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Speed limitation of a mobile robot and methodology of tracing odor plume in airflow environments

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Abstract

The methodology of tracing odor plume via a mobile robot is considered. In this research, two typical plume-tracing methods, i.e., a zigzagging method and an upwind method, are tested in four airflow fields with different long-time average wind speeds when the robot is set to possessing four different maximum speeds. According to the simulation results, it can be deduced that the zigzagging algorithms would be efficient when the robot moves faster than the odor plume or airflow, and the upwind algorithms are preferred especially when the robot is slow.

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1. Introduction

Olfaction is widely used by animals in many activities, such as searching for food, finding mates, exchanging information, and evading predators. Inspired by the olfaction abilities of these animals, in the early 1990s, researchers started to try building mobile robots with similar olfaction abilities to replace trained animals [1-4]. This research was called odor source localization (OSL) [4, 5]. It is expected that the odor source localization will play more and more roles in such areas as fighting against terrorist attacks, judging toxic or harmful gas leakage location, checking for contraband (e.g., heroin), searching for survivors in collapsed buildings or waters, and exploring mineral resources erupted in deep seas.

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The OSL can be classified into behavior-based methods and analytical-model-based methods [6], and most work has been done on the behavior-based methods due to original bionic background of the OSL. The behaviour based OSL was decomposed into three sub-procedures (plume finding, plume traversal, source declaration) by Hayes [5] or four sub-procedures (finding a plume, tracing the plume, reacquiring the plume, declaring the source) by W. Li [7]. The plume-finding sub-procedure aims to make the robot contact with odor plume [5, 7, 8]. Once the plume is detected, the plume traversal or plume tracing is switched on and it would make the robot approach the odor source iteratively. Most methods for this sub-procedure are biologically inspired, such as the gradient-following-based algorithms [8-10], the zigzagging algorithms [4, 7, 8, 11], the upwind algorithms [12, 13] and so on. In the final sub-procedure the robot locates the source [7].

A proper plume-tracing method can greatly reduce the time cost and enhance the precision of an OSL task. In airflow environment, as we know, the dispersal of the odor mainly depends on the transportation of the turbulent airflow, forming an intermittent and time-variant odor plume. A smooth concentration gradient is most unlikely to exist in such patchy plumes. Therefore, the gradient-following-based algorithms cannot be used in this case. The zigzagging algorithms try to make the robot follow the odor plume to arrive the odor source by keeping the robot in the plume and moving partially in upwind direction. In contrast, the upwind algorithms try to make the robot approach the source by moving against the wind when odor detection events happen.

This paper tries to provide a suggestion for selection of plume-tracing method considering the speed limitation of the robot in time-variant airflow environments. The maximum speed of the robot is considered because the plume changes with time in time-variant airflow field and apparently there is a requirement of the robot's speed to make the robot keep contact with the plume when a zigzagging algorithm is used. In this research, several airflow fields with different long-time average airflow speeds are used to test a typical zigzagging algorithm and a typical upwind algorithm when the robot has different speed limitations. It is expected to have a conclusion indicating what kind of plume-tracing method should be preferred in what case.

2. Plume-tracing algorithms

A typical zigzagging algorithm proposed in [11] and a typical upwind method named spiral-surge algorithm [13] are considered in this paper, where the concerned zigzagging algorithm is a designed plume-maintaining behaviour with active strategy.

2.1. Plume-maintaining behaviour with active strategy

The robot tries to trace the plume by keeping in the plume and moving partially in upwind direction, as illustrated in Fig. 1(a) [11], where the black dots represent the odor patches. When the first odor detection event happens at time t_f , the robot travels at an angle β relative to upwind direction. The angle β is maintained until another odor patch has not been detected for λ seconds, at which time the robot counterturns to travel at an angle γ with respect to the wind. During the counterturn, if another odor detection event happens in period T_w , the robot starts another plume-maintaining as described above; otherwise the plume-maintaining is thought to be failed and the robot switches to the plume finding again. In this research, $\lambda = 1$ s, $\gamma = \pm 90^{\circ}$, $T_w = 4$ s and β changes with time as follows [11].

$$\beta(t) = \begin{cases} 10^{\circ} & t - t_f < 0.2s \\ 65^{\circ} & 0.2s \le t - t_f \le 0.5s \\ 85^{\circ} & t - t_f > 0.5s \end{cases}$$
(1)



Fig. 1. (a) Depiction of the plume-maintaining behavior [11]; (b) Depiction of the spiral-surge algorithm [13]

2.2. Spiral-surge algorithm

As illustrated in Fig. 1(b) [13], when an odor detection event happens, the robot moves against the wind direction, and this upwind movement is also called surge. During the surge movement, if another odor-detection occurs, the robot resets the surge distance but doesn't resample the wind direction. When the surge distance reaches the step size, the robot begins a spiral movement to search for another odor patch. During the spiral movement, if an odor detection event occurs, the robot re-samples the wind direction and performs another surge movement; if no odor detection event happens in a given period (called cast time), the spiral-surge plume-tracing is thought to be failed and the robot switches to the plume finding again. In this research, the values of the parameters in the spiral-surge algorithm are best ones according to [13], i.e., step size is 1.82 m, spiral gap is 0.62 m, and cast time is 96 s.

3. Simulations

3.1. Simulation platform setup

The randomness is a natural characteristic of the turbulent environment airflow, and this feature will has effect on the procedure of the plume tracing. Therefore, a plume-tracing algorithm should be evaluated in statistical way with large samples which could cost lots of time. This is very difficult in real airflow environments. In this research, a simulation platform developed in [14] is used on which plume-tracing algorithms can be tested in repeatable and controllable environments.

On our simulation platform, each plume-tracing algorithm is tested in different airflow field (the longtime average wind speeds are 0.2, 0.5, 1.0, 2.0 m/s, respectively) with the virtual robot having different speed limitations (the maximum speed are also set to 0.2, 0.5, 1.0, 2.0 m/s, respectively). Therefore, there are totally $4\times4=16$ groups of simulations. In each group of simulation, the robot is started at different location at different time to obtain independent results. The initial locations of the robot are uniformly distributed in the form of 10×10 array (the spacing between adjacent rows or columns is 10m) within a $100 \text{ m} \times 100 \text{ m}$ search area. At each initial location of the robot, 20 different initial times are used in sequence to start the robot. Thus, a plume-tracing algorithm can be tested for 2000 times in total in a group of simulation. In each simulation, the robot starts from the designed position and time to find the plume with the plume finding behaviour proposed in [7]. Whenever an odor detection event occurs, the plume-tracing process is switched on. There are two cases in which the plume-tracing process has to be terminated. One case is that the distance between the robot and the odor source is small enough (<0.5m), the other one is when the plume is thought to be lost and the robot has to find plume again.

3.2. Criterion for Algorithm Evaluation

A criterion named approaching index is proposed and explained in Fig. 2. The red point S represents the odor source. The initial location of the robot is at A and the first odor patch is detected at the location B where a plume-tracing process starts. C stand for the end location where the plume is lost and a plume finding behaviour is launched again. Let d_{BS} and d_{CS} denote the linear distances from the position S to B and C, respectively, and $i_{app}(B)$ denotes the approaching index which is defined as follows. The approaching index indicates how close the robot approaches the odor source after a plume-tracing process.



Fig. 2. Sketch of a plume-tracing trajectory, i.e., the curve from B to C. The trajectory from A to B belongs to a plume finding.

3.3. Results and discussion

Table 1. The average approaching indexes of 32 groups of simulations

Maximum speed of the robot	Plume-maintaining behaviour with active strategy				Spiral-surge algorithm			
Average wind speed	0.2	0.5	1.0	2.0	0.2	0.5	1.0	2.0
0.2	0.11	0.17	0.29	0.35	0.48	0.62	0.70	0.72
0.5	0.06	0.09	0.13	0.16	0.36	0.37	0.41	0.40
1.0	0.05	0.07	0.07	0.06	0.51	0.62	0.65	0.57
2.0	0.05	0.07	0.09	0.06	0.70	0.70	0.76	0.78

* The unit of the speed (of the robot and the wind) is m/s.

For the two concerned plume-tracing algorithms, the average approaching indexes of 32 groups of simulations are shown in Table 1. It can be observed that, in a given airflow field, the average approaching index is increasing in general when the maximum speed of the robot is increasing for both plume-tracing algorithms. For the plume-maintaining method, when the maximum speed of the robot is smaller than or equal to the average wind speed, the robot cannot trace the plume efficiently because the plume changes fast with time in the time-variant airflow field and the robot having relative slow speed almost can not keep step with the plume so as to maintain in the plume and trace the plume to the source. In contrast, for spiral-surge algorithm, it seems that the average approaching index is insensitive to the average wind speed whichever speed limitation the robot has. This means that the spiral-surge algorithm is robust in a time-variant airflow environment. At the end of this section, it is worthy to denote that the average approaching indexes in Tab. 1 cannot be used to make comparisons between the two concerned plume-tracing methods because the parameters in both algorithms are not optimized in this research.

4. Conclusion

This paper provides a suggestion for selection of plume-tracing method considering the speed limitation of the robot in time-variant airflow environments. In this research, several airflow fields with different long-time average wind speeds are used to test a typical zigzagging algorithm and a typical upwind algorithm when the robot has different maximum speed. The simulation results show that, for the concerned zigzagging algorithm, the larger the maximum speed of the robot, the higher the approaching index is in general. When the maximum speed of the robot is smaller than or equal to the average wind speed, the robot cannot trace the plume efficiently in a time-variant airflow field. In contrast, for the concerned upwind algorithm, the approaching index is insensitive to the average wind speed. It can be deduced that the zigzagging algorithms should be used in a plume-tracing procedure when the robot moves faster than the plume or airflow, and the upwind algorithms is preferred especially when the robot is slow.

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