Advances in Computer, Signals and Systems (2023)
Clausius Scientific Press, Canada

DOI: 10.23977/acss.2023.070515
ISSN 2371-8838 Vol. 7 Num. 5

Design and Implementation of Smart Agriculture System Based on Wireless Sensors Networks

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Keywords: Wireless sensor network; Smart agriculture; LoRa

Abstract: The development of information and communication technology has provided the conditions for the advancement of smart agriculture. This article focuses on designing a smart agriculture system based on wireless sensor network technology for large-scale outdoor cultivation of grain crops, aiming to provide scientific guidance for increasing crop yield and applying scientific and technological advancements to modern agricultural production. The design of the smart agriculture system in this article is divided into two parts: the perception layer and the network layer. The perception layer includes data collection terminals and control terminals. The data collection terminals are used for acquiring and transmitting environmental parameters of crops, while the control terminals are used to regulate the environmental parameters of agricultural equipment. Both the data collection terminals and control terminals employ LoRa wireless communication technology to achieve long-range data transmission. The network layer consists of LoRa gateways, which connect to the network server via Ethernet and are responsible for uploading data from the data collection terminals and control terminals, as well as issuing control commands. Finally, the article conducted functional tests on the smart agriculture system, and the results indicated that all functions and performance of the system met the expected requirements. The system is capable of long-range data collection and transmission, meeting the demands of smart agriculture, and has promising application prospects.

1. Introduction

With the rapid development of technologies such as big data, the Internet, wireless communication, and sensors, Information and Communications Technology (ICT) has started to deeply integrate and develop in agriculture. Smart agriculture, characterized by intelligence, networking, and digitization, is gradually emerging and becoming a new direction for future agricultural development[1]. It is predicted that by 2050, the world's population will grow to 9.2 billion, and smart agriculture will be the key technology to address food shortages. Smart agriculture is the goal of modern agricultural development. It combines information and communications technology with modern agricultural techniques, deploying wireless sensor networks in agricultural production sites to comprehensively collect environmental parameters such as light, temperature, and humidity. Through the Internet and big data platforms, it enables intelligent sensing, transmission, analysis, and early warning, thereby achieving the digitization and intelligence of agricultural production and management[2].

Wireless Sensor Networks (WSN) have emerged based on embedded technology, wireless communication technology, and sensor technology. They are wireless communication networks formed by multiple mobile or fixed sensor nodes through single-hop or multi-hop connections. Each sensor node consists of a microprocessor, wireless transceiver, and multiple sensors. It is used to perceive, transmit, and process the state information of monitored objects within the network coverage range and report it to users.

In the 1990s, the United States began developing a series of sensors for the determination of trace elements in agricultural production. After entering the 21st century, scientific and technological advancements rapidly progressed, and precision agriculture in the United States experienced rapid development and gradually matured, becoming a new trend in agricultural development in developed Western countries. The US company Farmlogs has developed a professional farm management system utilizing big data technology, allowing farmers to remotely view their farm conditions through a mobile client. Currently, Farmlogs manages over 50,000 farms in the United States. CropX, another US company, is dedicated to smart irrigation in the field of agricultural technology[3]. Their soil sensors can calculate the water demand of soil based on its structure, topography, and moisture content. Users can receive cloud-based calculations such as soil moisture content and irrigation maps through a mobile client. Users can also adjust relevant parameters to calculate the water requirements for different regions, resulting in significant water savings for farmers.

Apart from the United States, developed countries such as Australia, Japan, and Israel have mature smart agriculture solutions and have established comprehensive industrial systems. These solutions can automatically control agricultural production equipment based on crop environmental parameters, allowing crops to grow in optimal ecological conditions without being affected by climatic conditions, thereby increasing crop yield and income. In comparison to developed Western countries, China started its research and development in smart agriculture relatively late, only proposing the concept of "smart agriculture" in 2014. The agricultural infrastructure in China is relatively backward, and there is a lack of capacity in promoting the application of agricultural technology. Additionally, there is a shortage of high-quality agricultural production management talents. Compared to developed Western countries, China still has a significant gap in the development of smart agriculture. Furthermore, many current smart agriculture solutions are mainly applied in greenhouse environments for fruit and vegetable production, and there are relatively few smart agriculture system cases suitable for large-scale outdoor cultivation of grain crops[4].

Therefore, this study focuses on the design and implementation of a smart agriculture system based on wireless sensor network technology for large-scale outdoor cultivation of grain crops. The system comprehensively collects crop environmental parameters, enabling holistic management throughout the crop's lifecycle and providing scientific guidance for increasing yield and income. The research in this paper includes the design of a smart agriculture data acquisition, transmission, and control system, as well as a crop lifecycle health management system. The smart agriculture data acquisition, transmission, and control system primarily consist of data collection terminals and control terminals. The data collection terminals are responsible for gathering crop environmental parameters, while the control terminals regulate the adjustment of relevant equipment based on the environmental parameters. The crop lifecycle health management system includes intelligent monitoring and early warning systems, smart irrigation systems, and integrated control systems for water, fertilizer, and pesticide management.

2. System Design

The smart agriculture system based on wireless sensor network technology aims to improve the quality and yield of grain crops in large-scale outdoor cultivation. Therefore, the system should be equipped with crop environmental parameter acquisition devices that employ corresponding sensors to collect these parameters. In the case of abnormal environmental parameters, the system should be capable of analyzing, determining, automatically controlling, and reporting to the user[5]. Therefore, the system should also have control terminals to regulate the environmental parameters of the crops by controlling the corresponding on-site equipment, providing suitable conditions for crop growth, and achieving comprehensive health management throughout the crop's lifecycle. The data collection terminals should perform periodic data acquisition tasks. After completing a task, they enter a low-power sleep mode to reduce energy consumption. When the next data acquisition cycle arrives, the collection terminals switch back to the working mode, and this cycle continues.

This system achieves comprehensive data collection of crop environmental parameters through the data collection terminals. The control terminals control the activation and deactivation of agricultural production equipment. The LoRa wireless communication technology enables large-scale network coverage. The Internet of Things (IoT) platform performs data analysis, processing, intelligent warning, decision-making, and control. The system can be divided into the perception layer and the network layer[6].

The perception layer of the smart agriculture system mainly includes data collection terminals and control terminals. The data collection terminals are equipped with various sensors to collect environmental parameters of the crops, which are then uploaded to the application layer through the network layer. The collection terminals need to collect parameters such as air temperature and humidity, light intensity, soil temperature and humidity, soil pH value, and soil nutrient content. According to the application scenarios of smart agriculture, the collection terminals should enter a low-power sleep mode after completing the data acquisition task and wait for the next collection cycle. The control terminals are equipped with multiple relays to control the activation and deactivation of agricultural equipment, such as battery valves, motors, and integrated water and fertilizer devices.

The network layer of the smart agriculture system is deployed through LoRa gateways, which are connected to the IoT platform via Ethernet, Wi-Fi, 2G/3G/4G/5G, or other methods. The network layer serves as a bridge for data upload and command delivery, uploading the data from the perception layer devices to the IoT platform and delivering control instructions from users to the perception layer devices.

3. Hardware design

The hardware components of the system mainly include data collection terminals, control terminals, and gateways. The system adopts LoRa wireless communication technology to achieve large-scale, low-cost, and low-power deployment of wireless sensor networks. The data collection terminals, control terminals, and LoRa gateways are all LoRa devices, with the data collection terminals and control terminals being sub-devices of the LoRa gateway. The hardware implementation scheme for LoRa sub-devices is illustrated in Figure 1. This scheme utilizes a microcontroller unit (MCU) and a LoRa RF transceiver for wireless communication. The MCU communicates with the LoRa RF transceiver through a serial peripheral interface (SPI) and controls it for wireless data transmission and reception[7]. This scheme uses two separate chips, which are directly connected through wiring, exposing the communication lines (SPI) to potential data theft and posing a data security risk. Designing the printed circuit board (PCB) based on this scheme would require a larger size and incur higher costs. Additionally, the software programming would involve the development of complex communication protocols between the MCU and the LoRa RF transceiver.

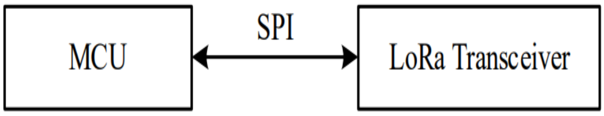

Figure 1: Hardware design for LoRa sub-devices

3.1 Acquisition terminal design

The data collection terminal consists of a LoRa wireless SoC control module, an illuminance detection module, an air temperature and humidity detection module, and a power module. The LoRa wireless SoC control module connects to the TTL-to-RS485 circuit and various sensor detection modules through the Inter-Integrated Circuit (I2C) interface. It controls the collection and transmission of crop environmental parameters. The power module supplies power to the air temperature and humidity detection module, illuminance detection module, and LoRa wireless SoC control module.

The air temperature and humidity detection module is used to measure the air temperature and humidity in the crop environment. The transpiration of crops is influenced by air temperature and humidity. Different crops have different requirements for air temperature and humidity, which need to be controlled accordingly to ensure their healthy growth. Therefore, it is necessary to select a suitable temperature and humidity sensor to collect information about the surrounding air temperature and humidity of the crops for timely regulation. Considering factors such as power consumption, cost, and size, the Sensirion SHTC3 digital temperature and humidity sensor, as shown in Figure 2, is chosen for the air temperature and humidity detection module.

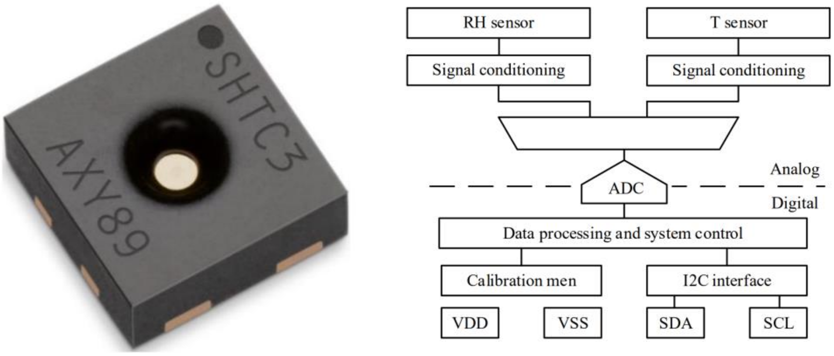

Figure 2: The physical diagram of SHTC3

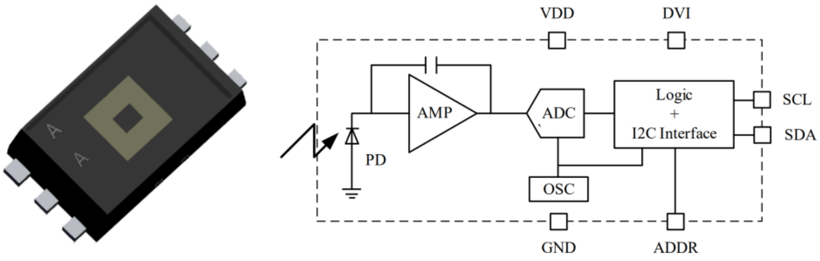

Figure 3: The physical diagram of BH1750

Crop growth is dependent on sufficient light for photosynthesis, which converts carbon dioxide and water into organic substances, facilitating nutrient accumulation. The photosynthesis process of crops is directly affected by the intensity of light. If the light intensity is too low, crops cannot carry out photosynthesis. If the light intensity is too high, it can cause an increase in leaf surface temperature, closure of stomata, and the inability to absorb carbon dioxide, leading to the cessation of photosynthesis. Therefore, the data collection terminal needs to incorporate an illuminance detection module to monitor the light intensity. The BH1750 illuminance sensor produced by ROHM Semiconductor, as shown in Figure 3, is chosen for the sensor selection.

3.2 Control terminal design

The control terminal consists of a LoRa wireless SoC control module, relays, field control switches, and a power module (Figure 4). The relays and field control switches are connected to the LoRa wireless SoC control module's general-purpose Input/Output (I/O) ports, allowing users to send control commands to the control terminal through either the field control switches or a remote client. The LoRa wireless SoC control module interprets remote or on-site control commands and controls the corresponding relays to turn agricultural equipment on or off, thereby regulating the crop's environmental parameters. The power module supplies power to the LoRa wireless SoC control module and the relays.

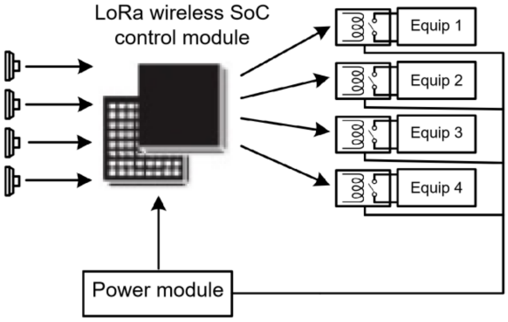

Figure 4: The hardware architecture diagram of the control terminal module

The control terminal requires a 3.3V power supply and a 5V power supply. The 3.3V power supply is for the LoRa wireless SoC control module, while the 5V power supply is for the relay control module. Since the external input voltage for the control terminal is 5V, only a single 3.3V power supply needs to be designed. The control terminal needs to remain in a working state for an extended period to promptly receive remote control commands and perform device control. The power consumption requirement for the control terminal is not as high as that for the acquisition terminal. As shown in the diagram, the control terminal adopts a cost-effective LDO (Low Drop-Out) design for a 3.3V step-down conversion circuit. The LDO model used is AMS1117-3.3, which can convert an input voltage range of 3.4V to 12V to a fixed output voltage of 3.3V [8].

3.3 Gateway hardware design

Figure 5 depicts the structural diagram of the system gateway. The gateway module consists of one SX1301 gateway digital baseband chip and two SX1255 RF front-end chips. The SX1301 communicates with two SX1255 chips through two sets of SPI interfaces. Low-temperature co-fired ceramic (LTCC) low-pass filters are inserted in the signal transmission path to suppress high-frequency harmonics. To enhance the gateway's operational bandwidth, two Surface Acoustic Wave (SAW) filters are added in the signal reception path. SAW filters are narrowband components that only allow signals within a specified frequency band to pass through. The operational frequency range of the gateway can be selected by switching the appropriate SAW filter using the three switches controlled by the Nucleo-F746ZG. A low-noise amplifier (LNA) placed before the SX1255 is utilized to improve the signal-to-noise ratio (SNR) of the input signal, thereby achieving higher reception sensitivity. The Nucleo-F746ZG communicates with the SX1301 through the SPI interface and is connected to the LAN8742A Ethernet transceiver via the Reduced Media-Independent Interface (RMII). By controlling the LAN8742A, internet connectivity can be established.

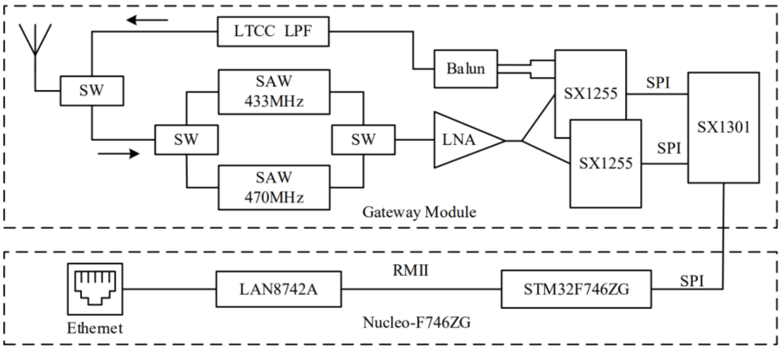

Figure 5: The structural diagram of the system gateway

4. System implementation

4.1 RF Circuit

The RF circuit is a crucial component for implementing a wireless sensor network system, responsible for wireless signal transmission and reception. The system's RF circuit includes an RF transmission circuit and an RF reception circuit. Figure 6 illustrates the structural diagram of the STM32WL55JCI6 RF circuit. The STM32WL55JCI6 features two RF transmission circuits and one RF reception circuit. The two RF transmission circuits provide two different RF power outputs. One path (RFO_LP→MN→RF(SW)→AM) can achieve a maximum output power of 15 dBm, while the other path (RFO_HP→MN→RF(SW)→AM) can reach a maximum output power of 22 dBm. The RF reception path (AM→RF(SW)→MN→Balum→RFI_P/RFI_N) offers a reception sensitivity of -148 dBm.

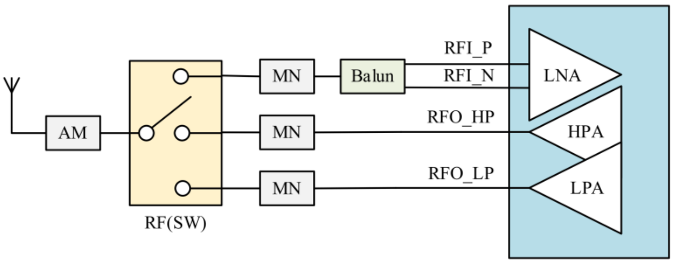

Figure 6: The structural diagram of the RF circuit

During the transmission of RF signals, impedance matching is usually required to enhance transmission efficiency and stability. Impedance matching consists of two parts: matching between the transmission line and the load, and conjugate matching between the signal source and the load. Matching between the transmission line and the load reduces reflection on the transmission line, minimizes noise interference, and improves the signal-to-noise ratio. Conjugate matching between the signal source and the load enables maximum power transfer and matching between the transmission line and the load. The common practice for RF circuit impedance matching is to insert a passive impedance matching network (Matching Network, MN) composed of inductors and capacitors between the antenna and the transmitter/receiver. Additionally, antenna matching (AM) is performed to optimize the impedance at the antenna end. To enhance signal transmission power and reception sensitivity, RF control switches are used for isolation between the antenna end and the RF transmission/reception end. During signal transmission and reception, the RF switches are controlled to switch the RF circuit.

RF testing primarily involves testing the actual maximum transmit power and reception sensitivity of the RF circuits in the data acquisition terminal and control terminal. By measuring the RF transmit power and reception sensitivity, the maximum transmission distance of the system can be calculated. This ensures that the system can achieve long-range transmission and data reception, enabling the outdoor large-scale deployment of smart agriculture data acquisition terminals.

The RF output of the data acquisition terminal operates at a center frequency of 470MHz, with a transmit power of 22dBm, a bandwidth of 125kHz, and LoRa modulation. Once the RF parameters are properly configured, the data acquisition terminal can start transmitting RF signals using the AT+TTONE command. At the spectrum analyzer end, the spectrum analyzer is configured to scan the center frequency of 470MHz with a scan bandwidth of 2MHz. After a period of scanning, the actual maximum transmit power of the data acquisition terminal is observed as 21.1dBm, and the maximum reception sensitivity is -128dBm in the spectrum analyzer window.

The calculation formula for LoRa device transmission distance is as follows:

$$D = 10^{\left(\frac{TP - RS - PS - 32.44 - 20\log_{10} CF}{}\right)}$$

TP: transmit power (21.1dBm), *RS*: reception sensitivity (-128dBm), *CF*: center frequency (470MHz), *PS*: path loss. The path loss depends on the specific usage environment. In the line-of-sight range, the path loss is approximately 25dBm in open areas, 30dBm in rural areas, 10-20dBm in forested areas, 35dBm in small towns, and 40dBm in large cities. In practical applications, there are usually multiple sources of path loss between the transmitter and receiver, so a total path loss of 45dBm is considered. Substituting the above parameters into the formula, the theoretical transmission distance of the device is approximately 8.14km. The test results demonstrate that the device is capable of long-range communication, meeting the requirements for outdoor large-scale deployment.

5. Conclusion

This paper presents the design and implementation of a smart agriculture system based on wireless sensor network technology, aiming to improve the production efficiency and yield of grain crops in outdoor large-scale plantations. The chosen wireless communication method for outdoor large-scale deployment is LoRa, and a comprehensive solution for the smart agriculture system is designed. It enables long-range data collection and transmission, intelligent system alerts, ultra-low power operation of devices, and automatic device control. The paper also conducts functional and performance tests on the smart agriculture system, and the test results demonstrate that all functions and performance of the system are functioning properly. The system is capable of long-range data collection and transmission, automatic device control, and intelligent alerts. It also features ultra-low power consumption, meeting the requirements of smart agriculture and demonstrating excellent application prospects.

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