Low-cost sensor node based on electrochemical sensor module for wireless sensor network

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Abstract. The low-cost sensor is now widely used in various applications ranging from the environment to daily live application. On the other hand, the low-cost sensor signal is dealing with noises due to external disturbances, quality of sensor material, or electronic circuits. The raw data provided by the low-cost sensor is also still in digital n-bit data and needs to convert. This research investigated the low-cost sensor node as part of the Wireless Sensor Network (WSN) for carbon monoxide (CO) measurement based on the electrochemical sensor module. Although the measurement signal consists of noise, a digital IIR filter attenuated this noise. By applying the Response Surface Method (RSM), the 10-bit data of the sensor has been calibrated to the commercially CO detector and resulted in the square transfer function equation. The sensor node measurement performance has a strong correlation ($R^2=0.98$) with the performance of the sensor module in the wireless sensor node system. The data has been transmitted well to a gateway with needed settling time about 5 minutes for getting stable measurement conditions. The results show that various applications can use this low-cost sensor.

1. Introduction

Wireless Sensor Network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors, which is called a sensor node, to monitor physical or environmental conditions [1,2]. A Sensor node in WSN has wireless connectivity to the coordinator or gateway in the network. According to its capability, WSN is very useful as a monitoring system for large areas via wireless connectivity, for example, as an environmental monitoring system [3,4].

The sensor node, as one crucial part in WSN, consists of several electronic devices such as sensors, processors, and transmitters. The aspect of the performance and number of sensor nodes in a WSN are essential, considering in the WSN designing. Regarding that, the cost is also essential considering aspect in the system designing. Jose et al. used low-cost WSN for the agricultural application. In their research, sensor nodes were spread in several kilometres and used UAV to gather the data [5]. In other work, Sacaleanu et al. used a low-cost sensor in sports applications. In their research employed low-cost sensor nodes to analyze athletes' reflexes [6]. For environment applications [7,8], many kinds of research are using a low-cost sensor [9,10], especially for air quality monitoring [11,12].

This report addresses the low-cost sensor node for ambient air quality monitoring, where the sensor node consists of an electrochemical CO (Carbon Monoxide) sensor, processor, a transmitter device, and battery as a power supply. The electrochemical CO sensor is integrated with a processor to be a sensor module. This work investigated the performance of the sensor module, which includes the sensor sensitivity, linearity, and accuracy. The accuracy of the sensor module was proved by calibrated the...
sensor module to the commercially CO detector. The transmitted data was investigated in the gateway to analyze the settling time for getting measurement in stable condition.

2. Material and method

Figure 1 shows the test circuit of the investigated electrochemical sensor, where A and B are electrodes, H is the heating coil, and \( R_L \) is the load resistance.

![Figure 1. Sensor circuit.](Image)

The sensor circuit is installed in one compact module consisting of a sensor circuit and I2C communication circuit, as shown in figure 2. This sensor is commercially available. A Microcontroller processed the output of the sensor directly.

![Figure 2. Sensor module, processor and transmitter.](Image)

As an electrochemical sensor, the sensor works in the specific temperature through the heating process. The sensor needs a heat process for a specific time before available to do the right measurement. In this research, signal conditioning circuits equipped the carbon monoxide sensor for heat processing. An additional resistor is needed to determine how long the optimum heating time. Furthermore, the sensor node used this sensor. This node, as shown in figure 2, consists of a sensor module, microcontroller, and transmitter device, with a power supply. This experiment used LoRa (Long Range), a low-power wide-area network (LPWAN), as transmission technology.

The experiment is started by investigated the performance of the sensor module. The investigation used various values of resistor for settling optimal heating time. Infinite Impulse Response (IIR) filter was applied in measurement to derive a stable condition. The data of stable measurement has been calibrated with the commercially CO detector through a linear calibration method according to the Response Surface Method (RSM). The digitally calibrated data of measurement was transmitted to the gateway by the transmitter device of LORA technology.

The microcontroller processed the data received from the sensor through I2C communication. There are two main challenges in using this low-cost sensor. First, the sensor characteristics compromise to trade-off issues around price, availability, and considered the signal quality. This work analyzed the provided data of the sensor toward the noise signal by using the digital IIR filter to reduce the noise and to remove the spike from the signal. Second, the output data of the sensor is still in 10-bit (0-1023 level) format and must convert to ppm-level. In this research, this conversion is carried out by the Response Surface Method (RSM).

Investigation with IIR used the first-order filter to avoid noises due to signal disturbance or internal sensor quality (Equation 1).
\[ H(s) = \frac{1}{T_c s + 1} \]  

(1)

where \( T_c \) is Time constant. The calculation to find the cut-off frequency \( \omega_c \) used Equation 2.

\[ \omega_c = \frac{1}{T_c} \]  

(2)

According to that, this signal conditioning based on a microcontroller and converted data to a discrete form. Equation 3 is the trapezoidal method to convert ‘s’ domain to ‘z’ domain with \( T_s \) as sampling time.

\[ s = \frac{2}{T_s} \left( \frac{1 - z^{-1}}{1 + z^{-1}} \right) \]  

(3)

Substitute equation 3 to equation 1, derived Equation 4.

\[ Y(z) = \left( \frac{2T_s}{T_s + 2T_c} \right) Y(z) z^{-1} + \frac{T_s}{(T_s + 2T_c)} \left( X(z) + X(z) z^{-1} \right) \]  

(4)

According to digital programming purposes, Equation 5 converted Equation 4 to a discrete equation.

\[ Y(n) = \left( \frac{2T_s}{T_s + 2T_c} \right) Y(n-1) + \frac{T_s}{(T_s + 2T_c)} \left( X(n) + X(n-1) \right) \]  

(5)

This work employed second-order Response Surface Equation (RSM) for converting the 10-bit format to ppm level, to find a relationship between the measured value from low-cost electrochemical CO sensor and commercially CO detector. This step optimized the response variable ‘\( y \)’, which is required to find a suitable approximation of the right functional relationship between independent variables and the response surface. Usually, the second-order model is utilized in RSM [13], and this work used the simplified form, which deals with one variable as Equation 6.

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_1^2 + \epsilon \]  

(6)

Furthermore, this investigation used matrix form \( Y = X \beta \) for Equation 6, where \( Y \) is a matrix of measured values, and \( X \) is a matrix of independent variables. The matrix approach Equation 7 obtained the solution for \( \beta \) where,

\[ \beta = (X^T X)^{-1} X^T Y \]  

(7)

Equation 8 measured the derived equation by using the \( R^2 \) correlation in Equation 8.

\[ R^2 = \frac{\sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \]  

(8)

Where:

- ‘\( y \)’ is measured data from Industrial CO Fluke sensor, and
- ‘\( \hat{y} \)’ is its average
- ‘\( \bar{y} \)’ is estimated data from the RSM equation.

The result is \( 0 \leq R^2 \leq 1 \), with \( R^2 = 1 \) is the perfect correlation, and \( R^2 = 0 \) is no correlation.
3. Experimental setup

There were two steps to experiment. The first step is the calibration of the low-cost CO sensor to the commercially CO detector to find the characteristics of the low-cost CO sensor. The second step is an integrated measurement of the low-cost sensor in a wireless sensor network system. The CO sensor measured in the restrictive environment during the calibration process to commercially CO detector. A box with 27-liter capacity represented this restrictive environment with smoke as the source of carbon monoxide. According to its natural characteristic, the sensor needs settling time to reach a stable situation.

The measurement started from high concentration smoke, which presented CO concentration to the lowest one, which can be read by a sensor. The investigation compared the sensor measurement with this various concentration of CO to commercially CO detector. The sensor reading is still in 10bit (0-1023 level) format. The relation of measurement result between the commercial detector and sensor module is relatively linear and shown in table 1.

Table 1. Measurement of various CO concentration.

| CO Fluke 220 (ppm) | The digital output of the sensor module (0-1023 level) |
|-------------------|-----------------------------------------------------|
| 7                 | 447,2962646                                        |
| 15                | 520,2042236                                        |
| 24                | 598,9671631                                        |
| 39                | 674,6715088                                        |
| 50                | 698,2399902                                        |
| 70                | 736,4345093                                        |

The second step is an integrated measurement in the WSN system. The sensor was installed in the sensor node and deployed in several places with building and tree as obstacles. Figure 3 shows communication among each sensor, sensor node, and gateway.

4. Results and discussion

4.1. Noise reduction by applying digital IIR filter

The experiment data was consisting of signal and noise. The investigation measured the frequency of noises firstly to find the cut-off frequency of the noise in radian/second and used the IIR Filter to reduce the noise.

The measurement result determined that the signal periodical time is 30.29 – 28.62 = 1.67 second. Therefore, the signal frequency is 0.598 Hz (3.76 rad/s). The first order filter in Equation 1 reduced the noise by applying a cut-off frequency of 0.12 rad/s.

The bode plot diagram of this filter yield the magnitude of transfer function -28.9 dB and phase -87.9 degree at frequency ω= 3.49 rad/s. Figure 4 shows the bode diagram of the filter.
The Equation 2 converted $\omega_c=0.12 \text{ rad/s}$ to $T_c=7.97s$. Measurement requirement for sampling determined time sampling ($Ts$) $0.05s$. Calculation using $T_c=7.97s$ and $Ts=0.05s$ in Equation 4 result the digital IIR filter in $Z$ domain in Equation 9 with block diagram in Figure 5.

$$Y(z) = 0.9937Y(z)z^{-1} + 0.0031\left(X(z) + X(z)z^{-1}\right)$$

(9)

Figure 5. Digital IIR filter diagram.

Equation 10 is a conversion of Equation 9 for programming purposes.

$$Y(n) = 0.9937Y(n-1) + 0.0031\left(X(n) + X(n - 1)\right)$$

(10)

Figure 6 shows the result of the filter. It shows that a digital IIR filter can significantly attenuate the noise.
4.2. Sensor calibration
According to the measurement result shown in Table 2, this investigation carried out the sensor calibration to a commercial detector by applying RSM in Equation 6. By using of 174.9855, -0.7173, and 0.0008 as the value of $\beta_0$, $\beta_1$, $\beta_2$ respectively, Equation 6 is converted to Equation 11.

$$y = 174.9855 - 0.7173x_1 + 0.0008x_1^2$$  \hspace{1cm} (11)

Through this calibration, the 10-bit data of sensor outputs were converted to ppm by referring to commercially detector data. The calibration result, called model, is presented in Figure 7 compared to commercially detector results.

The verification based on Equation 8 shows that the derived model has a strong correlation with $R^2=0.98$.

![Graph showing calibration results](image)

**Figure 7.** Comparison between model and commercially detector.

4.3. Settling time of low-cost sensor in WSN
Furthermore, this work investigated the effect of natural pre-treating of the sensor, communication, and application delay in WSN using the integration system. The result showed that the settling time of the sensor is about 5 minutes (see Figure 8). This condition can vary depending on the load of the sensor node and the quality of the communication system.

![Graph showing settling time](image)

**Figure 8.** Sensor reading profile in gateway.
5. Conclusion
This work has investigated the low-cost sensor node for CO measurement based on the electrochemical
sensor module. Applying a digital IIR filter could attenuate the noise. The sensor has been calibrated
to the commercially CO detector and resulted in the square transfer function equation. The performance
of the sensor node has a strong correlation with the performance of a sensor module in the wireless
sensor node system. The data has been transmitted well to the gateway, with settling time about 5
minutes for getting a stable measurement condition.

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References
[1] Akyildiz I F and Vuran M C 2010 Wireless Sensor Network West Sussex (United Kingdom: John
Wiley & Sons)
[2] Haseeb K, Bakar K A, Abdullah A H and Ahmed A 2015 Grid based cluster head selection
mechanism for wireless sensor network Telkomnika 13(1) 269
[3] Basha E A, Ravela S and Rus D 2008 Model-based monitoring for early warning flood detection
In Proceedings of the 6th ACM conference on Embedded network sensor systems
[4] Werner-Allen G, Lorincz K, Ruiz M, Marcillo O, Johnson J, Lees J and Welsh M 2006 Deploying
a wireless sensor network on an active volcano IEEE internet computing 10(2) 18-25
[5] Polo J, Hornero G, Duijneveld C, Garcia A and Casas O 2015 Design of a low-cost wireless
sensor network with UAV mobile node for agricultural applications Computers and electronics in agriculture 119 19-32
[6] Săcăleanu D I, Perișoară L A, Spataru E and Stoian R 2017 Low-cost wireless sensor node with
application in sports In 2017 IEEE 23rd International Symposium for Design and Technology in Electronic Packaging (SIITME) pp 395-398
[7] Ziga M, Galajda P, Drutarovsky M and Petrvalsky M 2014 Adaptable sensor node interface for
low-cost water quality monitoring In 2014 24th International Conference Radioelektronika pp 1-4
[8] Castell N, Schneider P, Grossberndt S, Fredriksen M F, Sousa-Santos G, Vogt M and Bartonova
A 2018 Localized real-time information on outdoor air quality at kindergartens in Oslo,
Norway using low-cost sensor nodes Environmental research 165 410-419
[9] Castell N, Dauge F R, Schneider P, Vogt M, Lerner U, Fishbain B and Bartonova A 2017 Can
commercial low-cost sensor platforms contribute to air quality monitoring and exposure
estimates? Environment international 99 293-302
[10] Hassan H H, Badr I H, Abdel-Fatah H T, Elfeky E M and Abdel-Aziz A M 2018 Low cost
chemical oxygen demand sensor based on electrodeposited nano-copper film Arabian Journal of Chemistry 11(2) 171-180
[11] Penza M, Suriano D, Pfister V, Prato M and Cassano G 2017 Urban air quality monitoring with
networked low-cost sensor-systems In Multidisciplinary Digital Publishing Institute Proceedings 1(4) 573
[12] Borrego C, Costa A M, Ginja J, Amorim M, Coutinho M, Karatzas K and Esposito E 2016
Assessment of air quality microsensors versus reference methods: The EuNetAir joint exercise Atmospheric Environment 147 246-263
[13] Kwak J S 2005 Application of Taguchi and response surface methodologies for geometric error
in surface grinding process International journal of machine tools and manufacture 45(3) 327-334