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Wireless Sensing System for Flexible Arrayed Potentiometric Sensor Based on XBee Module

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***Abstract*—In this study, the wireless sensor network (WSN) with ZigBee standard is integrated with the flexible arrayed potentiometric sensor such as flexible arrayed pH sensor and flexible arrayed glucose biosensor that achieve a wireless sensing system. The wireless sensing system is accomplished by the graphical language laboratory virtual instrumentation engineering workbench (LabVIEW) and the detection signals are displayed in real-time in the computer. Potentiometric electrochemical method is used to measure the output signal of potential difference between silver/silver chloride (Ag/AgCl) reference electrode and the flexible arrayed potentiometric sensor. We provide a wireless sensing system of XBee module, which has advantages of low cost, easy operation, portable device, high accuracy, real-time monitoring, and rapid detection. According to the experimental results of flexible arrayed pH sensor and flexible arrayed glucose biosensor, the range of pH values from pH 1 to pH 13 has good average sensitivity 51.38 mV/pH and linearity 0.995, and the range of glucose solution concentration from 100 mg/dL to 500 mg/dL has good average sensitivity 0.179 mV$(mg/dL)^{-1}$ and linearity 0.999. The actual target in this study is to provide a wireless sensing system for ion sensing and monitoring of human physiological data.**

***Index Terms*—Wireless sensor network, ZigBee, pH sensor, glucose biosensor, wireless sensing system, LabVIEW**

I. Introduction

Developed countries have a common problem that is aging society. The problem not only changes the population structure but accelerates the healthcare services which toward to treat the chronic diseases. The common chronic diseases include hypertension, diabetes, heart failure, etc. It is important issue that early detection and prevention can reduce the cost of medical treatment. The technologies of wireless sensor network (WSN) have the potential to change the way of living with many applications. The WSN is consisted of network nodes with sensors, which are designed to communicate via wireless radio. The recent development of WSN provides the advantages of low cost, low power consumption, small size, flexibility, and distributed intelligence that is compared with wired ones [1]. Some sensors are combined with WSN that have been widely used in various applications. According to the health applications for WSN are provided with diagnostics, disability patient, patient monitoring, and remote healthcare of human physiological data [2-8]. The monitored signals include heart rate (HR), electrocardiogram (ECG), blood glucose, and activity for ambulatory health monitoring. Literature [9], a wearable healthcare system was integrated with WSN for detecting falls of an elder person. The healthcare system could reduce the cost of medical care, and improved primary care services. The application of intelligent life was proposed in literature [10]. This literature developed a smart medication system which utilized the WSN technique. The functions of medication system were medication reminding, pill-dispensing assisting, and medication recording. The market of remote monitoring in United States of America (U.S.A.) is described two categories that are home healthcare and disease management, the common and typical application of home healthcare is elderly people. The disease management is focused on monitoring services of disease.

In recent years, the WSN is integrated for some sensors or biosensors to measure and provides a monitoring tool based on physiological parameter. In a common WSN architecture, the measurement nodes are deployed to acquire measurements such as temperature, voltage, or current. J. F. Cheng et al. [11] developed a multi-ions sensing system includes pH, potassium, sodium, and chloride ion sensors with a wireless homecare system. Syed M. Usman Ali et al. [12] presented a prototype wireless remote glucose monitoring system. The glucose sensor with glucose oxidase enzyme was immobilized onto ZnO nanowires in conjunction with a Nafion membrane coating, which could be effectively applied for the monitoring of glucose levels in diabetics. Sérgio Silva et al. [13] presented a Bluetooth prototype low power battery-less wireless sensor communication system capable transmitting the information to a mobile phone or wrist wireless phone. Wen Tsai Sung et al. [14] presented multiple physiological signals collection and analysis processing based on neural network methods and evidence theory using wireless XBee devices.

We provide a wireless sensing system of XBee module has advantages of low cost, easy operation, portable device, high stability, real-time monitoring, and rapid detection. The wireless sensing system is integrated with the flexible arrayed

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potentiometric sensor such as flexible arrayed pH sensor and flexible arrayed glucose biosensor. The wireless sensing system is accomplished by the graphical language laboratory virtual instrumentation engineering workbench (LabVIEW, National Instruments Corp., U.S.A.) and the detection signals are displayed in real-time in the computer.

II. Description of Sensing System

The flexible arrayed pH sensor and flexible arrayed glucose biosensor are based on polyethylene terephthalate (PET) substrate, and using the radio frequency (R.F.) sputtering system to deposit ruthenium oxide (RuO_2) as the sensing film. The conductive silver paste is coated as conductive wire and epoxy paste is coated as insulation layer by semi-automatic screen printer. A readout circuit device is composed of six instrumentation amplifiers AD623. Furthermore, the wireless sensing system is achieved by XBee module and graphical language LabVIEW.

A. Fabrication of RuO_2 film

The gun of R.F. sputtering system is set a ruthenium target and the power of power generator is kept at 100W. Then, the argon gas (40 sccm) and oxygen (20 sccm) are introduced into the chamber, respectively, and the distance of ruthenium target and substrate is 50 mm. The RuO_2 film is deposited for 5 minute under the working pressure of 1×10^{-2} torr. The temperature of depositing substrate is controlled at 25 ℃. The deposition parameters of RuO_2 film have described in previous literature [15].

B. Fabrication of conductive wire and insulation layer

The screen-printed technique is used to coat conductive wire and insulation layer that connect RuO_2 film on PET substrate. The fabrication processes have described in previous literature [15]. The top view of finished flexible arrayed pH sensor is shown in Fig. 1.

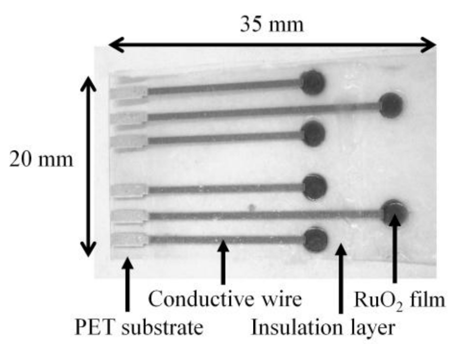

Fig. 1. Top view of finished flexible arrayed pH sensor.

C. Fabrication of glucose sensing membrane

The flexible arrayed pH sensor is washed by using deionized water that cleans the immobilization area. The glucose oxidase (GO_X) powder of 3 mg is premixed with phosphate buffer saline of 5 ml as glucose oxidase solution, and then the 5 wt% Nafion solution and glucose oxidase solution are mixed by the chemical solution method, after compositing the solution of 3 ul is dropped on RuO_2 films. The glucose sensing membrane is prepared by an optimal mixed volume ratio of 3:4 (vol %) with Nafion and glucose oxidase solution. The optimal mixed volume ratio has investigated in previous literature [16]. After the enzyme immobilization, the flexible arrayed glucose biosensor is stored at 4 ℃ in a refrigerator for 12 hours. The schematic diagram of cross-section for flexible arrayed glucose biosensor is shown in Fig. 2 [15].

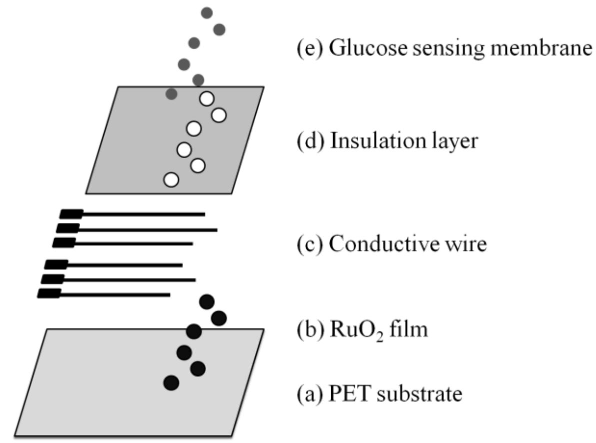

Fig. 2. Schematic diagram of cross-section for flexible arrayed glucose biosensor [15].

D. Fabrication and structure description of wireless sensing system

The wireless sensing device, which has low cost, real-time measurement and easy operation are needed, so the wireless sensing system is composed of Arduino Mega 2560, XBee module and readout circuit device. Arduino Mega 2560 is a microcontroller board based on the ATmega 2560 (Atmel Corporation) that is utilized to process the detection signals and provide power. The power supply supplies 9 V into Arduino Mega 2560 that the output voltages of Arduino Mega 2560 provide operating voltage for XBee router and readout circuit device are 3.3 V and 5 V, respectively. Arduino Mega 2560 has 54 digital input/output pins, 16 analog inputs, 4 universal asynchronous receiver transmitter (UARTs), a 16 MHz crystal oscillator, an universal serial bus (USB) connection, a power jack, an in circuit serial programming (ICSP) header, and a reset button. It contains everything are needed to support by the microcontroller, simply connect it to a computer with a USB cable. The power provides with an alternating current to direct current adapter or battery to start.

The cost of ZigBee is cheaper than other wireless techniques such as Bluetooth and Wi-Fi. Bluetooth and Wi-Fi are high power consumption and the topology based on star topology, which is difficult to be expanded. ZigBee is designed as a low power, low cost, low speed solution [17], and has many benefits over Bluetooth. ZigBee is an alliance of companies and also maintain the name of a standard by that alliance. The network layer below ZigBee is known as IEEE 802.15.4 that supports it advanced features. ZigBee is a set of standards that define power management, addressing, error correction, message formats, and other point-to-point specifics

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necessary for proper communication to take place from one radio to another [18]. IEEE 802.15.4 is an IEEE standard for low-power digital radios that are implemented in products such as the inexpensive and practical XBee module: XBee Series 2 (Digi International, U.S.A.). In this study, XBee module consists of XBee coordinator and XBee router. XBee router is responsible to connect with Arduino Mega 2560; moreover, it transmits detection signals to XBee coordinator. XBee coordinator is linked with computer, and furthermore it receives the detection signals from XBee router and display detection signals in computer by graphical language LabVIEW. The diagram of actual devices of XBee module is shown in Fig. 3. XBee module is simple and easy operation. The connected pins of XBee router use pin 1, pin 2, pin 3, and pin 10. The pin 1 and pin 10 are connected 3.3 V and 0 V to Arduino Mega 2650, respectively. The UART is a piece of computer hardware that translates data between parallel and serial forms. The pin 2 transmits the information can be called UART data out, and furthermore it is connected Arduino Mega 2650 with serial 0 pin. The pin 3 receives the information can be called UART data in, and furthermore it is connected Arduino Mega 2650 with serial 1 pin. The description of XBee router pins is shown in Table I.

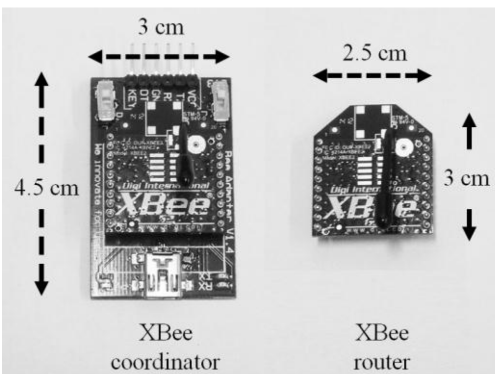

Fig. 3. Actual devices of XBee module.

TABLE I
DESCRIPTION OF XBEE ROUTER PINS

Pin number	Name(s)	Description
1	VCC	3.3 V power supply
2	DOUT	UART data out
3	DIN	UART data in
10	GND	Ground

The readout circuit device is composed of six instrumentation amplifiers AD623 (Analog Devices, Inc., U.S.A.), which only need single external source (3 V to 12 V) to operate, and it is applicable with Arduino Mega 2560. Each sensing window is installed an instrumentation amplifier AD623. According to the description of data sheet that instrumentation amplifier AD623 can decrease the dimension of device and it is easy to fabricate portable device. The instrumentation amplifier AD623 is an integrated single supply instrumentation amplifier. In Fig. 4, the descriptions of input and output pins are as follows. The second pin (−IN) of AD623 is connected with flexible arrayed potentiometric sensor such as flexible arrayed pH sensor or flexible arrayed glucose biosensor. The silver/silver chloride (Ag/AgCl) reference electrode is connected to ground at the third pin (+IN). The fourth pin ($-V_S$) is grounded, and the fifth pin (REF) is connected to an appropriate voltage. At the same time, the sixth pin (OUTPUT) is connected to the analog input pin of Arduino Mega 2560. Furthermore, the output signal appears the potential difference between the sixth pin (OUTPUT) and the fifth pin (REF). The power supply of AD623 is supplied 5V at the seventh pin ($+V_S$). The gain of AD623 is programmed by resistor in the first pin ($+R_G$) and the eighth pin ($-R_G$) and then set the unity gain (G = 1). The Electrical schema of readout circuit device is shown in Fig. 5. The actual installation of wireless sensing system is shown in Fig. 6.

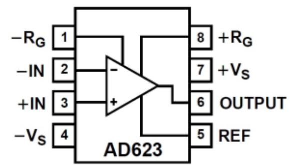

Fig. 4. Top view of instrumentation amplifier AD623.

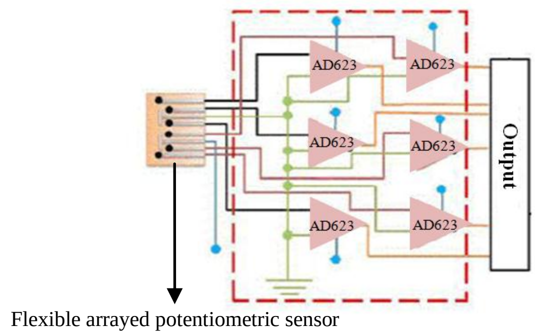

Fig. 5. Electrical schema of readout circuit device for flexible arrayed potentiometric sensor.

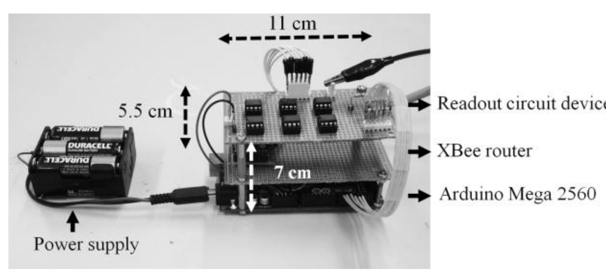

Fig. 6. Actual installation of wireless sensing system for flexible arrayed potentiometric sensor.

E. Description of graphical language LabVIEW

The graphical language LabVIEW is a kind of program language that is a method of graphic design to replace the traditional text program function. This study utilizes the graphical language LabVIEW to implement the wireless sensing system. Before running graphical language LabVIEW, the wireless sensing system should be installed and should connect with flexible arrayed potentiometric sensor and Ag/AgCl reference electrode. The operation of wireless sensing

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system is shown in Fig. 7. Fig. 8 shows the user interface of front panel on graphical language LabVIEW. At the beginning, we select the base path and key in the name of file. Then we set the measurement times of wireless sensing system.

III. Results and Discussion

A. Analysis of flexible arrayed pH sensor

In this study, we fabricate the flexible arrayed pH sensor to detect pH value, and it is integrated with the wireless sensing system. The detection signals are processed and are transmitted in real-time and then are displayed in the computer. The pH detection is measured in buffer solutions, and the environment temperature is controlled at room temperature 25 ℃. The volume of pH buffer solutions is about 25 ml to 30 ml.

The wireless sensing system is operated normally and the measurement times are 60. The detection signals are displayed per 2.5 seconds, which are controlled via the program of Arduino Mega 2560. We operate in different pH buffer solutions for pH 1 to pH 13 and the interval is two pH values. The optimum detection results are shown in Fig. 9. The average sensitivity and linearity of flexible arrayed pH sensor are 51.38 mV/pH and 0.995, respectively. Then the error bars of response voltage with pH 1, pH 3, pH 5, pH 7, pH 9, pH 11, and pH 13 are 20.1 mV, 21.8 mV, 27.7 mV, 31.4 mV, 32.6 mV, 23.1 mV, and 18.1 mV, respectively.

The flexible arrayed pH sensor was a potentiometric sensor, so the Fig. 9 was the detection results of response voltage-pH value. According to Nernst equation, the voltage difference of the electrode interface was attributed to the reaction of the analyte with the sensing electrode, which would accumulate ion onto the interface of the electrode. The Nernst equation was expressed as Eq. (1) [19].

$$E = E^0 - 2.303\frac{RT}{F}pH = E^0 - 0.05916\,pH \ldots\ldots(1)$$

where E^0 is the reference electrode potential, R is the gas constant, T is absolute temperature, and F is Faraday's constant. The entire term (2.303 RT)/F is called the Nernst slope, and the ideal value was 59.16 mV/pH at 25 ℃.

B. Analysis of flexible arrayed glucose biosensor

In this study, we fabricate the flexible arrayed glucose biosensor to detect concentration of glucose, and it is integrated with the wireless sensing system. The detection signals are processed and are transmitted in real-time and then are displayed in the computer. The flexible arrayed glucose biosensor is measured in glucose solutions, and the environment temperature is controlled at room temperature 25 ℃. The volume of glucose solution is about 25 ml to 30 ml. Fig. 10 shows optimum detection results of average sensitivity of flexible arrayed glucose biosensor is 0.179 $mV(mg/dL)^{-1}$ and the linearity is 0.999. The linear range is between 100 mg/dL and 500 mg/dL. The average response voltages with 100 mg/dL, 200 mg/dL, 300 mg/dL, 400 mg/dL and 500 mg/dL are about 2221.5 mV, 2204.5 mV, 2187.2 mV, 2168.5 mV, and 2149.3 mV, respectively.

From the equations (2)-(3) [20], the glucose and GOx would react and generated the H^+ ions. The different amounts of H^+ ions were generated in the different glucose concentrations. Therefore, the glucose concentration could be detected via electrochemical detection of the enzymatically released H^+.

$$H_2O+O_2+\beta\text{-D-glucose} \xrightarrow{\text{GOx}} \delta\text{-gluconolactone} + H_2O_2 \ldots\ldots (2)$$

$$\delta\text{-Gluconolactone} \xrightarrow{\text{spontaneous}} \text{gluconate}^- + H^+ \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The error bars of response voltage with 100 mg/dL, 200 mg/dL, 300 mg/dL, 400 mg/dL, and 500 mg/dL are 20.25 mV, 21.75 mV, 16.42 mV, 23.25 mV, and 25.67 mV, respectively. The error bars are around 20mV. The sources of error are perhaps the stability of glucose sensing membrane and frequency of use of flexible arrayed glucose biosensor.

C. Achievement of wireless sensing system

The detection results show the proposed wireless sensing system is successfully used to measure pH value and concentration of glucose that obtain good sensitivity and linearity. At the same time, the wireless sensing system is stable to operate. In addition, parameters of wireless sensing system are compared to similar studies [11, 21, 22]. The comparison is shown in Table II.

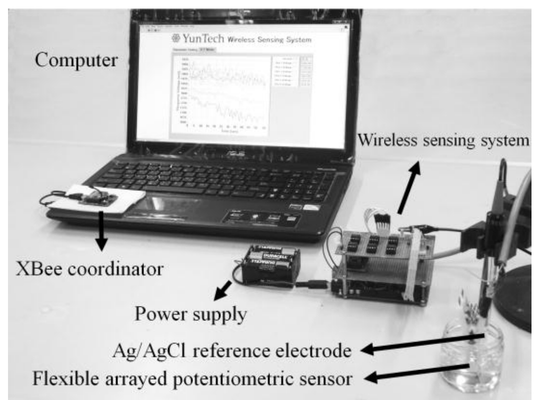

Fig. 7. Prototype of wireless sensing system for flexible arrayed potentiometric sensor.

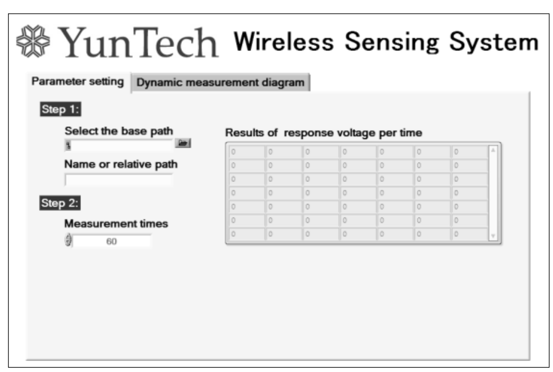

Fig. 8. Diagram of front panel on graphical language LabVIEW.

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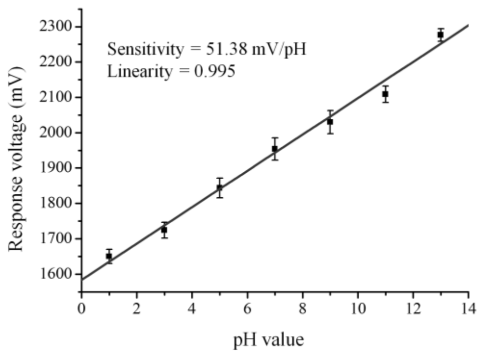

Fig. 9. Detection results with flexible arrayed pH sensor.

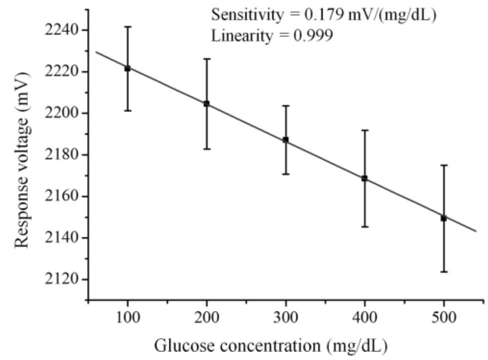

Fig. 10. Detection results with flexible arrayed glucose biosensor.

TABLE II
WIRELESS SENSING SYSTEM IN THIS STUDY IS COMPARED WITH OTHER LITERATURES [11, 21, 22]

References	In this study	[11] (2012)	[21] (2011)	[22] (2009)
Sensor substrate	RuO_2/PET	Tin oxide (SnO_2)/ indium tin oxide (ITO) glass	CMOS ISFET readout circuit	RuO_2/PET
Sensor window style	Arrayed	Single	Single	Single
Method of transmission, Communication port	ZigBee, USB	Bluetooth, RS-232	2.4GHz wireless transceiver, RS-232	Bluetooth, USB DAQ
A/D resolution	10 bits	10 bits	10 bits	12 bits
Transmission distance	120 m	100 m	–	short-range communication
Analytical apparatus	LabVIEW	LabVIEW	ASCII coding	LabVIEW
Application	pH, Glucose	pH, Potassium, Sodium, Chloride	pH, Temperature, Chlorine	pH, Uric acid, Glucose
Power supply	5 V	–	3 V	± 5 V
pH range	pH 1 – 13	pH 2 – 12	pH 4 – 10	pH 1 – 13
Sensitivity (mV/pH)	51.38	58.00	–	50.27
Linearity	0.995	0.993	–	0.993
Glucose linear range (mg/dL)	100-500	–	–	40-360
Sensitivity $(mV(mg/dL)^{-1})$	0.179	–	–	0.384
Linearity	0.999	–	–	≒0.954

–: The sign implies that the characteristics are not studied or not described in the literature.

Literature [21] provided single sensor and residual chlorine meter, and furthermore literatures [11, 22] provided single sensor and coated selective membrane as biosensors for many applications that above sensors are effective in wireless sensing. However, in this study, the wireless sensing system combined with arrayed sensor. Arrayed sensor can reduce differences of fabrication that offers more accurate and stable measurement. Arrayed sensor is suitable to reduce inaccuracy of detection. The research of data fusion for arrayed sensor has been studied in literature [23]. In this study, flexible arrayed pH sensor and flexible arrayed glucose biosensor have good average sensitivity and linearity that approach literature [22]. The flexible arrayed glucose biosensor is successfully detected although the error bars of response voltage have some range that can improve through replacing expiring materials, process of production, and enzyme immobilization. Literature [22] has good sensitivity of glucose sensor however the linearity has deviation that relative to the linearity is 0.999.

Graphical language LabVIEW is useful that for processing detection signals and monitoring in real-time. In addition, the graphical language LabVIEW is more simple and flexible than literature [21]. The graphical language LabVIEW is easily customized and controlled for different sensor devices. Universal serial bus (USB) is a universal technology of industry standard that is easily used in a bus for connection, communication, and power supply for electronic devices. In this study, XBee coordinator conveniently connects in USB to the computer. XBee module is easily operated that accomplishes a wireless sensing system. Literature [22] provided measurement system interface was executed at the local site on a personal computer with a data acquisition (DAQ, NI 6008, National Instruments Corp., U.S.A.) card. The measurement signals were processed in wired devices, and then appeared a remote site via an internet http service and used Bluetooth technology, which ran between a HP PDA and a personal computer. Literature [22] the method of wireless sensing is different from this study that we improve a system, which suitable in portable wireless sensing.

The cost, power supply, and dimension are the three chief considerations of portable device in wireless sensing system.

We spend around US$110 to make an economical wireless sensing system for the flexible arrayed potentiometric sensor. In addition, we fabricate a 9 V power supply into Arduino Mega 2560, which outputs steady 5 V to instrumentation amplifier AD623s. The transmission power output of XBee module is 2 mW. AD623 is an integrated single supply instrumentation amplifier that can decrease the dimension of device and it is easy to fabricate portable device. In this study, we provide a wireless sensing system has a length of 11 cm, a width of 5.5 cm, and a height of 7 cm. The dimension does not contains the 9 V power supply.

D. Transmission distance and stability of XBee module

We test the transmission distance of XBee module and observe that how long can transmit without failure. We use the long corridor without interference to test the transmission distance. XBee module can be divided XBee router and XBee coordinator. XBee router can get the detection signals from Arduino Mega 2560. Furthermore, XBee coordinator can receive the detection signals from XBee router and displays the results of response voltage in CoolTerm software in computer. CoolTerm software is a simple serial port terminal application that needs to exchange data with hardware connected to serial ports. We fix the position of XBee router and then we slowly move XBee coordinator. At the same time, we observe the results of response voltage in CoolTerm software, and then whether the detection signals miss by XBee coordinator. In the experiment, six response voltages are displayed in operation interface of CoolTerm software from XBee router per 2.5 seconds. The response voltages are corresponded to six sensing windows of flexible arrayed pH sensor. According to the calculation, the direct transmission distance of XBee device is up 70 meters.

We test the stability of XBee module, and the results are shown in Fig. 11. We assemble the wireless sensing system with flexible arrayed pH sensor in pH 13 buffer solution. The measurement times are 120, and the interval between detection results is 2.5 seconds. In the experimental process without failure, the curves of response voltage are stable and average response voltage is around 2300 mV.

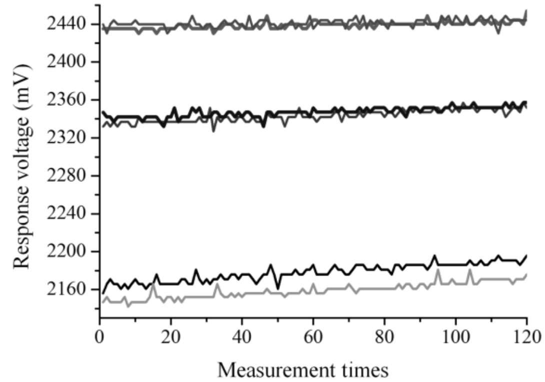

Fig. 11. Results of testing stability of XBee module.

E. Reproducibility and storage stability of flexible arrayed glucose biosensor

The reproducibility and storage stability of proposed flexible arrayed glucose biosensor have been studied in our research group. The lifetime of flexible arrayed glucose biosensor is affected by the number of uses, acid or alkaline environment in test solution, the temperature in test solution, and the storage environment et al. The lifetime of flexible arrayed glucose biosensor is measured in different concentrations of glucose solution from 100 mg/dL to 500 mg/dL per 7 days. After using, the flexible arrayed glucose biosensor is preserved in 4 ℃ and the measurement time is 30 days. The sensing characteristic of sensitivity of flexible arrayed glucose biosensor is kept about 78.0 % after 30 days. The analysis of measurement results and comparison are shown in Table III.

The main objective of reproducibility and stability is that the glucose biosensor is repeatedly used over a long period. The proposed glucose biosensor has been studied in literature [24]. The glucose biosensor is stored dry at 4 ℃ and measured at intervals of 1 week, and it remained about 75 % of the original sensitivity after 5 weeks. Literature [25] has evaluated the stability of glucose biosensor, which is stored at 4 ℃. The storage stability of glucose biosensor is tested by monitoring the response currents in 0.2 mM glucose concentration over 20 days. The optimum experimental result of literature [25] is the activity of the electrode remained about 83% that contrast the initial current response, after the storage periods of 10 days.

TABLE III
LIFETIME OF FLEXIBLE ARRAYED GLUCOSE BIOSENSOR IN OUR RESEARCH GROUP IS COMPARED WITH OTHER LITERATURES [24-26]

Sensing membrane	Measurement method	Measurement range	Lifetime (day) / maintainable proportion	References
RuO_2	Potentiometric	5.5 mM – 22.2 mM	30 / 78.0%	In our research group
Gold nanoparticles biocomposite	Amperometric	5.0 μM – 2.4 mM	35 / 75.0%	[24]
Silver nanowire	Amperometric	10.0 μM – 0.8 mM	10 / 83.0%	[25]
Woodceramics	Amperometric	0.5 mM – 7.0 mM	30 / 72.4%	[26]

Literature [26], the long-term stability of the glucose biosensor is studied by amperometric detection of 5 mM glucose solution every 2 or 3 days over a month. The glucose biosensor retains about 72.4 % of its initial response after 30 days. Although the maintainable proportion of glucose biosensor of literature [25] has been retained 83.0 % for 10 days, further the characteristic of glucose biosensor should be shown over 10 days whether its keeps superior proportion. We compare other literatures to demonstrate the proposed flexible arrayed glucose biosensor has excellent stability for long-term use.

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IV. Conclusion

In this study, we provide a wireless sensing system for ion sensing and monitoring especially for flexible arrayed potentiometric sensor such as flexible arrayed pH sensor and flexible arrayed glucose biosensor. According to the results of experiment, wireless sensing system of XBee module has advantages of low cost, easy operation, portable device, high stability, real-time monitoring, and rapid detection. In addition, we describe the wireless sensing system in detail that contains hardware and software. In our research group, we propose a standard manufacturing process of flexible arrayed potentiometric sensor. The stable flexible arrayed potentiometric sensor that we can try other ionic enzyme immobilization such as chlorine ion, calcium ion, sodium ion, and uric acid et al. The optimum ratios of above ionic enzyme immobilization have been studied in our research group. We propose a low cost and high stability wireless sensing system of XBee module that hope more researchers can refer the example of wireless sensing system for many applications. Besides, the system also provides a real-time monitoring and rapid detection.

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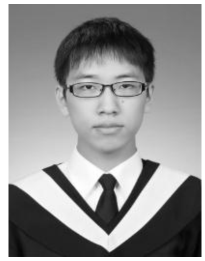

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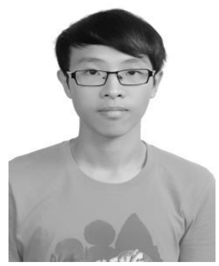

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