

Advancements in Environmental Sensor Technology: Analysis, Applications, and Future Prospects

Keyu Long

Glasgow College Hainan of University of Electronic Science and Technology of China, Chengdu, China

2022360901018@std.uestc.edu.cn

Abstract. With the rapid growth of science and technology and the quest to liberate labor and achieve a better quality of life, sensors have been invented to assist humans in detecting the environment and in human production and life. This technology has been updated at a high rate and has had a significant impact in different fields. This paper focuses on environmental sensors and provides an in-depth study of how sensors work, how data is processed, the results of the applications, and the related technologies. This paper analyzes the sensor technology by studying the sensors, analyzing some of the existing sensor systems, and researching the application results. Through the research, this paper investigates the specific role of sensors in human society in a wide range of important ways and describes the important role of sensor technology in protecting the environment and protecting human life and health. This paper concludes by summarizing the sensor technology, draws out the current shortcomings of the sensor technology, provides possible solutions to these problems, and predicts the future developments in sensor technology.

Keywords: Sensor fusion; IoT integration; Wireless communication.

1. Introduction

In the era of increasing technological advancement, technologies such as the Internet of Things and various communication methods have emerged, and sensor technologies have also reached a developed level and are widely used. At the same time, the natural environment has been gradually polluted by events such as climate warming and pollution emissions, and the demands of modern human beings for life safety and quality of life conflict with the declining quality of the natural environment and natural resources [1, 2]. Ordinary monitoring methods, such as sending monitors to conduct monitoring are very cumbersome, low efficiency, and high cost. There is an urgent need to utilize advanced science and technology to monitor the environment in real-time, including air quality, water quality, and other indicators to control the level of pollution and to ensure the safety of humans and wildlife through sensor systems such as forest fire monitoring systems [3, 4]. Not only can sensors be used to monitor environmental pollution, but they can also be used to monitor the state of the scene in which they are located and to assist humans in manufacturing [1, 5, 6]. The purpose of this paper is to study several practical and common environmental sensors, compare the performance of these common environmental sensors, and compare their strengths and weaknesses, which will help to make sensor technology more widely valued and promote the innovation of sensor technology in society. The sensors in this paper are not individual sensor components, but sensor nodes containing sensor modules, processing modules, etc. The research methodology of this paper includes researching the existing results of sensor technology and analyzing actual cases. The main content is to first introduce the sensor as a technology in general, then discuss the communication and processing technologies related to sensors, then introduce their working principles and practical use cases, and finally draw conclusions through the previous analysis and comparison. The research objective of this paper is to discuss the working principles of some of the existing sensors in the light of some of the current literature on specific environmental sensors, to provide some innovative insights into the existing environmental sensors, to provide some innovative insights, modification suggestions, and expectations, to provide some new ideas and to contribute to the future development of environmental sensors.

2. Introduction to Sensors

2.1. Category and Definition of Sensor

A sensor is an electronic component that collects physical signals from the outside world, such as chemical signals, electrical signals, etc., through a specific device, and converts the analog inputs internally into digital signals. In some complex systems, sensors are an important part of collecting specific external physical quantities at regular intervals. Sensors are very diverse and have a very wide range of applications, such as industrial production and smart homes. In the field of environmental monitoring, sensors can be broadly categorized into temperature sensors, chemical composition sensors, wind speed sensors, and so on, depending on the type of physical quantity they sense. Within the broad categories, depending on the application scenario and the specific substances to be detected, these sensors can be adapted to a structure more suitable for the situation at hand or the sensing element can be replaced.

2.2. Wide application of sensors in the field of environmental monitoring

Sensors for monitoring different physical quantities have an indispensable role in the technological environmental monitoring process. For example, temperature sensors, humidity sensors, barometric pressure sensors, and even more complex forest fire monitoring systems are mentioned in this paper. Different types of sensors with different levels of accuracy can be used to fulfill the different needs of human beings.

2.3. Requirements and design of sensor categories for detecting different environments

In practical applications, the environments are very different and different physical quantities require different sensor categories. Accuracy, energy loss, and monitoring period need to be considered in sensor design. The design and performance of sensors for different environmental conditions are discussed in this paper.

3. Data Acquisition and Communication Methods for Sensors

3.1. Communication within the sensor

Sensors with a simple structure and a single function are generally built based on a microcontroller. This subsection explores how the various components of the sensor work together and send information. Analog-to-digital converters (ADC) are used in the process where analog signals need to be converted to digital signals. Later, in microcontrollers, communication methods such as SPI, I2C, and UART are used. These are the digital communication methods commonly used by electronic components in microcontrollers for coordinated communication.

3.2. Communication methods for sensor return monitoring data

For researchers to analyze and study the data collected by the sensor after the sensor collects data, it needs to store the data or return the data. There are two ways to communicate back: wired communication and wireless communication. Wired communication can be realized by laying cable fiber optic cable and other transmission media. Wireless communication can be realized by choosing various technologies such as Bluetooth, ZigBee, LoRa, RFID, and Low Power Wide Area Network (LPWAN) depending on the actual situation [6, 7]. In terms of the number of node connections, ZigBee uses a star topology, which can serve more than 65,000 nodes, far exceeding other protocols [8]. Since many sensors are deployed in remote locations, laying cables and fiber optic cables can cause unnecessary costs, which makes wireless transmission technology more practical and important. In the case of zones where communication base stations are dense and communication distance is very close, Wi-Fi, Bluetooth, cellular networks, etc. can be chosen. However, if it is used in the field of agriculture monitoring, forest fire, etc., ZigBee, LoRaWAN, and other low-power and low-cost

wireless technologies based on the communication of IoT devices would be a more suitable choice [3, 4, 9]. It is worth noting that the designer needs to choose the appropriate communication module according to the actual situation such as the requirement of data transmission rate, energy consumption, and wireless transmission distance.

3.3. Data processing scheme and data analysis tools

The raw data collected by the sensors are affected by a series of factors such as equipment accuracy and environmental interference, and are subjected to data filtering, data fusion, and other data processing schemes to improve the accuracy of the data. After the data is processed, it is then further analyzed using software such as MATLAB, Python, and so on. Multi-sensor data fusion technique allows the computer system to process the data based on predetermined rules and calculations based on multiple sensor data obtained from time series so that the scenarios perceived by the sensor network can be parsed, thus assisting the computer system and the relevant personnel to make reasonable decisions [10]. The main steps in multi-sensor data fusion techniques are data collection, feature extraction, pattern recognition processing, group association, and deriving consistent interpretation and description [10]. Multi-sensor data fusion methods include stochastic class methods such as the weighted average method, Kalman filter method multi Bayesian estimation method, etc, and also artificial intelligence class methods, and artificial neural network methods [10].

4. Natural Environment Detection Sensor Categories

4.1. Temperature sensors

4.1.1 Principles of operation

Temperature sensors are simple and basic sensors that generally use thermistors or thermocouples for measurement. Temperature is calculated by measuring the resistance of the thermistor or by measuring the potential difference in the thermocouple circuit.

4.1.2 Utilization Cases

Temperature sensors are widely used in industrial production, meteorological observation, smart homes, health monitoring, and other fields. In industrial production, temperature sensors are used to control temperature changes in the production process to ensure product quality. In meteorological observation, temperature sensors are used to record real-time changes in ambient temperature. In the smart home, temperature sensors are used to measure the temperature inside the house and assist in controlling the room temperature within a constant range. In health monitoring, temperature sensors are used to always monitor the user's body temperature.

4.2. Humidity sensors

4.2.1 Principles of operation

Humidity sensors are another common type of environmental sensor. There are two main types of moisture-sensitive elements, capacitive and resistive. When water vapor in the air is adsorbed on the moisture-sensitive resistor, the resistance of the moisture-sensitive element will change or when the humidity in the air changes, the dielectric constant of the moisture-sensitive element will change together, and then the corresponding humidity in the air can be measured.

4.2.2 Utilization Cases

Humidity sensors are widely used in smart agriculture, food storage, and weather observation. In the field of smart agriculture, humidity sensors are used to monitor the air humidity in greenhouses to ensure the normal growth of plants. In the field of food storage, humidity sensors are used to monitor the air humidity in barns to prevent stored grains from getting damp and moldy, which can cause economic losses.

4.3. Barometric pressure sensors

4.3.1 Principles of operation

A barometric pressure sensor is a sensor used to monitor changes in atmospheric pressure. It usually has a film inside that is sensitive to air pressure, a thimble, and a resistor. When the membrane deforms due to changes in air pressure, it moves the thimble, which in turn moves the resistor. The atmospheric pressure of the air is then measured by converting the analog signal to a digital signal.

4.3.2 Utilization Cases

Barometric pressure sensors are widely used in meteorological observation and aerospace fields. In the field of meteorological observation, barometric pressure sensors can provide real-time feedback on air pressure, which is important in weather forecasting. In aerospace, barometric pressure sensors are used to measure the atmospheric pressure at the current altitude of the aircraft.

4.4. Light sensors

4.4.1 Principles of operation

Light sensors are commonly used to measure light intensity. The principle of operation includes the use of the photoelectric effect of semiconductors or photoresistors. The measurement of light intensity is achieved by measuring the voltage change caused by light intensity and then by analog-to-electric conversion.

4.4.2 Utilization Cases

The application of light sensors is very important for the field of smart agriculture, and light regulation. In the field of agriculture, light sensors are used to monitor the light intensity of crops to ensure that plants have a good growing environment. In the field of light regulation, light sensors are used to detect the ambient light level. Adjusting the brightness of the lighting system according to the ambient light level ensures the rational use of energy.

4.5. Wind speed sensors

4.5.1 Principles of operation

Wind speed sensors can be categorized into mechanical and ultrasonic sensors. In the case of mechanical wind speed sensors, the high-speed movement of the air pushes the sensor to rotate, and its central axis drives the sensing element inside the sensor to generate pulse signals. Within the measurement range of the sensor, the wind speed can be calculated because there is a linear relationship between the wind speed and the pulse frequency. In the case of ultrasonic sensors, the air passes through the measuring area of the sensor, which is equipped with two pairs of ultrasonic probes. The wind speed can be calculated by measuring the time difference between the transmission of the ultrasonic waves between the two points.

4.5.2 Utilization Cases

Wind speed sensors are widely used in meteorological observation, wind power generation, and other fields. In meteorological observation, wind speed sensors can measure the wind speed at the current location and provide important data for weather forecasting. In wind power generation, wind speed sensors can measure the real-time wind speed where the wind turbine is located in real-time, which can provide a reference for researchers to adjust the operation program of the wind turbine. It can also help researchers to identify suitable addresses for the construction of wind turbines.

4.6. Forest fire monitoring systems

4.6.1 Principles of operation

The forest monitoring system does not contain only a single sensor but a network of sensors with different functions such as temperature and humidity sensors, flame sensors, and smoke sensors connected through a wireless network [3, 4]. The sensors collect the data and send it first to the routing

node, then the data is sent to the coordinator node, gateway, cloud platform, and finally to the user [4].

4.6.2 Utilization Cases

Forest fire monitoring systems play an important role in the protection of forest resources. Nowadays, the world is beginning to realize the importance of forest resources and the limitations of traditional fire monitoring methods. With the development of the Internet of Things (IoT) technology, forest fire monitoring systems are gradually gaining importance because of their real-time, low-cost, and high-coverage characteristics.

5. Water Quality Testing Sensor Categories

5.1. pH sensors

5.1.1 Principles of operation

The pH sensor is a sensor that is commonly used to detect the pH of water bodies. Whether the pH of natural water bodies is within the range or not is an important indicator for assessing the quality of water bodies. The glass membrane in the pH sensor is utilized for its ability to allow the passage of hydrogen ions. The movement of hydrogen ions along the concentration triggers a difference in the concentration of hydrogen ions in the buffer inside the sensor and in the solution outside, resulting in a potential difference in the glass membrane. This potential difference is related to the pH of the solution. By measuring the potential difference, the pH of the solution can be measured.

5.1.2 Utilization Cases

pH sensors are widely and importantly utilized in water quality treatment, water quality testing, and water quality assessment. According to the literature, the pH value of a typical water sample is between 6.0 and 9.0 [5]. pH sensors can capture this data in real time and assist in adjusting water quality treatment programs and help researchers to investigate the factors affecting natural water sources.

5.2. Heavy metal sensors

5.2.1 Principles of operation

Heavy metal sensors are used to detect heavy metal concentrations in water samples. There are two main detection methods for heavy metal sensors: optical and electrochemical. The optical method is based on the spectral properties of the atoms or ions of heavy metals, and the heavy metal concentration is measured by measuring the spectra absorbed or reflected by the heavy metals. The electrochemical method is based on the electrochemical reaction between the heavy metal and the electrode, and the heavy metal concentration is measured by recording the current, voltage, and other data.

5.2.2 Utilization Cases

Heavy metal sensors are widely used in water quality testing and water treatment. Heavy metals are a major threat to the natural environment and human life and health. By measuring the concentration of heavy metals in water samples, related personnel can adjust the purification program of sewage treatment plants. Heavy metal sensors can also be used to monitor industrial effluent discharge from factories for compliance with standards.

5.3. Dissolved Oxygen sensors

5.3.1 Principles of operation

The oxygen content of a water body is an important indicator for assessing the suitability of that water body for living organisms and the health of that water body. A semi-permeable membrane is installed in the dissolved oxygen sensor, through which oxygen can pass and undergo a redox reaction

with the electrodes in the sensor. By recording the amount of current, the amount of dissolved oxygen in the water can be measured.

5.3.2 Utilization Cases

Oxygen levels in water have important applications in aquaculture and nature conservation. The oxygen content of the water body can be assessed to determine whether the water body is suitable for aquaculture and the dissolved oxygen level in the water can be monitored in real-time to prevent economic losses. In nature conservation, dissolved oxygen sensors can detect the ecological balance of the natural water body being measured.

5.4. Turbidity sensors

5.4.1 Principles of operation

Turbidity sensors can be used to measure the clarity of water which in turn can be used to assess the hygienic status of the water body, the turbidity of drinking water should be less than 1 nephelometric turbidity unit (NTU) [5]. In the turbidity sensor, there is an infrared light-emitting diode. When the water sample is more turbid, the less light is received at the receiving end. The receiving end converts the light intensity into the amount of current. The clearer the water sample, the higher the current. Afterward, the turbidity of the water sample can be measured by measuring the amount of current.

5.4.2 Utilization Cases

Turbidity sensors have a wide range of applications in the field of water quality testing and drinking water sources. Turbidity sensors are used to test whether drinking water meets drinking standards. In water quality testing, the turbidity of a body of water is an important indicator used to assess the pollution of a body of water and its suitability for animal life.

6. Application Results, Evaluation, and Future Prospects

6.1. Application results

Some advanced sensor technologies have been widely used in many countries and fields, for example, in Germany, Canada, and some other countries, the forest fire sensor network has been put into use and has good application results, in the protection of forest ecosystems and timely control of forest fires have excellent performance [3]. Moreover, according to some literature, the multi-functional water quality detector developed by combining a variety of sensor technologies has been technically mature and can be put into use. This technology will make a significant contribution to the field of river water quality monitoring and urban residents' water safety [5]. Water quality sensors based on IoT work and air quality detection systems based on ARM and Lora technologies have also been used for water quality analysis and assessment of air pollution [11]. Artificial Intelligence combined with IoT has made some progress even in the field of water quality monitoring [2]. In terms of overall sensor research trends, scholars and engineers are committed to making the operation of sensor systems simpler and more user-friendly [1]. This is a good trend, because a more modular design and more user-friendly interaction, such as directly displaying the decision made by the computer system after evaluating the data collected by the sensors, can promote the wider application of sensor technology, which can bring convenience and life protection to more human beings. The results of this wide range of applications and developments can be seen in other ways as well. At the hardware level, sensor modules with different functions, main processor modules, and communication modules have been developed as mature and simple commercial modules to choose from, such as the STM32 series microcontrollers and the PMS7003 as an air particle concentration collection module [11]. This means that the designer of the sensor can focus on the combination of different modules and the realization of the functionality, thus saving time in developing sensor modules based on the basic principles of the sensor. In terms of software and communication, IoT is

a technology that has progressed with the development of the Internet and the communication field, and it still has a very promising future and range of applications today. On the one hand, IoT technology can help sensors to form a network to transmit information to each other and form large mathematical models from the data they collect. On the other hand, the wide application of sensors can help various devices connected to the IoT to share information and work together. It improves the efficiency as well as accuracy of the entire device system.

6.2. Prospects

With the rapid development of industries such as artificial intelligence, neural networks, wireless communications, and manufacturing, combined with rising human demands for quality of life and work efficiency, sensor technology will advance at a faster rate. In the future, sensors may have a broader application prospect in the medical, intelligent machinery, big data collection, intelligent industrial manufacturing, and technology product industries.

7. Conclusion

In this paper, the basic content of sensor technology, the categories of sensors, the communication technology combined with sensor technology, the data processing method of the sensor system, the working principle, the utilization cases, the application results of sensors, and the prediction of the development prospect of sensors. This paper also discusses in depth the important roles of the environmental monitoring system based on the sensors in the air, water quality, and forests. This paper summarizes, analyzes, and concludes the current state of sensor technology as a whole, and makes reasonable predictions about the application and future development of sensors. Despite the remarkable achievements of sensors, there are still many shortcomings of sensors that need to be improved. The first is the energy problem. Many sensors or sensor networks deployed in the environment currently use batteries to power the sensors, and if the environment in which the sensors are installed is very complex, such as in a forest, it becomes very difficult to replace the batteries for the sensors. This leads to severe limitations in the design and functionality of the sensors. This also limits where the sensors can be deployed, how long they can operate, and how often they can operate. Secondly, there is the issue of communication. For some complex, wide-ranging, and remote applications, it is not possible for the sensor nodes to connect directly to the receiving end of the signal. This problem may affect the application range of the sensor. After that is the cost problem. Currently, some sensors and the communication technology used by the sensors still have the problem of high cost, which makes the application of sensor technology limited. It is hoped that in the future, researchers can solve some of the current problems of sensors by combining sensors with new energy generation such as solar power or wind power, developing better IoT communication methods or increasing the number of routing nodes and optimizing the production technology to reduce the cost of sensors, etc. In conclusion, sensors are currently providing a great help to the survival and production of human beings. Sensors and sensor-constituted environmental monitoring systems can provide humans with accurate and effective environmental information in real-time. The sensor industry is still in an upward stage and has great potential. By combining sensor technology with emerging technologies in other fields, the performance and application of sensors can be further developed to promote the intelligence of environmental monitoring and environmental protection, which in turn will assist the prospects of human development.

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