Proceedings of the 2007 IEEE
International Conference on Integration Technology
March 20 - 24, 2007, Shenzhen, China

Using Stationary Electronic Noses Network to Locate Dynamic Odour Source Position

Jie Cai
School of Electrical and Information Engineering
The University of Sydney
NSW 2006, Australia
jcai@cs.anu.edu.au

David C. Levy
School of Electrical and Information Engineering
The University of Sydney
NSW 2006, Australia
dlevy@ee.usyd.edu.au

***Abstract* - Source localization based on electronic nose system is a very interesting research. There are two basic methods to solve this problem. One is performed by robotics with build-in electronic nose (Enose) system. Another is performed by stationary electronic nose systems. First approach is well developed with the improving robotic techniques. However this approach will have difficulty to solve several situations, such as "instantaneous source" and complex landscape to prevent robotics reaching the source. Stationary electronic nose system has the capability to solve these problems. This paper presents a two-step approach based on a novel stationary electronic nose systems network to locate the dynamic odour source position. It is considered in a set of natural wind situations, including x axis advection, and wind with a break case. It is an extended work based on our previous research.**

Index Terms - Electronic nose, Dynamic source localization, Nature wind situation

I. INTRODUCTION

A combination of hardware (receptors) and software (temporal/spatial integration and recognition abilities) and behavioral search strategies is used by animals to locate an odour source position [1]. Several kinds of animals are using their olfactory systems to prey bait, to predict dangers, and to find mates. People already use some animals' olfactory abilities to prevent crime, such as suppress-drug dog. This gives us inspiration to utilize an array of chemical sensors (electronic nose) to mimic animals' behaviors. Electronic nose system has the capability to solve the problem more efficiently and flexibly. There are two major application areas of electronic nose systems, odour recognition and source localization. Odour recognition tells us what kind of "smell" it is, and source localization tells us where it is.

Odour recognition techniques is very well developed and applied in many kinds of industry areas, such as dairy industry and beverage industry [2-5]. On the other hand, source localization is usually performed by electronic noses (Enose) built-in robotics. This approach could successfully solve this problem even in natural environments [1, 6, 7]. But it will face difficulty to accomplish this task in some situations, for example, the source is instantaneous; or the landscape is very hard for robotic vehicle to reach the source position. Therefore, a requirement of stationary electronic nose to locate the source position is raised. Nakamoto et al. attempted to use a semi-stationary electronic nose compass solve source localization task in [8]. Their approach could only produce an approximate source direction each calculation and the accuracy increased with the increase of calculation times. Another weakness of the approach is that their compass need to be handled by hand [8]. Till now, not much scientific literatures about source localization using stationary electronic nose are published. Matthes established a three step method to locate the source position with spatially distributed electronic noses network in advection situations. They have successfully solve this problem with four or more electronic noses [9]. In our research group, we have developed a novel stationary electronic nose system. In addition, we successfully utilized a single such electronic nose to detect directions of a dynamic moving source [10].

This paper presents an extended work based on our previous research. An approach for locating dynamic source position based on a stationary electronic noses network will be developed and discussed in following aspects. In section II, structure of the novel electronic nose system and electronic noses network will be introduced. Source direction detection mathematical solution and models of source dispersal in different wind situations will be discussed in section III. A two-step approach for odour source localization with electronic noses network will be stated and a dynamic method to tracking odour path will also be discussed based on above in section IV. Simulation result and discussion will be presented in section V. Afterwards conclusion is drawn in VI.

II. CONSTRUCTION OF ELECTRONIC NOSES NETWORK

This electronic noses network is built up by two electronic noses. Such electronic nose has special structure which is introduced in [10]. Fig 1 shows such structure. We use four chemical sensors (TGS 2610) spatially equally separated by an impermeable separator. In 3D full view in Fig 1, the height of separator is 20 cm, which is much higher than the height of sensors (1.1 cm). This guarantees that the odour molecules around sensor 1 would not go to other sensors' space, vice verse. We have successfully detect source direction with a single such electronic nose in [10]. Based on the source direction detection method, we established an approach using a two electronic noses network to triangulate the actual source position. To reduce the dimension of the system, we assume that the source and the electronic nose network is placed on an impermeable surface z=0. Thus the system could be considered in a two dimensional xy plane.

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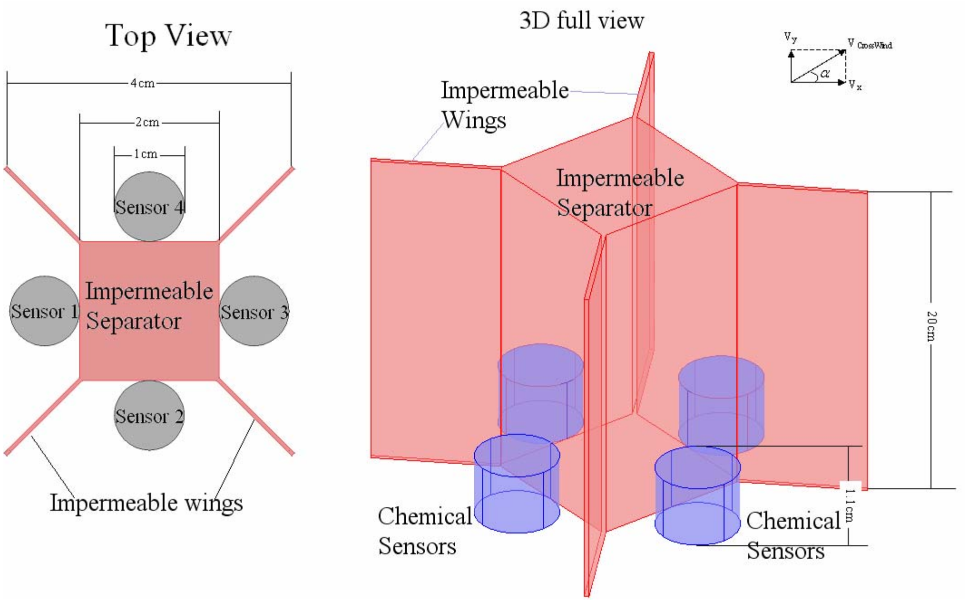


Fig 1. Novel electronic nose system structure

To construct the electronic noses network, firstly create a virtual coordinate system on xy plane and index the two electronic noses. We then placed the two electronic noses on y axis. The coordinate of the centre of Enose 1 and Enose 2 is A(0, y_0) and B(0, $-y_0$) respectively. Fig 2 shows this Enose construction diagram. $P_s(x_s, y_s)$ is coordinate of source position.

In Fig 2, we see that source position is denote by P(x,y), which is cross point of two source directions θ_1 and θ_2 relatively corresponding to Enose 1 and Enose 2 respectively. This is also the basic idea for locating source position.

III. ODOUR SOURCE DISPERSAL MODEL AND MATHEMATICAL SOLUTION FOR DIRECTION DETECTION

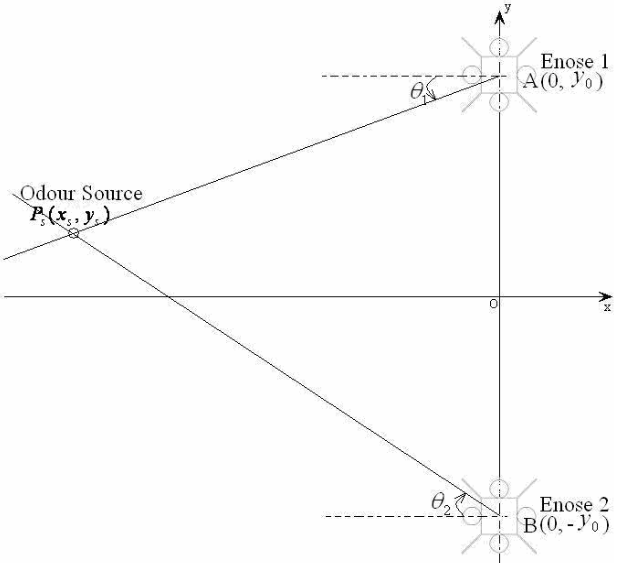


Fig 2. Construction of electronic noses network

There are several ways for odour source dispersing. Generally, it could be divided in to two major categories: diffusion and dispersed by airflow. We have discussed the equation for source concentration distribution in [10]. Normal diffusion could be treated as a special case of airflow dispersal case, in which speed of airflow is zero ($V_{x,y} = 0$). Thus, we will pay more attention to airflow dispersal case, which includes advection and break wind situation. The odour dispersal models and mathematics solutions will be discussed in this section.

A. *Advection case*

1) Dispersal Model: To consider an advection airflow speed (V_x), Matthes gave an equation of concentration advection in [9]:

$$\frac{\partial C}{\partial t} - D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^{2C}}{\partial z^2}\right) + V_x \frac{\partial C}{\partial x} \tag{1}$$

$$= 2q_0 \cdot 1(t - t_0) \cdot \delta(x - x_0) \cdot \delta(y - y_0) \cdot \delta(z - z_0)$$

where C stands for concentration, D is diffusion coefficient, q_0 is initial source rate, x y and z is spatial variables.

Under conditions: $C(P,t) \equiv 0$ for t<t_0 and for all P(x,y), let $P_s(x_s, y_s)$ denote for the source location, we can solve (1) for large time $t(t \to \infty)$, and a steady concentration profile as is given in [9]:

$$C(x,\infty,x_s,q_0) = \frac{q_0 \cdot \exp(-\frac{v_x}{2D}(d-(x-x_s)))}{2\pi Dd} \tag{2}$$

Where d is the distance from a certain point P(x,y) to the source location $P_s(x_s, y_s)$. Equation (2) shows us a steady solution for concentration in advection cases. We have analysis this solution in [10], which indicates that q_0 and d will not affect the ratio $\frac{C_n}{C_1}$ (n=2, 4), where C_n denotes simulated concentration for each sensor in an electronic nose system (see Fig 1). Therefore, $\frac{C_n}{C_1}$ was chosen as a generic discriminant of source direction detection.

2) Mathematics Solution for Direction Detection: The mathematics solution for source direction detection in advection case is given in [10].

We find that $\frac{C_n}{C_1}$ could be presented as a function of source direction angle (θ). Additionally, the ratios, C_2/C_1 and C_4/C_1, are symmetric about the 180^0 axis. A curve fitted (3) is given in [10]:

$$C_2/C_1 = f(\theta) = 2.061\cdot e^{-\left(\frac{\theta-154}{51.63}\right)^2} + 1.095\cdot e^{-\left(\frac{\theta-107.9}{101.7}\right)^2} + 0.6291\cdot e^{-\left(\frac{\theta-501.5}{191.2}\right)^2} \quad (3)$$

Based on above statement, source direction is measurable in advection case by inversely solving (3), $\theta = f^{-1}(\theta)$.

B. *Wind with a Break Case*

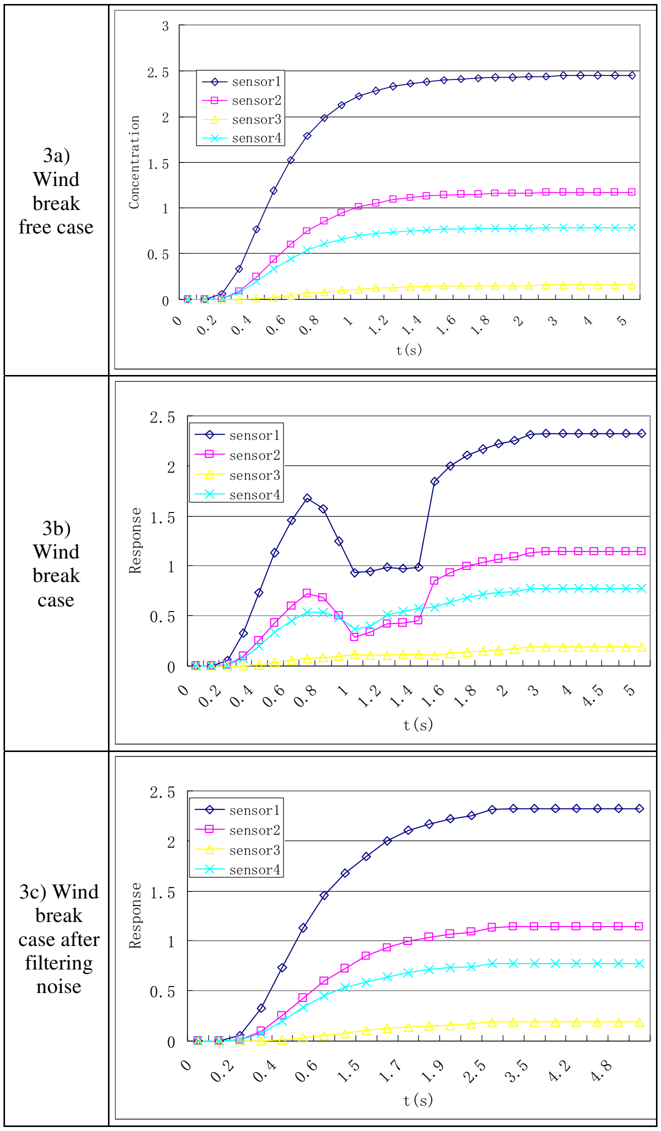
In this section, I will discuss another natural wind case, wind with a break case. This case reports a situation where wind breaks for a period, then recovers as before.

Fig 3 shows the comparison of simulated sensor responses during 5 seconds in wind without a break case and wind with a break between 0.7 and 1.4 seconds.

As well as we know, a break in the wind brings “noise” in the time-zone response of sensors. In Fig 3b), sensors responses interrupted and recovers quickly. By 1.6s, it is again stable. The noise interferes the calculation of odour source directions based on (3). Thus we need to filter the original signal to obtain a smoother curve. We interpolate the sensors’ responses at 1.6s to 0.7s. This simple interpolation technique permits the wind break case to be treated as if it were the wind break free case, by analyzing the steady responses of the sensors. Fig 3c) shows the sensors’ responses after filtering, which is very similar to Fig 3a) sensors’ response in a wind break free case. Obviously, the ratio C_2/C_1 will still track the angle, as it works in previous case.

IV. TWO-STEP METHOD OF SOURCE LOCALIZATION

After discussion of odour source dispersal model and derivation of mathematical solution for source direction detection, we have established the basis to accomplish the approach for source localization with a network containing two electronic noses. The two electronic noses is distributed spatially in the way shown in Fig 2.


3a) Wind break free case

3b) Wind break case

3c) Wind break case after filtering noise

Fig 3. Responses of Sensors for both Wind Break Case and Wind Break Free Case

A. *Static Source*

The approach to solve static source localization includes two steps:

(1) Two electronic noses obtain two source directions relatively;

(2) We then find out the intercross point of these two directions. The point is the source position.

We use θ_1 and θ_2 to represent those two directions detected by Enose 1 and Enose 2 shown in Fig 2. Corresponding to Fig 2, we see that θ_1 is anticlockwise directed and θ_2 is clockwise directed. We use an angle which is clockwise to present a negative angle. Then θ_2 is a negative angle. A$(0, y_0)$ and B$(0, -y_0)$ is coordinate of Enose 1 and Enose 2 respectively. $P_s(x_s, y_s)$ stands for coordinate of source position according to Fig 2.

We could have equation for straight line $\overline{AP_s}$

$$y_s = x_s \cdot \tan\theta_1 + y_0 \tag{4}$$

and an equation for straight line $\overline{BP_s}$:

$$y_s = x_s \cdot \tan\theta_2 - y_0 \tag{5}$$

Then we derive the intercross point of $\overline{AP_s}$ and $\overline{BP_s}$. A set of equations is used to present the coordinate of source position $P_s(x_s, y_s)$:

$$\begin{cases} x_s = \dfrac{2y_0}{\tan\theta_2 - \tan\theta_1} \\ y_s = \dfrac{y_0(\tan\theta_2 + \tan\theta_1)}{\tan\theta_2 - \tan\theta_1} \end{cases} \tag{6}$$

It is easy to utilize equation set (6) and (3) to calculate a static source position.

B. *Dynamic Source*

We have provided a method to detect dynamic source direction with a single electronic nose system in [10]. This method is here adapted to locate the actual source position.

Firstly, we need to convert continuous time into discrete time. Secondly, each discrete time point corresponds to a position. We mark these positions. Source will spend different time interval at different points, as the speed varies. Some positions report a period which is long enough for the electronic nose system to detect correct directions [10]. Those positions will be indexed. The un-indexed position will be ignored in the source movement path. Finally we are able to generate a brief dynamic source movement path. This generated movement path does not record all the details of movement, but it shows the correct movement trend. A sample sketch map shows the indexed movement in Fig 4.

In Fig 4, dot line shows the un-indexed movements, and solid line shows the chosen movements which briefly indicates the movement trend of a source.

We use P_i (i is an increasing integer to record the position index for source) to denote the indexed source positions. We then have a set of simulated concentration for sensor 1 to sensor 4 for both 2 Enoses, which can be denoted as C_{kij} (j=1,2,3,4 and k indicates the Enose numbers 1 and 2).

We then have a set of ratios, $\Psi_{ki2} = \dfrac{C_{ki2}}{C_{ki1}}$ and $\Psi_{ki4} = \dfrac{C_{ki4}}{C_{ki1}}$. At each source position we have a ratio set $\Lambda_{ki} = \{\Psi_{ki2}, \Psi_{ki4}\}$. Based on the static solution, we derive i sets of source directions $\{\theta_{1i}, \theta_{2i}\}$ from Λ_{ki}. Using these directions sets as input of equation set (6), we will get a set of estimated source positions $P_i(x_i, y_i)$. These source positions show us a brief trend of source movement.

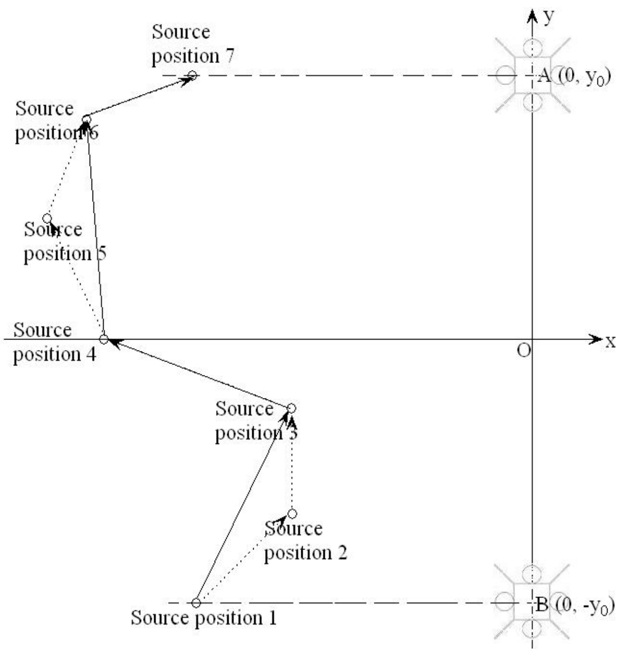


Fig 4. Sketch map for dynamic source movements

Based on analysis above we could have a iteration two step method for dynamic source localization:

a) Use the (3) to calculate θ_{11} and θ_{21} for source before movement;
b) Calculate source position P_1;
c) Repeat step a) and b) when responses of sensors are stable.
d) Generate P_i.

After P_i is calculated, we have an estimate of the source position although this scheme does not record all the details of the source movement.

V. SIMULATION RESULT AND DISCUSSION

We first did simulation in Femlab (Finite Element Analysis tool package) to get the simulated concentration of each sensor in two Enoses. We set wind speed V_x=5 m/s, distance between two Enoses is 1m (coordinates are (0, 0.5) and (0, -0.5) corresponding to Enose 1 and 2 respectively), source concentration is 1000ppm As this method is source and sensor category independent, we do not care about what kind of odour we are detecting. The dimensions of Enose system is based on real FIGARO sensors, shown in Fig 1. We simulate it in two dimensions and the simulation runs 93s for a series points (-1.5, -0.5), (-0.75, -0.3), (-1, -0.2), (-1.5, 0), (-2, 0.2), (-1.5, 0.3), and (-1.0, 0.5), (0, 1.0). Source spends different time at these points. We assume that source will not spend time to move from one point to another.

TABLE I

SIMULATION RESULT OF DYNAMIC SOURCE LOCALIZATION FOR CORRESPONDING POINTS AND TIME

i	Coordinate (m)	Spent time (s)	Time (s)	Enose 1 (ppm)					Enose 2 (ppm)				
				C_1	C_2	C_4	C_2/C_1	C_4/C_1	C_1	C_2	C_4	C_2/C_1	C_4/C_1
1	(-1.5,-0.5)	9	9	161.9	104.1	50.3	0.643	0.311	693.2	290.8	291.4	0.420	0.420
2	(-0.75,-0.3)	2	11	185.7	109.3	44.7	0.589	0.241	764.6	288.0	309.1	0.377	0.404
3	(-1,-0.2)	13	24	275.1	179.0	82.6	0.651	0.300	680.3	234.5	343.9	0.345	0.506
4	(-1.5,0)	20	44	466.5	245.0	162.8	0.525	0.349	466.2	162.8	245.0	0.350	0.526
5	(-2,0.2)	14	58	537.1	227.7	208.6	0.424	0.388	341.5	120.0	182.9	0.351	0.537
6	(-1.5,0.3)	1	59	572.2	291.7	221.5	0.510	0.387	324.9	112.6	245.3	0.347	0.755
7	(-1.0,0.5)	19	78	860.3	352.4	352.0	0.410	0.409	106.9	30.5	80.2	0.285	0.750
8	(0,1.0)	15	93	64.8	16.4	101.0	0.253	1.559	0.6	0.2	0.8	0.333	1.333

Table I shows the simulated concentration result of sensor 1, 2, 4 of Enoses 1 and 2 for corresponding points and time.

Based on the data shown in Table I, we calculate the source direction and coordinate for each indexed positions. The calculation results are shown in Table II.

Position 2 and 6 is shadowed in both Table I and Table II, which differentiates them from other positions, as source stays shortly (2s and 1s respectively) at these points. Sensor can not reach stable state under only 1 or 2 seconds. Thus the calculated coordinate is very far from the real coordinate (see Table II). Therefore, these two positions should be un-indexed.

In addition, we find that position 8 have very small simulated concentration for Enose 2, which could not be used to calculate the source direction and position. However Enose 1 detected it direction is 93.5 degree, which is very close to real direction 90 degree. This case shows us a blind line of this Enose network structure to locate the source. Direction will only be detected for such source lies on the y axis.

For other positions (1, 3, 4, 5, 7), according to Table II, we calculated the mean difference is 0.1m, which is acceptable. Additionally, we found that position 4 and 5 have much larger difference that position 1, 3 and 7, as (3) has largest curve fitting errors around 25 degree.

Fig 5 shows the comparison of estimated source movement path and real source movement path.

TABLE II

CALCULATED DIRECTION AND COORDINATE FOR INDEXED POSITION

i	Real			Calculated			Difference[b]
	θ_1[a]	θ_2[a]	coordinate	θ_1[a]	θ_2[a]	coordinate	
1	33.7	0	(-1.5,-0.5)	32.7	0	(-1.56,-0.5)	0.06
2	44.8	-14.9	(-0.75,-0.3)	27.1	-6	(-1.62,-0.33)	0.87
3	35.0	-16.7	(-1,-0.2)	33.5	-18.2	(-1.01,-0.17)	0.03
4	18.4	-18.4	(-1.5,0)	20.3	-20.3	(-1.35,0)	0.15
5	8.5	-19.3	(-2,0.2)	8.7	-21.6	(-1.82,0.22)	0.18
6	7.6	-28.1	(-1.5,0.3)	19	-43.5	(-0.77,0.23)	0.73
7	0	-45.0	(-1.0,0.5)	0	-42.9	(-1.08,0.5)	0.08
8	90	-90.0	(0,1.0)	93.5	---	---	---

[a] unit of θ_1 and θ_2 is degree

[b] Difference is distance between calculated coordinate to real coordinate

Corresponding to Fig 5, estimated source movement path shows the general trend of source movements.

VI. CONCLUSION

This paper presents an extensive work of our previous research. A two-step approach to locate a static or dynamic odour source position based on our novel electronic nose system network is stated. The estimated source movement path successfully presents the trend of source movement. However, from discussion in section 5, there is a blind line for source localization with this electronic nose system. To overcome this weakness, we could easily add another Enose into this network, which lies on x axis.

Additionally, we have a mean difference (distance between calculated source position and real source position) at 0.1m, which is caused by the accuracy of (3). Equation (3) is a curve fitted equation, which involves errors. Also, we avoid little influence that caused by *d* (see (2)) in this structure. Thus, to decrease this difference, we need to optimize our mathematics model further.

In conclusion, this approach well solved source localization with stationary electronic noses network. In

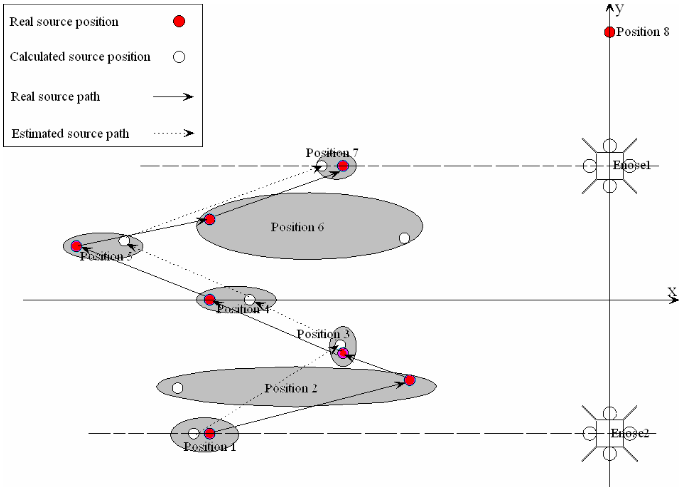


Fig 5. Comparison of estimated source movement path and real source movement path

future, we need to improve on our mathematical model of direction detection and test the method in hardware.

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