Experimental study on multi-robot 3D source localization in indoor environments with weak airflow

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Abstract. The purpose of this paper is to provide a new method for solving the problem of the 3D source localization in indoor environments with weak airflow by the experimental study on the multi-robot method. For this purpose, we developed a 3D MRO (mobile robot olfaction) system consisting of three mobile robots. The gas sensor carried with each robot has a moving range of 0.5 m to 1.5 m on the Z-axis. A total of 60 experiments were conducted to validate and compare the standard whale optimization algorithm (SWOA) and the standard particle swarm optimization (SPSO) methods in a 7.65 m×4.1 m experimental area with two source heights (0.75 m and 1.05 m). For two source heights, the success rate and localization step of the SPSO method are 56.7% (17/30) and 31.4 steps, respectively. In addition, the success rate and localization step of the SWOA method are 80% (24/30) and 32.9 steps, respectively. These results show that the SWOA method has strong application potential in indoor environments with weak airflow.

1 Introduction

In recent years, indoor environmental health and safety issues caused by the diffuse of indoor air pollutants/hazardous substances have attracted worldwide attention [1, 2]. Compared with a ventilated environment, in an unventilated or poorly ventilated indoor environment, pollutants are more likely to accumulate and reach harmful or dangerous concentrations, consequently causing some serious results. For example, in public buildings, insufficient fresh air can cause various respiratory diseases [3] and increase the risk of contracting COVID-19 [4]. In addition, in poorly ventilated confined spaces, dangerous gas leakage can easily lead to severe consequences such as people poisoning and explosion [5].

In indoor environments with weak airflow, the prerequisite of controlling pollutants is locating the sources. Among the existing source localization methods, one type of method is called mobile robot olfaction (MRO) method [6]. This type of method uses mobile robot with necessary sensors to actively search for pollutants in the surrounding environment. Typical algorithms that only use a single robot include planaria algorithm [7], spiral algorithm [8], E.coil algorithm [9], etc., while typical algorithms that use multiple robots include particle swarm optimization algorithm (PSO) [10], whale optimization algorithm (WOA) [11], Ant colony optimization algorithm (ACO) [12], etc. For a more detailed introduction to the MRO method, please refer to the review article [13]. Compared with the single robot method, the multi-robot method improves the localization success rate and localization efficiency.

In the following, representative studies on multi-robot method for indoor environments with weak airflow are introduced. Ferri et al. proposed a biologically-inspired Bombyx mori method [14]. The simulation results of this method showed that the localization efficiency of using multi-robot in cooperation is significantly higher than using a single robot. They further proposed an explorative particle swarm optimization (EPSO) algorithm based on the PSO algorithm [15], which further strengthened the collaboration between robots.

Although the multi-robot methods for indoor environments with weak airflow have made preliminary progress, these studies have assumed that the heights of the source and the gas sensor are unchangeable. Therefore, the existing multi-robot methods for indoor environments with weak airflow can be classified as 2D source localization studies [14, 15]. However, the 2D multi-robot methods may hard locate the sources of different heights in practical applications. Therefore, it is necessary to develop a 3D MRO system in that the gas sensor can move on the Z-axis and study the corresponding multi-robot method.

This study aims to achieve 3D source localization in an indoor environment with weak airflow. For this purpose, we develop a 3D MRO system consisting of three mobile robots. The gas sensor of each robot can move on the Z-axis. In addition, the SWOA and SPSO methods proposed in our previous study were reprogrammed to perform in this system. The feasibility of the SWOA and SPSO methods for 3D source localization are verified and compared in an indoor environment with weak airflow.

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2 Source localization method

2.1 Framework and process

Fig. 1 shows the framework and process of multi-robot methods in this study. The process of SWOA and SPSO methods consist of three phases: plume finding phase, plume tracking phase, and source declaration phase. The core of the above three phases is the plume finding algorithm, plume tracking algorithm, and source declaration algorithm. In addition, to avoid collisions with obstacles and robots, each robot integrated an obstacle avoidance algorithm [16].

As shown in Fig. 1, during the plume finding phase, when any robot detects a concentration higher than the threshold of plume finding $C_{\text{min}}$, all robots switch from the plume finding phase to the plume tracking phase. During the plume tracking phase, if the change of the global optimum location (the location where the maximum value of concentration detected by all robots at the current moment) within five step is not higher than the maximum step length of the robot, the robots consider they are trapped in a local extremum area (an area with a concentration higher than the adjacent areas). In the source declaration phase, if the robots determine that they have found the source, end the source location process. Otherwise, the robots use a plume finding algorithm to escape this area until they find the plume again.

![Fig. 1. The framework and process of multi-robot method.](image)

2.2 Plume finding algorithm

A divergent search strategy is used in the plume finding phase to allow the robots to explore more areas [17]. The robots diverge from the starting positions at the same speed and move in different directions along straight lines. The angles between the trajectories of the robots are the same.

2.3 Plume tracking algorithms

Particle swarm optimization algorithm is a swarm intelligence optimization algorithm inspired by the foraging behavior of birds [18]. The PSO algorithm was applied in the MRO field due to fast convergence and fewer parameters to be adjusted. However, the robots adopting the standard PSO algorithm will reduce the exploration behavior when converging to the global optimum location and easily trapped in the local extremum area.

Whale optimization algorithm is a meta-heuristic optimization algorithm inspired by the hunting behavior of humpback whales. The WOA algorithm searches for the global optimum through three strategies, namely, encircling prey, bubble-net attacking, and search for prey. In the following, we will introduce these three strategies.

(a) Encircling prey

In this strategy, the robots will approach global optimum location and update the coordinates in time to search for the source. The expression of the equation is as follows:

$$\tilde{x}(t + 1) = \tilde{x}^*(t) - \tilde{a} \cdot \tilde{D}$$  \hspace{1cm} (1)

$$\tilde{D} = \tilde{C} \cdot \tilde{x}^*(t) - \tilde{x}(t)$$  \hspace{1cm} (2)

where $\tilde{x}(t)$ and $\tilde{x}(t + 1)$ are the location vectors at step $t$ and step $t + 1$ of robot $R_i$, respectively; $\tilde{x}^*(t)$ is the global optimum location at step $t$; $\tilde{a}$ and $\tilde{C}$ are the coefficient vectors, which equations are as follows:

$$\tilde{a} = 2 \tilde{a} - \tilde{a}$$  \hspace{1cm} (3)

$$\tilde{C} = 2 \tilde{C}$$  \hspace{1cm} (4)

where $\tilde{a}$ will decrease linearly from 2 to 0; $\tilde{C}$ is a random vector distributed between [0, 1].

(b) Bubble-net attacking

During this strategy, the robot selects shrinking encircling or spiral updating randomly with a 50% probability. The shrinking encircling is achieved by Eqs. (1) and (3). The spiral updating calculate the path of a robot according to Equation (5).

$$\tilde{x}(t + 1) = \tilde{D} \cdot e^{bl} \cdot \cos(2\pi l) + \tilde{x}^*(t)$$  \hspace{1cm} (5)

$$\tilde{D} = \tilde{x}(t) - \tilde{x}^*(t)$$  \hspace{1cm} (6)

where $b$ is a constant and $l$ is a random number in the range $[-1, 1]$.

(c) Searching for prey

The robots also randomly explore more areas during the approach to the global optimum location. This mechanism is modeled as follows:

$$\tilde{x}(t + 1) = \tilde{x}_{\text{rand}}(t) - \tilde{a} \cdot \tilde{D}$$  \hspace{1cm} (7)

$$\tilde{D}' = \tilde{C} \cdot \tilde{x}_{\text{rand}}(t) - \tilde{x}(t)$$  \hspace{1cm} (8)

where $\tilde{x}_{\text{rand}}$ is the location vector of the randomly selected robot.

2.4 Source declaration algorithm

The maximum concentration method is used for source declaration. According to the method, if the maximum value of concentration detected by all robots is higher than the threshold of source declaration $C_{\text{max}}$, the robots determine they have found the source.

3 Experimental setup
3.1 Experimental site

All experiments in this study were conducted in a machining workshop (Fig. 2(a)). The movement range of the robots is an area with a length of 7.65 m and a width of 4.1 m (Fig. 2(b)). The starting positions of the robots and the source positions are shown in Table 1. In the experiments, ethanol vapor is used as a tracer gas.

![Fig. 2. Experimental site: (a) Photo; (b) Schematic diagram of the experimental area (SP1–SP3: starting positions of robots).](image)

| Number | Coordinate (m) | X  | Y  | Z   |
|--------|----------------|----|----|-----|
| Source |                | 7.35 | 3.05 | 0.75/1.05 |
| SP1    |                | 1.50 | 0.30 | 0.65 |
| SP2    |                | 1.02 | 0.90 | 0.85 |
| SP3    |                | 0.40 | 1.36 | 1.05 |

3.2 3D MRO system

To test the multi-robot methods in an indoor environment with weak airflow, we developed a 3D MRO system consisting of three robots (Fig. 3). Each robot of the MRO system carried a laser ranging sensor (TFmini-S), a DC motor (JGB37-520), and a gas sensor (MICS 5524). The gas sensor of each robot can move on the Z-axis (0.5 m–1.5 m).

![Fig. 3. The robot of 3D MRO system.](image)

3.3 Source localization experiment

A total of 60 experiments were conducted to verify and compare the SWOA and SPSO methods for 3D source localization. Each method was repeated 15 times at the source heights of 0.75 m and 1.05 m, respectively.

Each robot adopted a "move-stop-move" strategy, that is, after each robot reached a target location, it stayed for 6 s to detect gas concentrations and then continued to move. The movement speed and maximum step length of each robot are 0.3 m/s and 0.5 m. The maximum step length of the gas sensor on the Z-axis is 0.08 m. The thresholds for plume finding and source declaration are 25 ppm and 100 ppm, respectively. In addition, the maximum number of steps of each robot is 50 to avoid spending more time on an experiment.

If the distance between the source location detected by robots and the actual source is within 0.5 m, the experiment is considered successful. Otherwise, the experiment is considered to have failed.

4 Result and discussion

4.1 Analysis of source localization results

All experimental results of the SPSO and SWOA methods are listed in Table 2. The pros and cons of SPSO and SWOA methods were evaluated by the success rate and the localization step. The localization step is the mean number of total steps in successful experiments.

| Source heights (m) | Success rate | Localization step (Steps) |
|--------------------|--------------|----------------------------|
|                    | SPSO         | SWOA                       |
| 0.75               | 53.3%        | 80%                        |
| 1.05               | 60%          | 80%                        |
| Mean               | 56.6%        | 80%                        |

As shown in Table 2, the mean success rate of the SWOA method is 80%, which is higher than the SPSO method (56.6%) by 23.4%. The mean number of localization steps of the SWOA method is only 1.5 steps more than that of the SPSO method (31.4 steps vs. 32.9 steps). Further analysis of Table 2 shows that the SWOA method is insensitive to the height of the source. When the source heights changed from 0.75 m to 1.05 m, the success rate of the SWOA method still was 80%, and the localization step decreased by 0.8 steps. These results show that the SWOA method has strong application potential in indoor environments with weak airflow.

4.2 Source localization process

Fig. 4 shows a successful experiment adopting the SWOA method to locate the source at the height of 0.75 m. Robots determine they have found the source at the 26th step.

As shown in Fig. 4(a), the robots diverge from the starting positions to explore the surrounding environment. After R2 found the plume at 10th step, all robots switched to the plume tracking phase. At 16th step, the robots determine that they have found a local extremum area. However, the maximum value of the concentration up to the current is less than the threshold $C_{\text{max}}$ (Fig. 4(b)).
Subsequently, the robots used the divergence search strategy to escape this area and try to find the plume. After 18th step, the robots escaped from the local extremum area and found the plume again. At 24th step, R2 detected a maximum value of concentration and reached the vicinity of the source (Fig. 4). According to the source declaration algorithm, the robots determined that they had found the source. The distance between the source location determined by the robots and the actual source location is 0.44 m. Therefore, the experiment was successful.

**5 Conclusions**

In this study, we investigate the possibility of the multi-robot source localization method to locate the source in indoor environments with weak airflow. We developed a 3D MRO system consisting of three robots to test the SWOA and SPSO methods in indoor environments with weak airflow. A total of 60 experiments were conducted at two source heights. From the experimental study, the conclusions can be concluded as follows:

1. In an indoor environment with weak airflow, the SWOA method successfully locates the contaminant source, with a success rate of 80% (24/30).
2. Compared with the SPSO method, the SWOA method has strong application potential in indoor environments with weak airflow. The success rate of the SWOA method was higher 23.4% than the SPSO method. Even with a change of source height, the SWOA method still has a success rate of 80%.

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