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HYDROGEN SULFIDE DETECTION SYSTEM BY WIRELESS SENSOR NETWORK FOR THE PETROCHEMICAL INDUSTRY

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Abstract

This study applies a wireless sensor network (WSN) to a toxic gas sensor system in petrochemical refinery plants to improve the shortcomings of the existent wired gas sensor systems. Specifically, a one-hop ZigBee transmission module is coordinated to design a simple hydrogen sulfide sensor circuit, thereby fabricating a ZigBee hydrogen sulfide sensor. In addition, a gas monitoring and warning system is designed. To enhance the reliability of the system, three sets of sensors are used to monitor an area and decrease the risk of operation failure. Accordingly, a hydrogen sulfide WSN prototype is established.

Introduction

Industrial development and increased work safety awareness have prompted relevant governmental, industrial, and employed personnel to emphasize industrial safety. However, compared with advanced industries worldwide, Taiwanese industries have incurred a higher incidence of industrial disasters. Because Taiwan has limited land space and high population density, factories are usually built near communities; hence, an industrial disaster can lead to substantial damage and develop into various social, economic, and even political problems.

In recent years, the domestic petrochemical industry has continually incurred major safety incidents, thus raising the public's concerns toward the safety of petrochemical plants. Therefore, improving the management and measures of industrial safety and environmental preservation is a pressing goal of the petrochemical industry[10,17,22,23].

During the process of petroleum refining, various toxic or combustible gasses (e.g., ammonia, hydrogen sulfide, and sulfur dioxide) can be generated in addition to the desired oil products. In particular, hydrogen sulfide is a common manufacturing gas generated during the desulfurization of crude oil, the ultimate goal of which is to isolate sulfur from hydrogen sulfide. Because hydrogen sulfide is harmful to the human body and highly corrosive to equipment, it is an extremely hazardous gas [~~1~~1, 2~~17~~,8,13,18,19].

In recent years, the continual development of wireless communication technology has enabled creating low energy-consuming, low-cost wireless sensor networks (WSNs), which facilitate reliable and robust wireless communication. WSNs are feasible to a wide scope of applications, particularly in natural environmental surveying, industrial environment monitoring, and public safety maintenance. Numerous domestic studies have examined WSN technology, including volcano activity monitoring [~~1~~3], bridge and housing structure safety monitoring [~~2~~4], and drug production monitoring [~~3~~5]. Currently, WSN technology has matured, and its applicability to industrial environments has been verified [~~4~~6,22]. However, because related technology has only been developed for a short period, the benefits, stability, cost, and power storage of WSNs warrant investigation. Accordingly, the applications of WSN technology are not prevalent.

On the basis of the recent petrochemical plant leakage incidents that have led to fire disasters, the purpose of this paper is to utilize the advantages of WSN technology to improve the shortcomings of hydrogen sulfide detection systems used in petrochemical plants, thereby improving the industrial safety. Specifically, we propose a WSN-based system framework for detecting hydrogen sulfur, and a warning and notification system is included. This paper first introduces and discusses the current standard specifications of WSNs, including the advantages of IEEE 802.15.4/ZigBee[9,14,20,22]. Next, we introduce various types of gas detection modules and the proposed WSN and

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hydrogen sulfide detection system framework, which include the following components:

1) Hydrogen sulfide detector framework
2) ZigBee transmission module
3) Warning system software framework
4) Notification system framework

Finally, relevant conclusions are addressed.

Background

The petrochemical industry is essential to people's livelihood as it provides raw materials for various industries; hence, it plays an irreplaceable role in national economic growth and development. However, petrochemical manufacturing processes are complex and involve numerous types of equipment and rigorous parameter configuration; hence, an operating error can lead to severe disasters [8,13,18,19]. From raw material preparation to product manufacturing and finalization, the various nodes of a petrochemical production chain involve high levels of risk. Explosion and fire incidents in petrochemical plants can lead to severe financial losses, injuries, and deaths. Therefore, industrial safety and disaster preventive measures are highly crucial to the industry. The breakage of pressure vessels and transmission lines by corrosive materials is a profound problem of the petrochemical industry. In particular, sulfur stress cracking, hydrogen induced cracking, and stress corrosion cracking frequently lead to subsequent injuries and deaths, equipment breakage, production losses, and environmental pollution. Reaction mechanisms inducing these types of cracking vary substantially [10, 17, 22, 23].

Hydrogen sulfide is a common manufacturing gas that is colorless, highly toxic, and highly corrosive. Low-concentration hydrogen sulfide emits a preserved egg-like odor. Its specific gravity is 1.1895 and is heavier than that of air. Different concentrations of hydrogen sulfide incur dissimilar levels of damage to the human body. When the concentration reaches 4.3%–46%, an explosive compound can be formed. When the working temperature is lower than 93 °C, hydrogen sulfide is highly corrosive to metal seals, thereby easily inducing hydrogen embrittlement damage. This can lead to well pipe breakage and damage ground equipment, manifolds, meters, well equipment, resulting in blowouts and fire incidents. Therefore, toxic gases such as hydrogen sulfide must be controlled and monitored adequately to ensure the safety of operating personnel and the environment [10, 17, 21].

Currently, the domestic petrochemical industry mainly applies wired detectors to monitor toxic gases. Such detectors form systems that are highly reliable but feature several disadvantages:

1) The monitored area may limit and impede the installation of related wirelines.
2) The wirelines are fixed; hence, relocating the detectors is difficult.
3) The installation of the wirelines incurs excessive costs but provides few detection points, thereby ineffectively reflecting the overall gas leakage condition.
4) Excessive amounts of wirelines result in insufficient space allocation and impede the installation of new wirelines.

Figure 1. Existent Wired Detectors

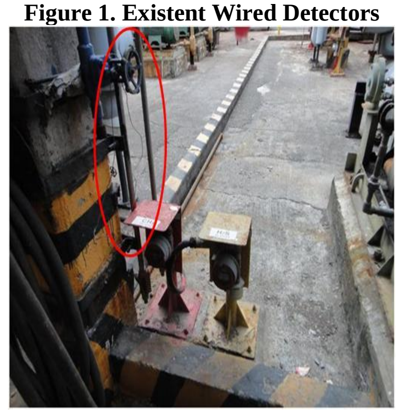

Figure 2. Existent Wired Detectors

Figure 1 illustrates that the amount of signal wires (orange wires) increases with increasing number of sensors and other equipment, resulting in insufficient space for installing new devices.

Figure 2 shows that the signal wires must be installed onto the surfaces tightly. This shortcoming in wire installation limits the locations feasible for sensor installation.

In addition to the inadequacy of the current detector hardware, the warning system software also features several deficiencies. Specifically, it lacks a comprehensive notification system; hence, when an abnormality occurs, only the on-site monitoring personnel is alerted about the incident, which can lead to disasters if the alert is overlooked by the personnel. Therefore, this paper employs the advantages of WSN technology to improve the shortcomings of the existent system and design a new system.

Introduction to IEEE802.15.4/Zigbee

Recently, the rapid advancement of micromanufacturing, communication, and embedding processing technology has enabled installing precision sensors, computation modules, and communication modules in microscale electronic devices featuring diverse functions. Such sensors can only detect environmental changes but also analyze the collected data. Moreover, a wireless communication function is adopted to transmit the data to the terminal server. In recent years, various research units and industrial personnel have recognized the prospect and applicability of such micro devices. In particular, micro WSNs have garnered the most attention. The hardware design of a sensor mainly focuses on its cost, volume, and energy consumption. Therefore, in a WSN, the power supply memory and computation function of each device node are constrained substantially. Accordingly, WSNs are perceived as a mission-oriented application.

Generally, a WSN framework involves deploying a large number of sensor nodes in the target area to collect various environmental data, which are then transmitted to the administrator or user through the wireless data collector. Because the sensors might be randomly distributed in the target area, the relative position of each sensor is unknown to the other sensors; hence, the WSN must adopt a self-organizing protocol to automatically organize a communication network among the sensors to facilitate data transmission to the wireless data collector through the established network [57].

Currently, the main protocol used in WSNs is ZigBee, which is formulated by the ZigBee Alliance of Honeywell International. The protocol was conceived in 1998, the bottom layer of which adopts the physical layer and medium access control (MAC) layer of IEEE 802.15.4. Zigbee [11] is advantageous for its low data rate, energy consumption, and cost. In addition to being simple, fast, reliable, and safe, it supports a high number of network nodes and multiple types of network topology.

A. Framework of IEEE 802.15.4/ZigBee

IEEE 802.15.4/ZigBee defines the physical layer and MAC layer for the low-rate wireless area personal network. ZigBee defines the network layer and application support sublayer above the IEEE 802.15.4 layer.

B. IEEE 802.15.4 topology

IEEE 802.15.4 only supports two types of basic network topology, namely the star topology and peer-to-pear topology. ZigBee further expands these two topology types to star, tree, and mesh types as shown in Figure 3.

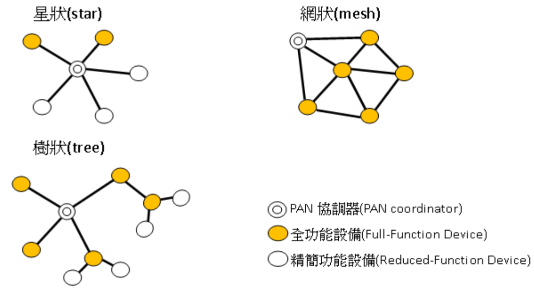

Figure 3. Types of topology supported by ZigBee

IEEE 802.15.4 defines the configurations of full-function devices (FFDs) and reduced-function devices (RFDs) in a network. In a star network topology, a ZigBee coordinator executes the initialization and maintenance of the FFDs and RFDs, whereas other devices (i.e., terminal devices) directly communicate with the ZigBee coordinator. In a mesh or tree network topology, a ZigBee coordinator is responsible for network establishment and key parameter selection; in addition, the network can be expanded through a ZigBee router. In a tree network topology, the FFD router employs a hierarchical routing strategy to transmit and control data.

C. Advantages of IEEE 802.15.4

The three common 2.4 GHz wireless communication specifications are compared as follows (Table1):

Table 1. Comparison of the 2.4 GHz Specifications

IEEE standard	802.11B	802.15.1	802.15.4
Technique alliance	Wi-Fi	Bluetooth	ZigBee
Frequency	2.4GHz	2.4GHz	2.4GHz
Modulation	CCK,PBCC	GFSK	O-QPSK
Communication distance	100m	10m	30m
Data rate	11Mbps	1Mbps	250Kbps
Network size	32nodes	7nodes	65536nodes
Stack size	1MB	250KB	16Kb~128KB
Battery life	Hours	Days	Years
Application	Wireless LAN	Audio	Measurement, control

Of the 2.4 GHz specifications, IEEE 802.15.4 is advantageous for its low communication speed, low energy consumption, low cost, and high network capacity; hence, it is more applicable to WSNs compared with other types of specifications.

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Introduction to Gas Sensor

A. Gas sensor component

Currently, common gas sensors are divided into various types according to their sensing principles and mechanisms:

- Catalytic combustion gas sensor
- Metal oxide semiconductor gas sensor
- Infrared sensor
- Liquid electrolyte gas sensor
- Field effect transistor senor

1. Catalytic combustion gas sensor

This type of electrochemical gas sensor detects the changes in the interelectrode current or differences in the ion concentration of the electrolyte induced by the electrochemical reaction between the gas sample and electrolyte.

2. Metal oxide semiconductor gas sensor

This type of sensor is mainly assembled with a tin oxide n-shaped semiconductor and heater. Such a sensor features a fine stainless steel mesh for facilitating rapid heat transduction and preventing gas explosion. The internal heater of the sensor attains a temperature between 200 and 300 °C. When placed in a clean air environment, the heater adsorbs the negatively charged oxygen molecules in the air to decrease the electron density of the semiconductor, thereby increasing the electrical resistance. When the heater adsorbs reducing gases (e.g., liquid gases, natural gases, hydrogen gas, and carbon monoxide), the adsorbed oxygen molecules are released, and the reducing gas molecules that are positively-charged are adsorbed to the surface of the metal oxide semiconductor. Because electrons are released through deoxygenation and adsorption of reducing gas molecules, the electron density of the oxide semiconductor increases, thereby decreasing the electrical resistance and increasing the electrical conductivity. When the heater is subjected to clean air again, the metal oxide semiconductor automatically adsorbs the negatively charged oxygen molecules, returning the electrical resistance and electrical conductivity to the initial levels. Accordingly, the changes in the electrical conductivity enable measuring the changes in the output voltage to determine the concentration of the gas sample.

3. Infrared gas sensor

This type of gas sensor employs a sensor component that is preheated to 300–400 °C under a charged condition, thus heating and oxidizing the gas sample on the component surface. This approach is known as direct contact combustion gas sensing. Conversely, a catalyst can be used to heat and oxidize the gas sample on the component surface, hence the name catalytic combustion gas sensing. The heated component surface undergoes changes in its electrical resistance. Therefore, the difference in the resistance value or current value can be calculated to determine the gas sample concentration.

Table 2. Comparison of the Gas Sensor Types

Detect technique	Detect gas	Disadvantages	Advantages
Catalytic combustion gas sensor:	Flammable gas	High temperature, unstable	Linearity signal output, insensitive
Metal oxide semiconductor gas sensor:	Toxic and flammable gas	High temperature, unstable, slow response time	Repeatable, reliable, long lifetime, anticorrodent, quickly recovery(about 8 min.
Infrared gas sensor	CO2, CH4, and hydrocarbon	Humidity sensitive, high cost, larger size	Linearity signal output, pervasively apply in environment and industrial detection
Electrochemical gas sensor:	O3, O2, CO, SO2, NO, NO2, H2, CN, H2S, Cl2, HCl, CCl4, COCl2,NH3, PH3, H2 soluble and ionizable chemical compound	Need to resupply electrolyte and septum, short life time	Small size, low power, and Linearity signal output
Field effect transistor sensor	NO, NH	Long recovery (need heated to 200℃, about 1Hr)	Room temperature, low latency (2~10sec), small size, low cost, sensitive

4. Electrochemical gas sensor

Because gases exhibit dissimilar capabilities in absorbing infrared light, this type of sensor uses this characteristic to measure the concentration signals of gas samples. A

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noncontact approach is used to determine gas concentrations, in particular pollutants such as carbon monoxide and carbon dioxide.

5. Field effect transistor sensor

This type of sensor is assembled through a two-electrode or three-electrode chemical sensor manufacturing technique and can be used to analyze highly volatile organic compounds. When a volatile organic compound contacts and reacts with a metal that can be catalyzed, the reaction product changes the electrical property of the sensor through transistor gate diffusion.

The characteristics, advantages, and disadvantages of the aforementioned gas sensor types are compared as Table 2.

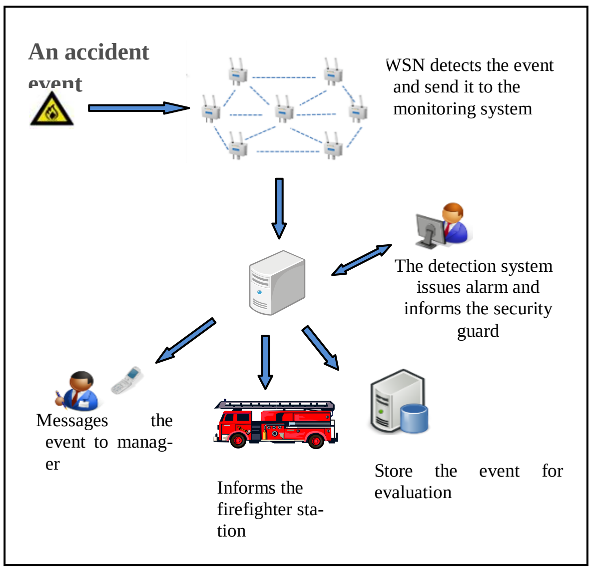

Figure 4. Functions of the Proposed Monitoring and Warning Notification System Framework

Overall, the semiconductor sensor is advantageous for its low cost and high durability. Therefore, this type of sensor is prevalently applied to detect combustible gases and carbon monoxide. However, it has yet to be adopted by portable gas analyzers because of its high energy consumption. In addition, each semiconductor sensor exhibits distinctive characteristics, and its temperature-dependent analysis results cannot be adjusted easily. Therefore, applying such sensors to portable analyzers involves additional variables and energy-consumption problems.

System Framework

A. System framework

A hydrogen sulfide sensor is coordinated with the ZigBee communication module and a back-end computer system to design a monitoring system. In addition, the local network of a petrochemical plant is adopted to establish a notification system for the industrial safety department of the plant. The system notifies the relevant personnel when a hydrogen sulfide leakage is detected. Furthermore, when the leakage warning lasts for an extensive period, the system automatically sends online messages to relevant authorities and employs the remote connection function of the local network to notify the fire department and industrial safety authority. Sent messages and sensing data are also stored in the database of the monitoring computer to conduct subsequent analyses. Through this system framework, we envision to improve the existent warning system. The proposed system framework is illustrated as Figure 4.

Hardware and network framework

The system hardware is divided into three components, namely 1) hydrogen sulfide sensor module, 2) ZB2530-01 ZigBee communication module, and 3) back-end monitoring computer. The hardware framework is described as Figure 5.

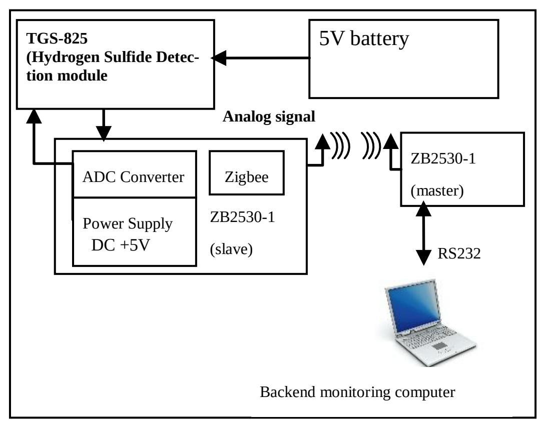

Figure 5. Hardware framework

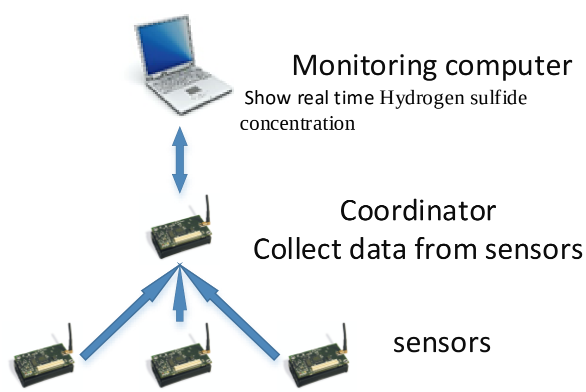

Figure 6. Framework of the Sensing Node Network

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1. Node network framework

To increase the reliability of the system hardware and prevent the failure of a single node and relevant measurement errors, we place three sensor modules and three transmission modules in the same area. This also enables evaluating the accuracy of the sensor module in measuring hydrogen sulfide concentration. The data collected by the three sensor modules are sent to a coordinator node, which then transmit the data to the back-end computer through RS232 as a transmission medium. The node network framework is depicted as Figure 6.

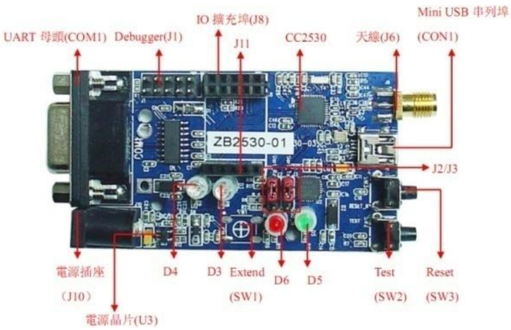

Figure 7.CC2350 Board

2. Communication module

The network involves the ZigBee communication module ZB2530-01 developed by DMATEK. This module adopts the latest Texas Instruments CC2530 ZigBee standard chip[, which is applicable to 2.4 GHz, IEEE 802.15.4, ZigBee, and RF4CE specifications. The chip also includes an excellent one-hop radio frequency transceiver, an enhanced industrial-standard 8051 MCU microcontroller, coding flesh memory, 8 kB RAM, and various other functions; hence, it is prevalently applied to 2.4-GHz IEEE 802.15.4 systems, RF4CE control systems, and ZigBee systems in various domains, including family/hospital/building automation, industrial control, measurement, and monitoring, and low energy-consumption WSNs. The J8 input/output (I/O) connector on the ZB2530-01 module captures the signal of the CC2530 chip (as shown in Figure 7.) by linking to the I/O port of the chip. The external circuit is connected with the I/O connector to input analog signals, which are converted to digital signals through the analog-to-digital convertor (ADC) of the CC2530. The digital signals are then transmitted to other devices. The communication module board also features a J11 power connector port to provide 5 V of power to the sensor module.

3. Sensor module

The hydrogen sulfide sensor component TGS-825 developed by Figaro is applied. TGS-825 is a highly sensitive hydrogen sulfide sensor component with a tin oxide semiconductor unit. The lowest threshold concentration is 5 ppm; hence, it is feasible for gas leakage detection. The relative concentration of hydrogen sulfide in air changes the internal resistance of the semiconductor. A sensitivity characteristic curve is plotted [~~10~~12] to determine the internal resistance value with respect to various hydrogen sulfide concentrations in the ambient air.

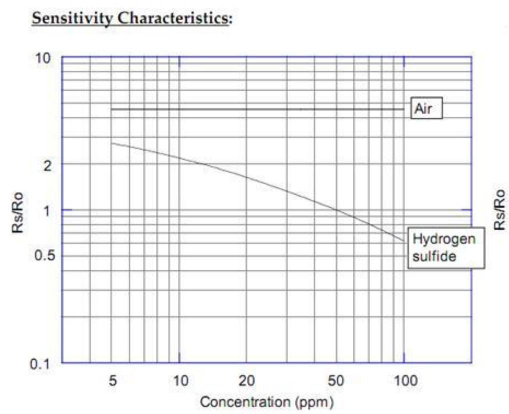

Figure 8. Hydrogen Sulfide Concentration Characteristic Curve of TGS-825

Although the characteristic curve of each Figaro module is identical, its initial internal resistance value varies. Therefore, the internal resistance of the module must be first measured in a clean air environment, and then the characteristic curve is employed to derive the relationship between the internal resistance value and hydrogen sulfide concentration. This enables determining the actual hydrogen sulfide concentration reflected by the internal resistance value of the module in the actual test environment. A preheating heater voltage of 5 V should be provided to ensure the adequate operation of the module. In addition, a load voltage should be provided. The output voltage data of TGS-825 are transmitted as analog signals; hence, the CC2530 ADC is used to convert them to digital signals. Because the maximum input voltage of the CC2530 ADC Vin is 3.6 V, the output voltage of TGS-825 must be lower than 3.6 V.

According to the characteristic of the sensor module, the voltage divider rule is used to control the output voltage to be <3.6 V. When the hydrogen sulfide concentration is higher than 10 ppm, a comparator enables sounding a warning alert through a buzzer. The output port of TGS-825 is connected to the CC2530 ADC port to configure the input circuit of the ZigBee communication module.

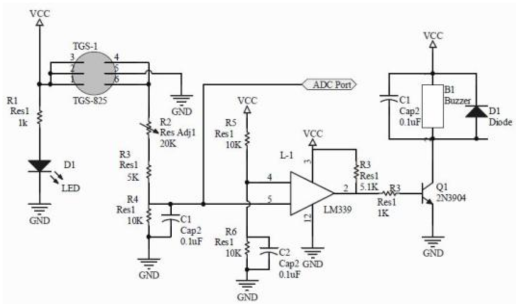

Figure 9. Circuit of the Sensor Module

The voltage divider of the TGS-825[12] component can adjust the output voltage according to the varying characteristics of each TGS-825, thus conforming to the voltage constraint of the CC253 ADC. The LM339 IC comparator is employed to compare the output signal of TGS-825. When the output voltage is higher than the preset voltage, the switch circuit consisting an NPN transistor activates the buzzer to sound the alert. Figure 10 shows the sensor module assembled by connecting relevant components to the circuit board.

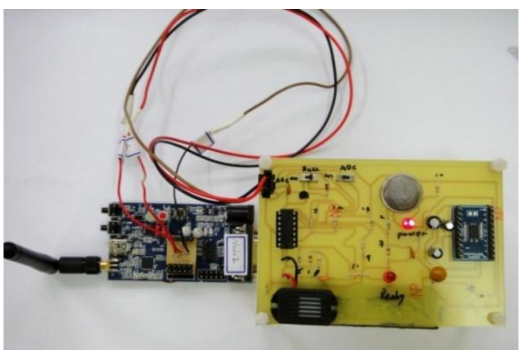

Figure 10. Circuit of the Proposed Gas Sensor

4. Back-end monitoring computer

The main function of the back-end monitoring computer is to receive the signals transmitted from the ZigBee module, and a program is used to monitor the hydrogen sulfide concentration and notify relevant personnel through the Internet. The program is designed using Visual Basic 2005 and features the following functions:

- Concentration warning alert and concentration trend diagram
- Alert record and concentration measurement database
- Remote connection monitoring and warning
- Automated sign in for sending web messages

Figure 11. Sensor Node Status Display

As shown in Figure 11, when an alert occurs, the status display shows the alert message, incident time, and node number, and the alarm is sounded. The relative position diagram of the equipment and nodes can be used to determine the actual position of the alerted node. The buttons displayed on the right are described as follows:

- Alert confirmation/cancel
- Trend diagram of the measurement values of a node
- Alert record

The trend diagram (displayed as a curve) can be used to observe the changes in gas concentration. Pointing the mouse to the curve enables observing the concentration at each time period, as shown in Figure 12.

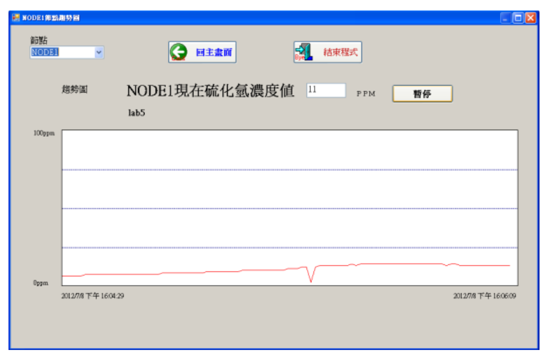

Figure 12. Trend Diagram of a Monitored Node

Conclusion

This paper aims to improve the shortcomings of the existent wired sensor system through a WSN approach. However, gas sensor components are faced with the problem of insufficient battery life in practice. This problem is attributable to the semiconductor component of the sensor, which detects gas concentrations through voltage heating;

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the power consumption rate is approximately 660 mW/h. Therefore, a regular lithium battery (200 mA/h) can only power the sensor for less than 100 hours. Moreover, semiconductor sensor component is likely to be affected by the interference of other organic gases during the detection process, leading to notable disadvantages in practice. Although senor components of different working principles can be applied to mitigate these shortcomings, the resulting effect might be undesirable. For example, the data regarding the working properties of electrochemical sensor component can be difficult to obtain; hence, applying such components to gas sensors cannot extend the battery life effectively. Therefore, we employ a semiconductor approach to assemble the proposed WSN-based senor system. Regarding the applications of ZigBee for detecting toxic or combustible gasses, designing such applications should focus on not only improving the detection accuracy but also enabling an energy-saving measurement approach to extend the battery life. In addition, other types of power recharge method can be employed, such as solar energy.

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