A 3D source localization method based on whale optimization algorithm: Experiments for locating a time-varying source in a dynamic indoor environment

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Abstract. To solve the problem of pollutant source localization in an indoor environment with dynamic mechanical ventilation better, this paper designed and built a 3D source localization system composed of three 3D source localization robots whose sensors can move under control in the height direction (0.5 m–1.5 m). Through adopting the 3D source localization system, we realized the application of the previously developed the improved whale optimization algorithm (IWOA) method in 3D source localization and proposed the 3D_IWOA method. To validate the feasibility of the 3D_IWOA method and compare the performance of the 3D_IWOA method and other three 3D source localization methods (the 3D_SPSO, 3D_WU II, and 3D_IPSO methods), each method repeated 15 independent experiments in a Training-Center under the same conditions, respectively. For locating the periodic source at a height of 1.05 m in the downwind zone of this environment, the numbers of successful experiments of the 3D_SPSO, 3D_WU II, 3D_IPSO, and 3D_IWOA methods were 5, 6, 11, and 13 (the success rates were 33.3%, 40.0%, 73.3%, and 86.7%, respectively. In addition, the means of total steps of the 3D_SPSO, 3D_WU II, 3D_IPSO, and 3D_IWOA methods were 36.29 steps, 35.96 steps, 31.75 steps, and 38.15 steps, respectively.

1 Introduction

In recent years, according to data reported by WHO, in developing countries, diseases and premature deaths caused by household air pollution have caused about 3.8 million deaths each year, accounting for 7.7% of global deaths [1]. At the end of 2019, the ravages of COVID-19 [2] around the world triggered a new round of thinking about the new challenges of public health security. The pollution/hazard source location usually needs to be determined first, which is the premise of further implementing countermeasures such as source control, ventilation, decontamination, and personnel evacuation [3].

Aiming at the problem of indoor pollution source localization, most studies use the mobile robot olfactory (MRO) methods. According to the number of robots, MRO methods can be divided into two categories: single-robot and multi-robot active olfactory methods. Multi-robot active olfactory methods are usually based on swarm intelligence, and the typical methods include genetic algorithm [4], PSO [5], ant colony optimization algorithm (AOC) [6], and WOA [7]. At present, the studies of multi-robot active olfactory methods in 2D source localization (the height of the source was fixed and consistent with the height of the source) had made remarkable achievements. However, how to realize the application of multi-robot active olfactory method in 3D source localization (the height of the source is unknown or indeterminate) is still an urgent problem to be solved.

With the gradual deepening of the research on the MRO methods, many scholars are studying new MRO methods to locate constant source in indoor dynamic flow field environment or to locate time-varying source in indoor steady flow field environment [6,8,9]. Among them, the studies on the source localization methods in the indoor dynamic flow field environment mainly focused on the indoor environment with steady mechanical ventilation, and most of the studies were about locating the constant source[10]. Only Feng [11] et al. adopted simulation to validate the feasibility of the PSO method to locate time-varying source in 3D indoor environments. So far, experimental studies on the 3D source localization of time-varying sources in a real indoor environment with dynamic mechanical ventilation have not been reported.

This paper designed a 3D source localization system composed of three 3D source localization robots and proposed the 3D_IWOA method. For locating the periodic source at a height of 1.05 m in the downwind zone of experimental chamber with dynamic mechanical ventilation, the four 3D source localization methods (the 3D_SPSO, 3D_WU II, and 3D_IPSO methods) repeated 15 independent experiments under the same conditions respectively.
2 3D source localization methods

2.1 Overall framework of the source localization method

The 3D IWOA source location method mainly included three stages: plume-finding stage, plume-tracking stage and source-confirming stage, as shown in Fig. 1.

![Flow chart of the 3D source localization methods.](image)

The source localization process was shown in Fig. 1. First, the three robots diverged from the starting position using the plume-finding algorithm. When one robot finds the plume, three robots switched to the plume-tracking stage. In the plume-tracking stage, the robots will constantly track the plume until they found a local extremum area, and then all three robots would enter the source-confirming stage. Once the source was confirmed to be found, the robots terminated the source localization process and reported the source location. Otherwise, they would escape the local extremum area by using the plume-finding algorithm. When the robots found the plume again, it was considered that they have escaped from the local extremum area, and entered the plume-tracking stage until the source was found.

2.2 IWOA algorithm for plume-tracking

The search strategies of the IWOA algorithm mainly simulated the three behaviour patterns of humpback whales: the encircling prey, bubble-net attacking and searching for prey [12].

(1) Encircling prey behaviour

The search strategy of the encircling prey behaviour is the contraction mechanism. Assuming the global maximum location \( P(t) \) of the \( i \)-th robot \( R_i \) at time step \( t \) is the source location, all robots will update their locations according to Eqs. 1 and 2 to approach \( P^*(t) \).

\[
P(t+1) = P^*(t) - \alpha \cdot D + V^*_i \\
D = |C \cdot P^*(t) - P_i(t)|
\]

where \( D \) indicates the random distance between \( P(t) \) and \( P^*(t) \), which is also named the random optimal distance of \( R_i \) at step \( t \); \( A \) and \( C \) are coefficient vectors, as described by the following equation:

\[
A = 2a \cdot r_i - a \\
C = 2r_i
\]

where \( a \) linearly decreases from 2 to 0 as \( t \) increases, resulting in a gradual decrease of the optimal distance \( A \cdot D \) of \( R_i \). It means that the robots can approach \( P^*(t) \) to achieve contracting the encirclement.

(2) Bubble-net attacking behaviour

The search strategy of the bubble-net attacking behaviour is designed with two mechanisms: the contraction mechanism and the spiral renewal position mechanism. Robots move spirally around \( P^*(t) \) while shrinking the encirclement, as described by the following equation:

\[
P_{t+1} = \begin{cases} 
\alpha \cdot P(t) + (1 - \alpha) \cdot P^*(t) & |N| < 1 \\
\frac{P_{\text{rand}}(t) - \alpha \cdot D_{\text{rand}} + V^*_i(t)}{2} & |N| \geq 1 
\end{cases}
\]

\[
D_{\text{rand}} = |C \cdot P_{\text{rand}}(t) - P(t)|
\]

where \( P_{\text{rand}}(t) \) is the location of a randomly selected robot; \( D_{\text{rand}} \) is the optimal distance of a randomly selected robot.

In the plume-tracking stage, if the change of \( P^*(t) \) within \( \Delta T \) is less than or equal to \( V_{\text{max}} \), the robots find a local extremum area and then enter the source-confirming stage.

2.3 Other algorithms

In our previous simulation studies, we have carried out some explorations on the 3D plume-finding and 3D source-confirming algorithms. For details, please refer to our previous related study [7].

2.3.1 3D_Plume-finding algorithm

This paper adopted a simple divergent search strategy to find the plume or escape the local extremum area quickly. In plume-finding stage or escaping the local extremum area, robots diverged from the starting location at the same speed and move in straight lines with same spatial angle to find a larger concentration.

2.3.2 3D_Source-confirming algorithm

In the source-confirming stage, this paper used the maximum concentration method to confirm the source location and terminate the source localization process. After the robots were trapped into the local extremum area, robots will constantly track the plume until they found a local extremum area and then all three robots would enter the source-confirming stage.
area, if the $C^r(t)$ detected by the robots was greater than the $C_{\text{max}}$, the robots would consider the $P^r(t)$ corresponding to the $C^r(t)$ was the source location.

3 Experimental setup

3.1 Experimental environment settings

(1) Experimental site
The source localization experiments were carried out in a Training-Center under the same conditions, where the size of experimental area (the movement range of robots) was $7.65 \times 4.1$ m (Fig. 2(a)). The air supply shutters of the cabinet air conditioner (CAC) were controlled to swing periodically.

![Fig. 2. Experimental environment settings: (a) experimental site photo; (b) the ethanol vapor release device.](image)

(2) Release source
Ethanol vapor was used as a tracer gas in the experiments[13]. As shown in Fig. 2(b), during the experiments, a flask containing ethanol liquid (95%) was heated in a water bath (65 °C) to result ethanol vapor. The periodic switch is set to control the start and stop of the air pump to realize the periodic release of ethanol vapor.

3.2 Development of robots for 3D source localization
To realize sensors can move under control in the height direction, three 3D source localization robots are designed and built (Fig. 3). The components of the robot are divided into three modules according to their functions: the movement, 3D carrier and data acquisition modules. Among them, the movement module includes a robot chassis and a laser ranging radar; the 3D carrier module enables make the sensor move under control in the height direction (0.5 m–1.5 m). The data acquisition module includes an anemometer and gas sensor. And the 3D carrier module was used to control the movement of the anemometer and gas sensor in the height direction.

![Fig. 3. The configuration configuration of the 3D source localization robot.](image)

3.3 Experimental validation framework
As shown in Fig. 4, a total of 60 experiments were conducted in this paper.

![Fig. 4. Schematic diagram of the experimental validation framework.](image)

In the experiments, the plume-finding threshold $C_{\text{min}}$ was 30 ppm, and the source-confirming thresholds $C_{\text{max}}$ was 70 ppm, respectively. If the change in the global optimal position did not exceed 0.4 m within 5 consecutive steps, the robots considered that they had become trapped in a local extremum area. In addition, if the robot moves up to 50 steps, the experiment was terminated and the source localization was considered to have failed. We set the positioning error to 0.5 m[14]. Within 50 steps, if the distance between the source location determined by the robots and the actual source location did not exceed 0.5 m, the experiment was considered successful; otherwise, the experiment was considered to have failed.

4 Results and discussion

4.1 Analysis of source localization results
All experimental results of the four 3D source localization methods are listed in Table 1.

| Source type | Source localization method | Number of successful experiments | Success rate | Mean of total steps (step) |
|-------------|---------------------------|--------------------------------|--------------|---------------------------|
| Periodic source | 3D_IWOA | 13 | 86.7% | 38.15 |
| (1.05 m, at the DZ) | 3D_IPSO | 11 | 73.3% | 31.75 |
| Periodic source | 3D_WU (2) | 5 | 33.3% | 36.29 |
| 3D_SPSO | 6 | 40.0% | 35.96 |

$\$ 15 experiments were conducted for each scenario.

As shown in Table 3, for periodic source at a height of 1.05 m in the downwind zone of an indoor environment with dynamic mechanical ventilation, the success rates of the four 3D source localization methods (the 3D_WU (2), 3D_SPSO, 3D_IPSO and 3D_IWOA methods) were 33.3%, 40.0%, 73.3%, and 86.7%, respectively. The 3D_IWOA method had the highest success rate, indicating the 3D_IWOA method can better locate the periodic sources in the indoor environment with dynamic mechanical ventilation. In addition, from the perspective of the locating efficiency, the means of total steps of the 3D_SPSO, 3D_WU (2), 3D_IPSO, and 3D_IWOA methods were 36.29 steps, 35.96 steps, 31.75 steps, and 38.15 steps, respectively. The mean of total steps of the 3D_IWOA method was only slightly more than those of the other three 3D source localization methods.
4.2 Analysis of the 3D source localization process

Fig. 6 shows the 3D source localization process in which the 3D_IWOA method is used to locate a periodic source at a height of 1.05 m at the DS, and the maximum time-averaged concentration collected by R1–R3 at each step. During the source localization process, the three robots all went through 41 steps and successfully found the source.

As shown in the Fig. 5, at the 6th step, R2 detected a concentration higher than the $C_{\text{max}}$. Due to the global optimal position had not changed from the 14th to 19th step, the plume-tracking algorithm determined that R2 was trapped in a concentration extremum area at the 14th step. But, the concentration detected by R2 at the 14th step was less than the $C_{\text{max}}$, which indicated that the robots were trapped in a local extremum area. And at the 24th step, R2 detected a higher concentration, indicating the robots had successfully escaped the local extremum area and found plume again. Meanwhile, at the 24th step, R3 was trapped into the local extremum area and found plume again. Meanwhile, at the 24th step, R3 was trapped into the local extremum area again, and adopted the 3D_plume-finding algorithm to escape the local extremum area and found plume again at the 31st step. At the 36th step, R2 detected a higher concentration which was more than the $C_{\text{max}}$ and the source confirmation algorithm determined that the source had been successfully located and ended the source localization process. The distance between the source location determined by the robots and the actual source location was 0.21 m (less than 0.5 m). Therefore, this source localization experiment was considered as successful.

From the 3D source localization process of the 3D_IWOA method shown in Fig. 6, it was easy to find that the robots would be trapped into the local extremum area when the robots were conducting 3D source localization. The robot adopted the 3D_IWOA method will move in different directions in the plume-tracking stage, which would expand the search range of robots and help robots escape from the local extremum area.

5 Conclusions

This paper designed a multi-robot 3D source localization system and proposed the 3D_IWOA method. For locating the periodic source at a height of 1.05 m in the downwind zone of the indoor environment with dynamic mechanical ventilation, 15 independent experiments were conducted with four 3D source localization methods (the 3D_SPSO, 3D_WU II, 3D_IPSO, and 3D_IWOA methods), respectively.

(1) The success rates of the four 3D source localization methods (the 3D_SPSO, 3D_WU II, 3D_IPSO, and 3D_IWOA methods) were 33.3%, 40.0%, 73.3%, and 86.7%, respectively.

(2) The means of total steps of the four source localization methods (the 3D_SPSO, 3D_WU II, 3D_IPSO, and 3D_IWOA methods) were 36.29 steps, 35.96 steps, 31.75 steps, and 38.15 steps, respectively.

(3) The trajectories of the robots show that the plume-tracking strategy of the 3D_IWOA method will expand the search range of the robots and help robots escape the local extremum area.

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