Overcoming Long Recovery Time of Metal-Oxide Gas Sensor With Certainty Factor Sensing Algorithm

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Abstract—Gas leaking in gas production industry is a serious issue which could cause explosion or pose a high risk to human life. The searching of leaking gas can be performed by robots. It is better than using human beings because searching of leaking gas is a high risk task. Most of the gas sensors used in industries is semiconductor metal-oxide (MOX) type due to its low cost, ease of use, high sensitivity and fast response time in gas sensing, and ability to detect large number of gases. However, there is a fatal limitation i. e. long recovery time after the exposure of the target gas. It definitely causes robots to fail in gas/odour plume searching tasks due to delay of responses during the absent of gas plume. This paper proposes a sensing algorithm based on evidential theory which is using certainty factors and evidential reasoning to overcome the long recovery problem. Based on the conducted experiments, the proposed algorithm has improved the accuracy and reliability while maintaining its performance in recovery time. It performs better than other algorithms such as simple threshold methods, transient response algorithm and system modelling approach.

Keywords—Gas detection, Certainty Factor Sensing, Odour plume tracking, MOX Gas Sensor.

I. INTRODUCTION

Gas leaking is a serious issue in gas production industry which it could cause explosion or pose a high risk to human life. Thus far, most of the searching tasks of gas leaking are accomplished by man using gas detection sensor. This type of manual searching of leaking gas comes with shortcomings. For example, high risk in safety as the rescuer might try to search poison leaking gas location. Besides, it is also ineffective because human beings cannot employ any searching algorithm but just performing random searching. Moreover, the detection of leaking gas by gas sensors is not perfect all the time which causing poor performance in manual searching. Gas sensors are only working well under certain conditions because they are highly influenced by humidity, temperature and effectiveness of chemisorptions reaction towards target gas. There are four types of gas sensors i.e. semiconductor metal-oxide (MOX), conducting polymer, optical and gravimetric sensor[1]. Among these four types of gas sensors, MOX gas sensor is the most commonly used in industry due to its high sensitivity and fast response time in gas sensing. Besides, it also has the characteristics of easy to use, low maintenance cost, simple electronic interface, ability to detect large number of gases, and most importantly it is low cost[2]; it is worth mentioning also that most of the electronic-nose products are the compilation of MOX gas sensors array that are targeting to sense different types of gases[3]–[5].

The characteristic of MOX gas sensor is its fast response in detecting gas however it requires a very long recovery time after the exposure of the target gas[6]–[8]. It takes around 15 to 70 seconds to recover back to the baseline level after the target gas is removed[9]. The baseline level is a threshold of the sensor output signal during absence of target gas. The reason for long recovery time of MOX gas sensing is due to its working principles. During the presence of target gas, the molecules of target gas contact with the detecting surface of MOX gas sensor, and then the chemisorptions takes place at the detecting surface of the metal-oxide, this chemisorptions reaction will result in chemical electrode effects and changes in sensor resistance value. Through the measurement of sensor resistance values, the target gas concentration percentage can be calculated as the chemisorption’s reaction is proportional to gas concentration percentage, and the changes of sensor resistance is proportional to the chemisorption’s reaction[10]. Therefore, during the removal of target gas, there are still some gas molecules remain at the detecting surface of MOX gas sensor, and it takes a long period of time for all these molecules to desorbs from the detecting surface of MOX gas sensor. As a consequence, it causes the long recovery time of MOX gas sensor after the exposure of the target gas. Fig. 1 shows the response of a MOX gas sensor when exposed to a gas plume (during blue region), and it take approximately 70 seconds to recover back to its baseline.

![Figure 1. Long recovery time of a MOX gas sensor[6].](image-url)
The long recovery time of MOX gas sensor causes serious pitfall in gas/odour plume tracking when it is applied in sniffer robots. It causes delay in responses when sniffer robots are off-track of gas/odour plume and eventually leads to failure in tracking. For example, a sniffer robot is employing Moth inspired plume tracking strategies or Zigzag algorithm, the sniffer robot will perform “surge” action to track along the gas plume when its gas sensor is detecting the presence of gas. However, the pattern of gas/odour plume is non-linear when dispersed into the air and it caused the sniffer robot loses track of the gas/odour plume during this “surge” action. For this reason, whenever the gas sensor does not detect the presence of gas, the sniffer robot will perform zigzag movements orthogonal to the wind direction and this action is called ‘casting’[11]. The “casting” action is required to perform immediately after loses of tracking so as to track back to the gas plume track. However, with the limitation of MOX gas sensor in long recovery time, it causes delay response of “casting” action and eventually leads to failure in tracking.

In this paper, a sensing algorithm based on evidential theorem is proposed to overcome the long recovery problem of gas sensor. Certainty factors and evidential reasoning theory are used to determine whether sniffer robot is in-track or off-track of gas/odour plume, which can overcome the delay response of sniffer robot in “casting” action whenever off-track of gas/odour plume. The remainder of this paper is organized as follows: Section II reviews the related work; Section III discusses the proposed algorithm; Sections V discusses the results and finally the conclusion of the works is presented in Section VI.

II. LITERATURE REVIEW

The long recovery time problem of MOX gas sensors in sniffer robot can be solved by either using software or hardware solution. For hardware solution, Javier G.J et al.[6] propose a special design of sensors chassis called Multi-Chamber Electronic Nose. The design comprises of several identical sets of gas sensors accommodated in separate chambers; airflows are circulating between each chamber. There are two pumps: one aspirating clean air and the other targeting gas. At each time, only one chamber is receiving the target gas while the other chambers are being purged with clean air, as illustrated in Fig. 2. This method can cover up the limitation of long recovery time of MOX gas sensors because while one of the sensors is sensing, the others can take time to recover.

However, the limitation of this hardware solution is the bulky and heavy design of the sensors chassis. The research trend of gas/odour plume tracking of sniffer robots is heading towards 3D space tracking instead of 2D space tracking. This is because gases/odours are released into air in the formation of a 3D plume. 2D space tracking is ineffective due to its inability to capture the gases/odours within 3D space that are located above the ground. Therefore, 3D space tracking and flying sniffer robots are emphasised in current research trend[12]. With these reasons, the hardware solution is not suitable for 3D space tracking flying sniffer robots because it is too bulky and heavy that causes flying sniffer robot fail to carry the sensor’s chassis during flight.

As for the software solution, Ishida et al.[13] propose a method called transient-response based sensing so as to enhance the sensing response. The working principle of this algorithm is simple, if there is a certain degree of changes in the maximum or minimum local odorant concentration, the sniffer robot should make an immediate response. With these settings, the long recovery time problem of MOX gas sensor could be solved because sniffer robot is depending on transient-response of sensor for making reaction instead of depending on full response of sensor. Javier G.M. et al.[14] adopt the idea of transient-response based sensing but they enhance this method by proposing a system modelling approach to estimate steady output value from the transient state signal of gas sensor. They use an inverse dynamical model of fast response of gas sensor to estimate the virtual fast recovery steady state value. In fact, they are creating fake fast recovery value of gas sensor.

Software solution that purely relies on transient signal has limitation which is too sensitive and over response to noisy and distorted transient signals. It is because MOX gas sensors have signal noise, response drift problem, and highly influenced by humidity and temperature, hence the false and distorted transient signals occur too frequent will cause the software solutions over response to them. For this reason, this paper proposed a sensing algorithm based on evidential theorems which are using Certainty factors theory and evidential reasoning to overcome long recovery time problem. The proposed algorithm does not purely rely on transient signal of MOX gas sensor which enables it to overcome the problem of over response to the false and distorted transient signals.

III. PROPOSED ALGORITHM

As mentioned in section above, if a software solution is purely relied on transient signal, it will respond over sensitively to the noisy and distorted transient signals which happen quite frequent due to its signal noise, response drift problem and highly influenced by humidity and temperature issues. The proposed algorithm is to overcome this problem by using certainty factors theory and evidential reasoning. The proposed algorithm is not only relying on transient signals but also observes other important factors such as threshold value, gradient of transient response, sensing timing, and signal dynamics pattern as evident to reasoning and judge the sensing of MOX gas sensor.

Certainty factors theory and evidential reasoning are based on the measurement of hypothesis’ belief and the measurement.
is determined by certainty factor (cf). For instance, if the hypothesis’ belief is definitely true, then the maximum value of \( cf \) is +1.0. Whereas, if the hypothesis’ belief is definitely false, then the minimum value of \( cf \) is -1.0. Apart from that, the hypothesis’ belief is reasoned from evidences. For example, if a hypothesis’ belief has some evidence is almost certainly true, a \( cf \) value of >0.8 would be assigned to this evidence. In expert systems with certainty factors, the knowledge base consists of a set of rules that have the followings syntax[15]:

\[
\text{IF } \langle \text{Evidence } E \rangle \text{ THEN } \langle \text{Hypothesis } H \rangle \{ cf \}
\]

*Where, \( cf \) represents belief in hypothesis \( H \) given that evidence \( E \) has occurred.

Therefore, the formula can be defined as follow:

\[
 cf(H, E) = cf(E) \times cf
\]  

(1)

The expert system with certainty factor that have conjunctive rules with multiple antecedents can be stated as:

\[
\text{IF } \langle \text{Evidence } E_1 \rangle \text{ AND } \langle \text{Evidence } E_2 \rangle \text{ AND } \ldots \langle \text{Evidence } E_n \rangle \text{ THEN } \langle \text{Hypothesis } H \rangle \{ cf \}
\]

For conjunctive rules, the formula can be defined as follow:

\[
 cf(H, E_1 \cap E_2 \cap \ldots \cap E_n) = \min [cf(E_1), cf(E_2), \ldots, cf(E_n)] \times cf
\]  

(2)

The expert system with certainty factor that have disjunctive rules with multiple antecedents can be stated as:

\[
\text{IF } \langle \text{Evidence } E_1 \rangle \text{ OR } \langle \text{Evidence } E_2 \rangle \text{ OR } \ldots \langle \text{Evidence } E_n \rangle \text{ THEN } \langle \text{Hypothesis } H \rangle \{ cf \}
\]

For disjunctive rules, the formula can be defined as follow:

\[
 cf(H, E_1 \cup E_2 \cup \ldots \cup E_n) = \max [cf(E_1), cf(E_2), \ldots, cf(E_n)] \times cf
\]  

(3)

For two or even more rules can affect the same hypothesis, the formula of certainty factor combination can be applied as follow:

\[
 cf(cf_1, cf_2) = \begin{cases} 
 cf_1 + cf_2 \times (1 - cf_1) & \text{if } cf_1 > 0 \text{ and } cf_2 > 0 \\
 cf_1 + cf_2 & \text{if } cf_1 < 0 \text{ or } cf_2 < 0 \\
 1 - \min [cf_1, cf_2] & \text{if } cf_1 < 0 \text{ or } cf_2 < 0 \\
 cf_1 + cf_2 \times (1 + cf_1) & \text{if } cf_1 < 0 \text{ and } cf_1 < 0 
\end{cases}
\]  

(4)

Unlike other software solutions, certainty factors theory and evidential reasoning do not need to rely on a transient signal of MOX gas sensor to judge the sensing result. It can use transient signal at a particular time as evident E1, transient signal at next cycle of time as evident E2, so on and so forth until it can make up a series of evidence to analyse the signal pattern and judge the MOX gas sensor’s sensing result. Some other factors such as threshold value, gradient of transient response, sensing timing, and signal dynamics pattern are observed as evident to reasoning the hypothesis’s belief of MOX gas sensor’s sensing result. For instance, if the judgement of the target gas plume is removed from a MOX gas sensor based on a transient signal at particular time only, the judging might not be correct because a single transient signal at that particular time might be a signal noise or distortion transient signal. On the other hand, if the consideration of a series of evidences such as transient signals from a range of period time, threshold value, gradient of transient response, sensing timing, and signal dynamics pattern to judge the removal of gas plume, the judgement will be more reliable and accurate. Even though the signal noise or distortion transient signal might occur at particular time, it will not affect the judgement because it is based on the transient signals from ranges of time to identify the signal pattern.

This paper develops a knowledge base of MOX gas sensor’s expert system with certainty factors consists of a set of rules that have the followings syntax:

\[
* \text{MOX Gas sensor expert system with certainty factors}
\]

*PGGT = Positive Gas Gradient Threshold

*NGGT = Negative Gas Gradient Threshold

Rule: 1

IF Gas Sensing value > Gas Sensing value \(_1\) AND Transient signal \(_n\) > PGGT

THEN Gas plume is detected \{cf 0.8\}

Rule: 2

IF Gas Sensing value > Gas Sensing value \(_1\) AND Transient signal \(_n\) < PGGT AND Gas sensor value < Gas Sensing Threshold

THEN Gas plume is detected \{cf 0.2\}

Rule: 3

IF Gas Sensing value < Gas Sensing value \(_1\) AND Transient signal \(_n\) < PGGT AND Gas sensor value > Gas Sensing Threshold

THEN Gas plume is detected \{cf 0.4\}

Rule: 4

IF Gas Sensing value < Gas Sensing value \(_1\) AND Transient signal \(_n\) < NGGT

THEN Gas plume is not detected \{cf 0.70\}

Rule: 5

IF Gas Sensing value < Gas Sensing value \(_1\) AND Transient signal \(_n\) < NGGT AND Gas sensor value < Gas Sensing Threshold

THEN Gas plume is not detected \{cf 0.75\}

Rule: 6

IF Gas Sensing value < Gas Sensing value \(_1\) AND Transient signal \(_n\) < NGGT AND Gas sensor value > Gas Sensing Threshold
THEN Gas plume is not detected \{cf 0.15\} 

Evident of Fired Rule 6 at current time, \( t \)

Rule: 7
IF Current Fired Rule is Rule 6
AND Previous Fired Rule at \( t-1 \) is Rule 6
AND Previous Fired Rule at \( t-2 \) is Rule 6
AND Previous Fired Rule at \( t-n \) is Rule 6
THEN Series of Evidences of Fired Rule 6 \{cf 1.0\}

Rule: 8
IF Series of Evidences of Fired Rule 6
THEN Gas plume is not detected \{cf 0.68\}

For the set of rules, gas sensor value signal patterns are observed as evidences. First, the gas sensor value at current time \( t \) is to compare with gas sensor value at previous time \( t-1 \), this will be an evident of positive or negative transient signal. Second, the transient signal is to compare with Positive Gas Gradient Threshold (PGGT) or Negative Gas Gradient Threshold (NGGT) as evident of dynamics response. Third, gas sensing threshold will be considered as evident of previous sensing status. Last, series of evidences of Fired Rule 6 will be used to reasoning the long recovery time problem of MOX gas sensor.

Fig. 3 shows the flow chart of MOX Gas sensing expert system with certainty factors and evidential reasoning. The gas sensor raw data with unsmooth signal and noises will be filtered by Kalman filter. Kalman filter is a data fusion algorithm which is more than a filtering algorithm that filters noises, but it also provides estimation of parameter which acts as an optimal state estimator that minimizes the variance of the state estimation error with Gaussian error statistics[16]. Hence, filtered signals and smooth data will be produced by Kalman filter that reduces the noisy and distorted transient signals. Subsequently, the set of rules of MOX gas sensor’s expert system with certainty factors will be applied to reasoning the sensing of MOX gas sensor.
The proposed algorithm is compared with other software solutions such as simple threshold method, Transient response algorithm and system modelling approach as mentioned in section II. The performance measurements are based on the response time, accuracy and reliability. For comparison, it is divided into four experiments to test four different sensing scenarios: (A) from non-detecting to detecting, (B) from detecting to non-detecting, (C) saturated detecting, and (D) continue switching on-off detection. In these experiments, Tin Oxide (SnO2) type of MOX gas sensor is to detect Ethanol vapour as target gas plume.

A. From Non-detecting to Detecting

This Scenario is to test the response time of each algorithm from non-detecting to detecting. The MOX gas sensor is located away from gas plume, and then moving it to detect the presence of target gas plume as illustrated in Fig. 4.

![Figure 4. Sensing scenario from Non-detecting to detecting.](image)

In Table 1, the response time for each algorithm is recorded five times and the average response time for each algorithm is calculated. Among the algorithms, transient response algorithm has the fastest response time (which has average response time of 1.054 seconds) because it relies on a single transient signal to determine that MOX gas sensor is detecting gas plume. However, it is also less reliable because it is too sensitive and over response to the noisy and distorted transient signals. For the certainty factor sensing algorithm, it has the slowest response time (which has average response time of 1.876 seconds) but it is more accurate and reliable. The slightly slower response time of certainty factor sensing algorithm (0.822 seconds slower) is because of Transient response algorithm’s average response time in this scenario is acceptable because it will not affect much in gas/odour plume tracking task of sniffer robots. The sacrifice of response time of certainty factor sensing is to increase the accuracy and reliability so as to overcome the problem of noisy and distorted transient signals.

<table>
<thead>
<tr>
<th>Trials</th>
<th>Simple Threshold</th>
<th>Transient Response</th>
<th>System Modeling Approach</th>
<th>Certainty Factor Sensing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.55</td>
<td>0.85</td>
<td>1.55</td>
<td>1.71</td>
</tr>
<tr>
<td>2</td>
<td>1.85</td>
<td>1.46</td>
<td>1.93</td>
<td>2.21</td>
</tr>
<tr>
<td>3</td>
<td>1.25</td>
<td>0.59</td>
<td>1.35</td>
<td>1.51</td>
</tr>
<tr>
<td>4</td>
<td>1.61</td>
<td>1.32</td>
<td>2.1</td>
<td>2.28</td>
</tr>
<tr>
<td>5</td>
<td>1.46</td>
<td>1.05</td>
<td>1.54</td>
<td>1.67</td>
</tr>
<tr>
<td>Average Response time (Seconds)</td>
<td>1.544</td>
<td>1.054</td>
<td>1.694</td>
<td>1.876</td>
</tr>
</tbody>
</table>

B. From Detecting to Non-detecting

This scenario is to test the recovery time of each algorithm from detecting to Non-detecting. The MOX gas sensor is located inside the gas plume, and then moving away from gas plume as illustrated in Fig. 5.

![Figure 5. Sensing scenario from detecting to non-detecting.](image)

Table 2 shows the recovery time (recorded five times) for each algorithm and also the average recovery time is calculated. Among the algorithms, transient response algorithm has the fastest recovery time (which has average recovery time of 1.126 seconds). The second fastest recovery time is certainty factor sensing algorithm (which has average recovery time of 2.258 seconds), it is just 1.132 seconds behind of transient response algorithm. The reason behind of slightly slower recovery time of certainty factor algorithm is to increase the accuracy and reliability so as to overcome the problem of high sensitivity and also over response to the noisy and distorted transient signals which is the limitation of transient response algorithm. Although certainty factor sensing algorithm has slower response time as compared to system modelling approach from table I (0.182 seconds slower), it has better and faster recovery time than system modelling approach from Table II (13.242 seconds). This result proves that certainty factor sensing algorithm can deliver better performance in gas/odour plume tracking task of sniffer robots as compared to system modelling approach. To emphasize again, the critical failure factor of gas/odour plume tracking task of sniffer robots with MOX gas sensor is the long recovery time (which is 48.522 seconds from Table II). Therefore, the result of certainty factor sensing algorithm in recovery time is significant.

<table>
<thead>
<tr>
<th>Trials</th>
<th>Simple Threshold</th>
<th>Transient Response</th>
<th>System Modeling Approach</th>
<th>Certainty Factor Sensing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.82</td>
<td>1.39</td>
<td>15.24</td>
<td>2.36</td>
</tr>
<tr>
<td>2</td>
<td>1.56</td>
<td>1.21</td>
<td>15.5</td>
<td>2.34</td>
</tr>
<tr>
<td>Average Recovery time (Seconds)</td>
<td>48.522</td>
<td>1.126</td>
<td>15.5</td>
<td>2.258</td>
</tr>
</tbody>
</table>

C. Saturated Detecting

Thus far, transient response algorithm has better performance than certainty factor sensing algorithm in terms of response time and recovery time. However, this scenario is to test the accuracy and reliability of algorithms. MOX gas sensor is allocated at the presence of gas plume for a long period of time until it is saturated in detection. During saturated detecting, noisy and distorted transient signals might occurs due to MOX gas sensor’s signal noise and response drift problems, thus the performance of accuracy and reliability can be measured. In this scenario, the duration of saturated detecting is 600 seconds. From Table III, it shows that only transient response algorithm has 87.9% in accuracy which is
72.6 out of 600 seconds that not reflecting the correct detection status. On the other hand, the rest of the algorithms are having 100% accuracy.

### TABLE III. REALIBILITY OF SENSING SCENARIO OF SATURATED DETECTING

<table>
<thead>
<tr>
<th></th>
<th>Simple Threshold</th>
<th>Transient Response</th>
<th>System Modeling Approach</th>
<th>Certainty Factor Sensing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy (%)</td>
<td>100%</td>
<td>87.9%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

#### D. Continue Switching On-Off Detection

This scenario is to test the accuracy and reliability of algorithms. The MOX gas sensor is continuously switching from one scenario to another so as to compare which algorithm can reflect the correct sensing status. In Table IV, symbol “✓” indicates the sensing status is correct and symbol “X” indicates the sensing status is incorrect. Certainty factor sensing algorithm has better performance in reliability because of its expert system designed with certainty factor evidential reasoning to judge the sensing status from series of evidences. Table III and IV prove that certainty factor sensing algorithm has improved the accuracy and reliability significantly because Table III & Table IV shows that certainty factor sensing has 100% accuracy and reliability in reflecting the correct detection status. Even though certainty factor sensing algorithm has slightly slower response time and recovery time than transient response algorithm it has the best performance in terms of accuracy and reliability. In summary, certainty factor sensing algorithm is the best solution amongst all the software solutions.

### TABLE IV. REALIBILITY OF SENSING SCENARIO OF CONTINUE SWITCHING ON-OFF DETECTION

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Simple Threshold</th>
<th>Transient Response</th>
<th>System Modeling Approach</th>
<th>Certainty Factor Sensing</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>C</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>A</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>C</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>A</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

| Reliability(%) | 70% | 60% | 80% | 100% |

#### V. CONCLUSION

From the results, it proves that the proposed algorithm has better performance in recovery time, accuracy, and reliability as compared to simple threshold method, transient response algorithm and system modelling approach. Although it has slightly slower response time and recovery time (as compared to transient response algorithm), it does not compromise the performance of gas/odor plume tracking. Most importantly, the proposed algorithm has better accuracy and reliability which will definitely enhance the performance of gas/odor plume tracking. The proposed algorithm has overcome the problems of over sensitive and over response to the noisy and distorted transient signals of MOX gas sensor which making it more reliable than other software solutions especially transient response algorithm. For the future works, the proposed algorithm will be implemented on a flying sniffer robot with Moth inspired plume tracking strategies or spiral-casting search strategies. This is due to the fact that the performance of gas/odor plume tracking can be improved through the proposed algorithm i.e. certainty factor.

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#### REFERENCES