatly improve real-time performance of the system [12]. FPGA/CPLD has currently becomes more popular than MCU in multisensor data acquisition in IoT environment. However, in IoT environment, different industrial WSNs involve a lot of complex and diverse sensors. At the same time, each sensor has its own requirements for readout and different users have their own applications that require different types of sensors [13]. It leads to the necessity of writing complex and cumbersome sensor driver code and data collection procedures for every sensor newly connected to interface device, which brings many challenges to the researches [14]–[16].

Sensor data acquisition surface device is the key part of study on industrial WSN application [17]. In order to standardize a wide range of intelligent sensor interfaces in the market and solve the compatibility problem of intelligent sensor, the IEEE Electronic Engineering Association has also launched IEEE1451 smart transducer (STIM) interface standard protocol suite for the future development of sensors [18]. The protocol stipulates a series of specifications from sensor interface definition to the data acquisition [19]. The STIM interface standard IEEE1451 enables sensors to automatically search network, and the STIM promotes

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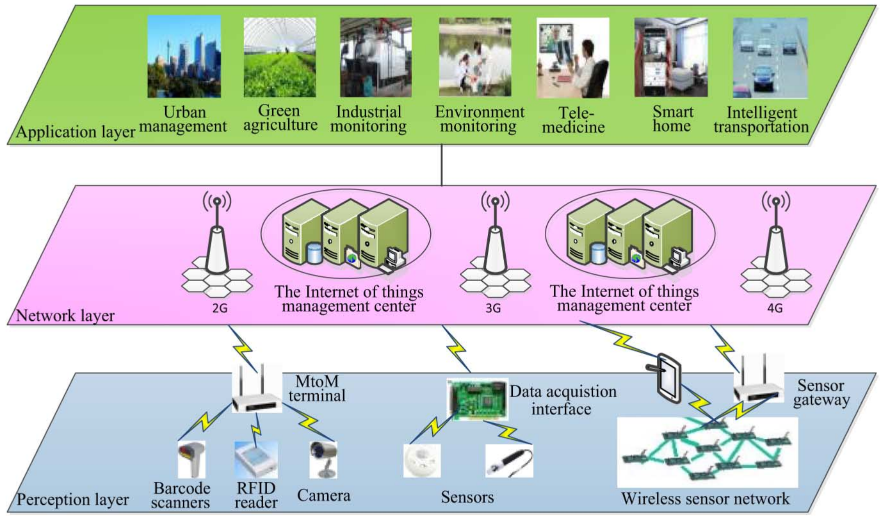


Fig. 1. Architecture of IoT.

the improvement of industrial WSN [20]. But, the sensors with the protocol standard have a high cost and still lack popularity in industrial WSN in IoT environment. Nevertheless, at present, examples of intelligent sensors available on the market and compliant with this standard are still limited [21]. To solve these problems, some dedicated hardware interfaces based on the IEEE 1451 have been recently proposed, and they are capable of interfacing with different sensor typologies [22]. These interface devices are usually based on relatively complex dedicated electronic boards [23]–[25]. It is obvious that such restriction should be released [26], and a reconfigurable multisensor data acquisition interface with good compatibility and normative interface standard needs to be developed in IoT environment.

By focusing on the above issue, this paper designs and realizes a reconfigurable smart sensor interface for industrial WSN in IoT environment. This design presents many advantages as described below. First of all, CPLD is used as the core controller to release the restriction on the universal data acquisition interface, and realize truly parallel acquisition of sensor data. It has not only improved the sensor data collection efficiency of industrial WSN, but also extended the application range of the data acquisition interface equipment in IoT environment. Secondly, a new design method is proposed in this paper for multisensor data acquisition interface that can realize plug and play for various kinds of sensors in IoT environment. The design system applies the IEEE1451 interface protocol standard that is used for smart sensors of automatically discovering network. For the sensors not based on IEEE 1415 protocol standard, the data acquisition interface system can achieve the function of plug and play. In this paper, this design take full advantage of CPLD characteristics, such as high execution speed, flexible organization structure, IP design could reuse, etc. The design adopts IEEE1451 smart transducer (STIM) interface standards, which makes our device better compatible in the field of industrial WSN in IoT environment.

The rest of this paper is organized as follows. The architecture is presented in Section II, and detailed hardware and software implementations are described in Section III. The application in water quality monitoring is discussed in Section IV. Finally, we conclude our work in Section V.

II. The Relation With IoT

With the advancements in Internet technologies and WSNs, a new trend is forming in the era of ubiquity [27], [28]. "IoT" is all about physical items talking to each other, where machine-to-machine (M2M) communications and person-to-computer communications will be extended to "things" [29], [30]. Key technologies that drive the future of IoT are related to smart sensor technologies including WSN, nanotechnology, and miniaturization [28]. Since IoT is associated with a large number of wireless sensor devices, it generates a huge number of data [31]. Sensor data acquisition interface equipment is one of the key parts in IoT applications. Data collection is the essential application of WSN and more importantly it is the foundation of other advanced applications in IoT environment [32].

IoT is a major drive to support service composition with various applications [33]. The architecture of IoT is illustrated as in Fig. 1. It consists of three layers: 1) perception layer; 2) network layer; and 3) application layer [34]. The design of data acquisition interface is mainly applied to the perception layer of IoT [35]. The perception layer of IoT is mainly composed of sensors, RFID readers, cameras, M2M terminals, and various data collection terminals [36]. The data acquisition interface is responsible for the integration and collaboration of various environments and collection of sensor data.

Examples of such a workflow include a water environment monitoring system that adopts sensors to detect pollution and water quality [37]. Water environment monitoring is one of the IoT application fields, where complex water quality information, is used to determine the water environmental quality at the same time. However, currently, there are few data collection devices that are dedicated to water quality monitoring on the market. Such devices can ensure high speed of data acquisition for multiple sensors and adapt to complex and various sensor types well. Thus, we design and implement a WSN data acquisition interface that can be used for water environmental monitoring. Detail of this example is elaborated in Section V. Other application areas in IoT also need to collect sensor data. If there is a data acquisition interface compatible with the sensor of each

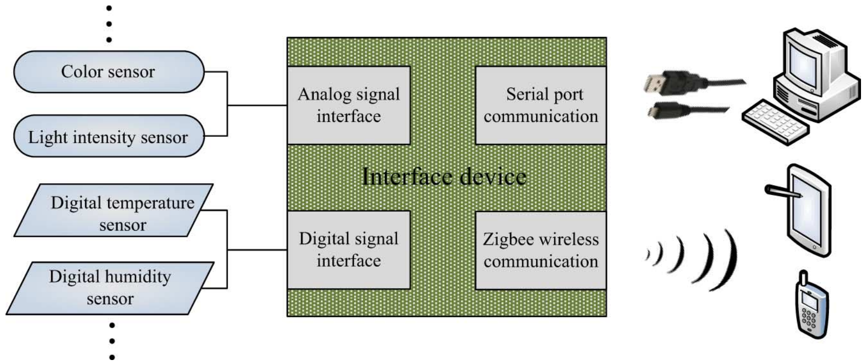


Fig. 2. Application and working diagram of the reconfigurable smart sensor interface device.

application field in IoT. It well greatly promote IoT development. So this design combines with the standard of IEEE1451.2 intelligent sensor protocol, and we design and implement a reconfigurable smart sensor interface for industrial WSN in IoT environment.

III. Architecture

We design a reconfigurable smart sensor interface device that integrates data collection, data processing, and wired or wireless transmission together. The device can be widely used in many application areas of the IoT and WSN to collect various kinds of sensor data in real time.

We program IP core module of IEEE1451.2 corresponding protocol in its CPLD. Therefore, our interface device can automatically discover sensors connected to it, and to collect multiple sets of sensor data intelligently, and parallel with high-speed.

CPLD is core controller of the interface device. It is used to control data acquisition, processing, and transmission intelligently, and make some preprocessing work for the collected data [38]. The driver of chips on the interface device is also programmed inside the CPLD.

Multiple scalable interfaces are designed on the equipment. It can be extended to 8-channel analog signal interface and 24-channel digital signal interface. This ensures that our device can connect with a number of sensors among the application of industrial IoT or WSN and guarantees the diverse collection of the information.

In terms of data transmission, our design can achieve wired communication through Universal Serial Bus (USB) interface and wireless communication through Zigbee module. Therefore, we can choose different transmission mode of the device in different industrial application environments.

Fig. 2 is the application and working diagram of the reconfigurable smart sensor interface device.

In practice, the designed device collects analog signal transmitted from color sensors, light intensity sensors, and other similar sensors through an analog signal interface. It can also collect digital signal transmitted from the digital sensors, such as temperature sensors, digital humidity sensors, and so on, through a digital signal interface. The Analog to Digital Converter (ADC) module and signal interface on the interface device are controlled by the CPLD, which makes it possible to collect the 8-channel analog signals and 24-channel digital signals circularly, and sets

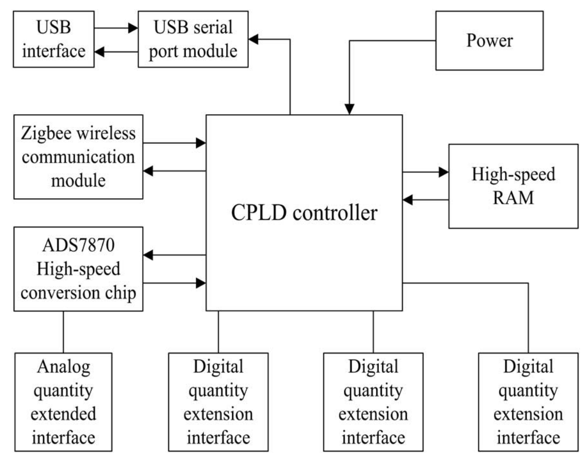


Fig. 3. CPLD hardware block diagram.

these collected data into the integrated Static Random Access Memory (SRAM) on the interface device. The collected data can be transmitted to the host computer side by way of USB serial wired communication or Zigbee wireless communication, so that the user can analyze and process the data.

IV. Implementation

A. The Introduction of the Hardware Architecture

The overall structure of reconfigurable smart sensor interface consists of CPLD chip (XC2C256 chip), crystals and peripheral circuit, communication circuit for turning USB to serial port (PL2303HXC chips and peripheral circuits), power supply of 1.8 and 3.3 V (LM1117 chip, voltage regulator and filter circuit), an SRAM memory (TC55V400 chip), high-speed 8-channel ADC (ADS7870 chip and peripheral circuit), LED indicator light, an analog extended interface, and three digital extended interfaces. Every extended interface among them can connect eight independent sensors, namely, the reconfigurable smart sensor interface device can access eight analog signals and 24 digital signals. Fig. 3 shows the CPLD hardware block diagram.

The hardware system can also send and receive data besides the basic sensor data acquisition. It can send data to the control center via USB serial port or Zigbee wireless module. Zigbee wireless communication module can be connected with the board through the mini-USB interface or the extensible GPIO interface

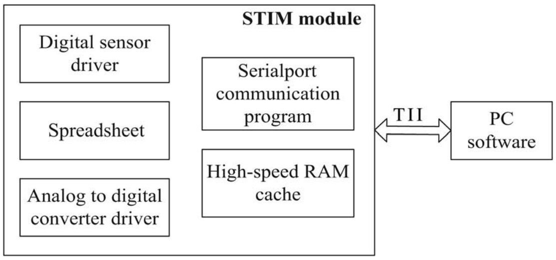


Fig. 4. Overall structure diagram of VHDL part of the system.

on the device. It can be used as wireless data transceiver node when the main controller receives trial or executive instructions [39]. After the data control center finishesh further processing for the received data, it needs to feed back related actions to sensor interface device. Data communication function can also control the running status of corresponding peripheral device.

B. VHDL Design

Very-High-Speed Integrated Circuit Hardware Description Language (VHDL) design of the system includes two parts. One part to uses the VHDL language as the basic tool and write related features of the reconfigurable smart sensor interface device by referring to the standard of IEEE1451.2 agreement. It reflects the difference between reconfigurable smart sensor interface device and general data acquisition card, which has a great effect in intelligently collecting sensor data. The other part is programming the interface driver based on VHDL hardware description language. It mainly covers programming of each hardware chip driver and sensor driver on the device. Fig. 4 shows the overall structure diagram of VHDL part of system.

1) IEEE1451.2 Protocol Based on VHDL Language Design: The designed reconfigurable smart sensor interface device can not only be used to collect sensor data, but it has also added sensor compatible IEEE1451.2 protocol standard features. This design has been written into the IP core module of IEEE1451.2 corresponding protocols in CPLD. Through this, the ordinary sensors (these sensors do not have the function of IEEE1451.2 protocol) can be connected to the device interface with specific functions of IEEE1451.2 protocol. This model is suitable for the application that different kinds of sensors access to different occasions. This model also solves the bottlenecks on lacking IEEE1451.2 agreement applications and the high cost of intelligent sensor.

a) Overall Design of the Intelligent Transmitter STIM: The design of STIM is the key to realization of the smart sensor data acquisition part. Functional design refers to the design framework of smart sensor data acquisition put forwarded by the standard of IEEE1451.2. STIM overall design structure diagram is shown in Fig. 5. STIM contains the following four functions: 1) the spreadsheet Transducer Electronic Data Sheet (TEDS); 2) the data transmission module (the part of transducer independent interface (TII)); 3) channel trigger module; and 4) registers management module.

Realization of the functions of intelligent transducer is mainly controlled by three state machine modules, which are master state machine, data transmission state machine, and channel trigger

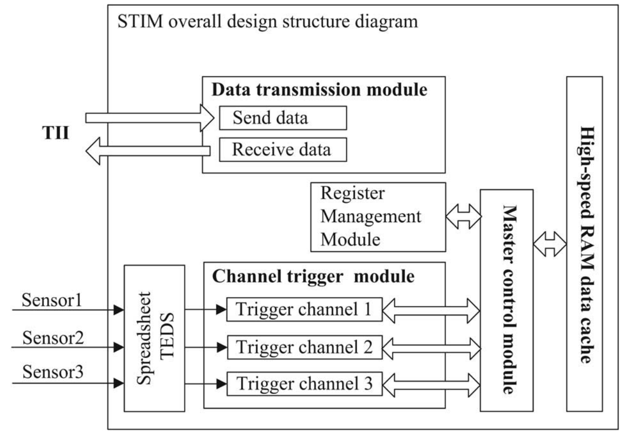


Fig. 5. STIM overall design structure diagram.

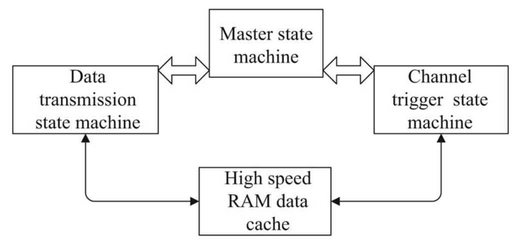


Fig. 6. STIM state machine design structure diagram.

state machine. Another data signal cache is also included in it. Relationship among each other is shown in Fig. 6. In Fig. 6, the master state machine is responsible for scheduling each function module of the acquisition system, and also has comprehensive control effect on the other two state machines. The data transmission state machines are used for data communication between the upper levels; the channel trigger state machine is responsible for collecting sensor data of each channel, and the data can be shared by caching between them.

The master state machine manages the switching process between each STIM state, including data transmission, triggering the sensor channel, control of data storage, etc. According to related characteristics of IEEE1451.2 protocol, the master state machine switches operations of the process as shown in Fig. 7. The signal marks of " Tri_Sig" and " Tra_Sig" determine when the state machine changes into each function module.

Data transmission state machine transmits bit data through the TII. The upper layer application software sends control signals to start the state machine. The state machine can encode or decode the memory address of the corresponding sensor of each channel, and drive different types of sensors.

The channel trigger state machine is responsible for reading data from the sensors in different channel. Every STIM channel has its corresponding controller of independent channel trigger state machine. These independent channel trigger state machines hidden in the sensor channel' trigger state machine. Fig. 8 shows each channel data reading state machine.

These independent channel trigger machines can be started through the corresponding trigger signal. Otherwise, they will be dormant. Each independent sensor channel' trigger state machines possesses the same structure, and its implementation

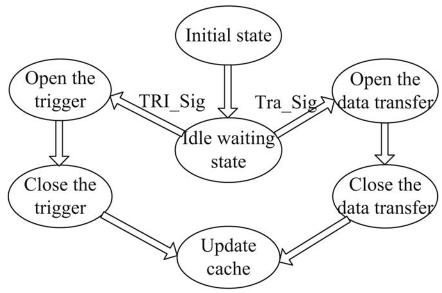


Fig. 7. STIM main state machine processes diagram.

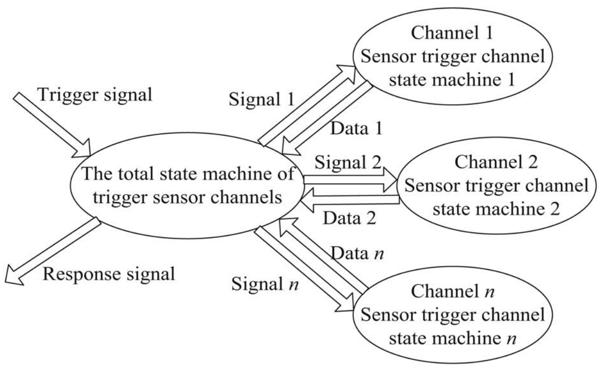


Fig. 8. Data reading channel state machine.

process can be executed in parallel. It ensures minimum delay, real-time performance and reliability of data collection in the process of multiple sensor data collection. The differences of different channel types are just reflected in the independent channel types, and the last transmitted data are previously stored in the cache.

b) Module Design of the Spreadsheet TEDS: Spreadsheet is an independent IP core module existing in CPLD in the form of circuit. Its main function is to operate various kinds of sensor data to be normatively collected by trigger sensor channel [40], [41], and make some corresponding modifications by filtering out invalid or false sensor data according to the characteristics of a variety of sensors. Schematic diagram of TEDS state machine is shown in Fig. 9.

Initial state of the system is defined by its idle state. When the start signal ranges from state 0 to 1, the state will jump from the idle state to the reading state of spreadsheet. Data can be saved to the register through serial and parallel transformation. The state updated to the contrast state of data format after reading a set of data. At the same time, the status flag pos will automatically adds 1 and prepares for contrasting the next message. At this point, the internal sensor data information that has been defined at the initialization time will compare it with the data read from the external. Otherwise, the contrast state of data format will return to idle state. If comparative success, it will automatically start the next data comparison.

In our design, the sensor channel trigger state machine is assigned with a specific ID number. At the same time, the ID also represents the priority of data collection. There are numerous methods to define priority, such as sensor conversion rate data length etc. Data length is used as the standard to set priority. When data has different length, the "short data priority" principle

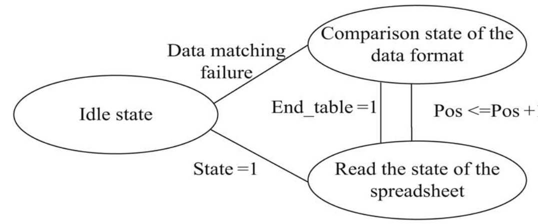


Fig. 9. TEDS state machine's schematic diagram.

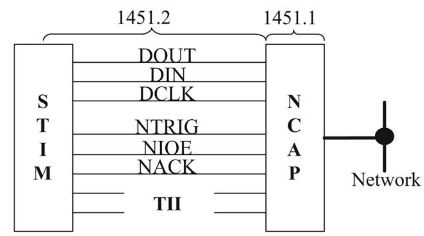


Fig. 10. Independent sensor interface functional schematic.

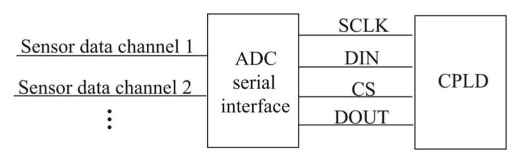


Fig. 11. Data and control signals of ADS7870 schematic diagram.

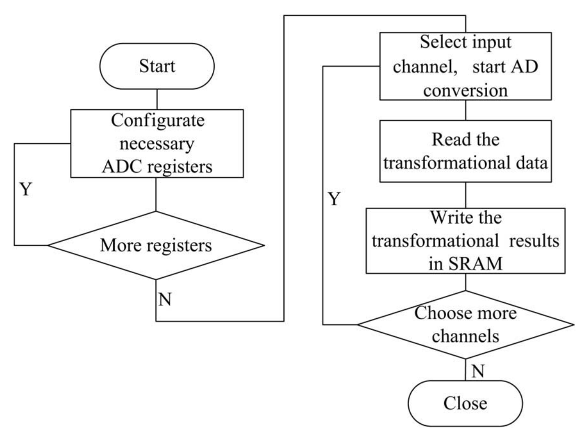


Fig. 12. Configuration ADS7870 program flowchart.

can effectively guarantee the overall time consumption of the whole data collection, so as to enhance real-time character of acquisition system.

c) Module Design of the Sensor Independent Interface TII: Sensor independent interface TII is the communication part of the smart transmitter STIM and network capable application processor (NCAP) [42]. Fig. 10 is the TII interface function diagram. TII is not complicated in concept. It interconnects with NCAP through the synchronous serial interface. TII usually includes data output (DOUT) and data input (DIN), which are used to shake hands for data and communication, DCLK is used to make data synchronization, and other signal lines such as special function signals are used as alternative choices.

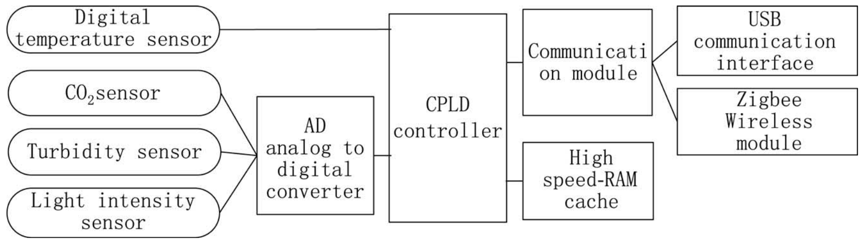


Fig. 13. System's block function design.

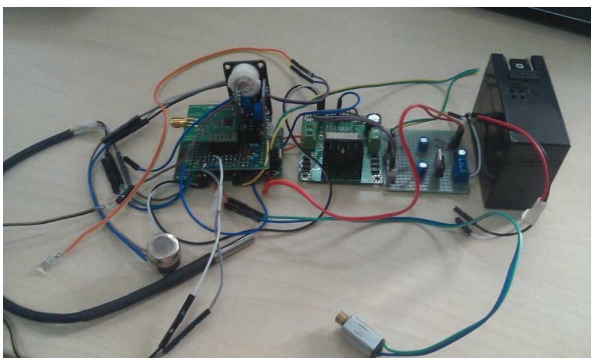


Fig. 14. Water quality monitoring hardware physical map. The reconfigurable smart sensor interface device is on the left side and we expand a Zigbee module on it. We use these wires around the device to attach sensors that we have used. Power of the whole system is on the right side. The two pieces of circuit boards are some corresponding configuration circuit in the middle of the figure.

RS232 communication protocol is adopted in design to support the TII interface. The feature of RS232 is completely in accordance with the TII. Function of the interface owns good versatility and usability. As slave device in the system, STIM remains in the standby state, until awaking notification is received from the master device. The notification message is sent from the main equipment, NCAP, or network equipment connected to NCAP. NCAP can communicate with STIM through TII's NIOE line and activate the specific channel of sensors through TII's NTRIG line. STIM makes response information through NACK line. This system sends or receives the corresponding control or feedback signals through DIN cable and DOUT cable, so as to finish communication between STIM and the upper application software.

2) The Design of the Interface Device Driver: CPLD is used as the main control unit in the device. Therefore, hardware programming language is needed to write complete drivers for every used chip [43]. In this paper the modulus conversion chip is taken as an example. The modulus conversion chip plays a key role in the system and introduces how to write chips driver via hardware description language VHDL when the analog sensor signal accesses the system under the standard of IEEE1451.2.

In our design, ADS7870, a modulus conversion chip produced by TI Company is adopted. ADS7870 is connected to CPLD processor through four serial interfaces, including clock line (SCLK), serial DOUT, serial DIN, and line selection (CS). These interfaces can implement ADS7870' function of reading or writing data. In this system, the data and control signals of the modulus conversion chip are shown in Fig. 11.

In our system, the ADC is mainly controlled mainly by writing signal DIN from the connected CPLD to operate registers inside the chip. First, the system controls ADC to collect analog signals of sensor input. These digital signals after conversion are first stored in the internal registers of ADC. Then, these digital signals are sent to the CPLD through DOUT port. In this system, DOUT port is set to automatically send ADC conversion results on the SCLK clock rising edge. CPLD controls initialization of the ADC, sensor data collection, and data conversion during the whole process. The flowchart is shown in Fig. 12.

After finishing ADC configuration, we implement the function of collecting analog sensor signals. This process is accomplished by sending collection command circularly.

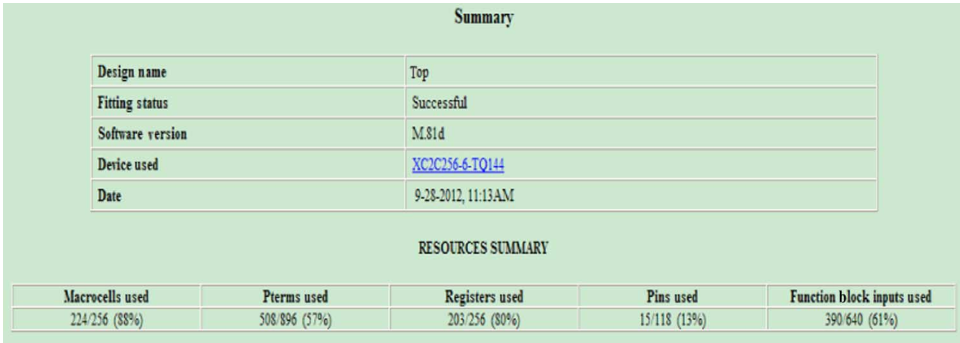
V. Application in Water Quality Monitoring

With gradual improvement of people's environmental protection consciousness, environmental monitoring has become an important direction of WSN application in IoT environment [44]. Environmental monitoring has higher requirements for equipment and more complex environmental information is needed. Water environmental information should be collected water environmental information as much as possible on the kinds and the accuracy. But the environmental monitoring equipment used now has many disadvantages, such as bulkiness, complex design, and high cost, etc. It is not suitable for monitoring conducted by small organizations or individual. In terms of water quality monitoring, it mainly involves the following aspects.

1) We can monitor water purity, internal and external water temperature, CO_2 concentration and light intensity on the surface of water in real time 2.
2) Multiple nodes are distributed in different areas of pond.
3) Low power battery provides power for the system.

A. Water Quality Monitoring Software and Hardware Design

1) Hardware Design: The core module of this system is CPLD-based reconfigurable smart sensor interface device designed by ourselves. It can well meet the requirements mentioned above. Here are the main solutions: Firstly, we suggest that water turbidity sensor, water proof temperature sensor, CO_2 sensor, and light intensity sensor should be used to collect required data; Secondly, Zigbee wireless module connected to the device is adopted for sending and receiving data; Thirdly, 1.8-V battery is offered to supply power for the system, and one battery can work for more than 10 hour. Block function design of the system is shown in Fig. 13.



Summary

Design name	Top
Fitting status	Successful
Software version	M.81d
Device used	XC2C256-6-TQ144
Date	9-28-2012, 11:13AM

RESOURCES SUMMARY

Macrocells used	Pterms used	Registers used	Pins used	Function block inputs used
224/256 (88%)	508/896 (57%)	203/256 (80%)	15/118 (13%)	390/640 (61%)

Fig. 15. CPLD system hardware resource consumption.

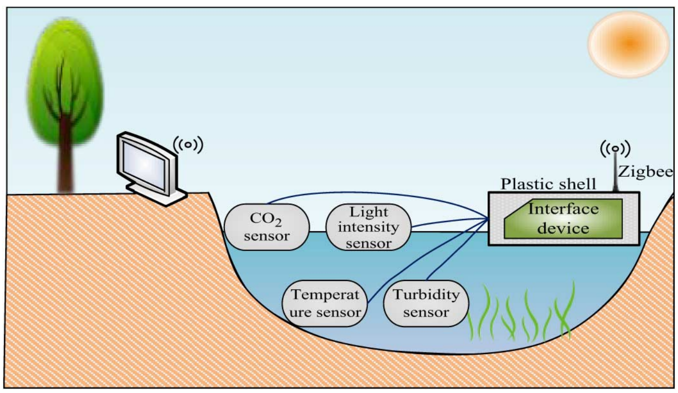


Fig. 16. Schematic diagram of monitoring equipment installation.

After combination of the above hardware, the system gains low cost, low power consumption, small volume, and other characteristics. Compared with the general water quality monitoring system using large equipment, it is more flexible and convenient. It is quite suitable for the project of water quality monitoring. Multinode monitoring can be realized through Zigbee wireless module. Under the premise of reducing project cost, the system can collect multiple sets of data as much as possible from different nodes and ensures monitoring of the whole water quality environment. Fig. 14 presents the physical map of water quality monitoring hardware.

2) Software Design: Software design of water quality monitoring system also includes two parts. Firstly, the program uses the hardware description language based on CPLD, to control different sensor data acquisition and the last communication processing. The modular grouping development mode is adopted to develop various functional modules. First, we implement respective functions in the development process, and then summarize the functions to a complete system by way of original instantiation. Secondly, because the sensor data is defined in the spreadsheet (TEDS), we just simply modify the corresponding sensor data format in spreadsheet according to different application systems. The requirements of data acquisition are met well and the difficulty of modifying the program is solved. CPLD system hardware resource consumption is shown in Fig. 15.

What's more, we have programmed a software client, to send control signals through a serial port and obtain the collected data and display the collected data in the window. So far, we have achieved data display in the serial debug terminal. This program still requires further improvement. These data collected from the text are a group of 16 hexadecimal data. The data transmission format is $0\text{xFD} + \text{data length} + \text{target address} + \text{data}$.

Length of the experimental data can be flexibly adjusted according to the number of sensors connected to the system. The data bit without connected sensors will display 00. After a sensor is connected to the system, the system will automatically search for data format of the equipment through a predefined physical interface and the corresponding relation of the spreadsheet. Then, the system completes standard conversion of the data format automatically. Finally, the transformed data are presented on the serial port terminal.

TABLE I
SPECIFIC SENSOR TYPE

Name	Type
Temperature sensor	DS18B20
Temperature and humidity sensor	SHTxx series
CO_2 sensor	MG811
Light intensity sensor	GY-30
Turbidity sensor	KIE-TS-300B
Pressure sensor	MPX5999D
PH sensor	YBK10-WQ201

B. Actual Effect Evaluation

As it is the monitoring service of pond water, it includes water turbidity monitoring, temperature monitoring, and carbon dioxide monitoring above the water. The device is put into the pool, so that the turbidity and temperature can be measured by using sensors in the depths of water, and the carbon dioxide sensor and light intensity sensor can be exposed above the water. Therefore, the equipment is covered with a waterproof shell to collect data, and good effects have been achieved. We design the schematic diagram of monitoring equipment installation as shown in Fig. 16.

Through actual test, we learn that the system can immediately collect sensor data when it is connected to power. The system has good compatibility and expansibility for different types of sensors. We have successfully tested different types of sensors on this system. Table I is the specific sensor types that we have tested.

VI. Conclusion

This paper describes a reconfigurable smart sensor interface for industrial WSN in IoT environment. The system can collect sensor data intelligently. It was designed based on IEEE1451 protocol by combining with CPLD and the application of wireless communication. It is very suitable for real-time and effective requirements of the high-speed data acquisition system in IoT environment. The application of CPLD greatly simplifies the design of peripheral circuit, and makes the whole system more flexible and extensible. Application of IEEE1451 protocol enables the system to collect sensor data intelligently. Different types of sensors can be used as long as they are connected to the system. Main design method of the reconfigurable smart sensor interface device is described in this paper. Finally, by taking real-time monitoring of water environment in IoT environment as an example, we verified that the system achieved good effects in practical application.

Nevertheless, many interesting directions are remaining for further researches. For example, the IEEE1451 protocol can be perfected and the function of spreadsheet should be expanded. It will have a broad space for development in the area of WSN in IoT environment.

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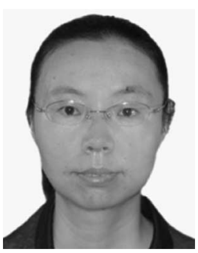

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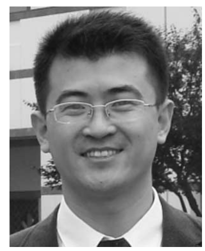

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