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Abstraction of Odor Source Declaration Algorithm from Moth-Inspired Plume Tracing Strategies

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***Abstract*—A moth behavior-inspired strategy, including tracing a chemical plume to its source and declaring the source location, was tested in near shore ocean conditions via a REMUS underwater vehicle. The field experiments demonstrated the plume tracing distances over 100 m and the source declaration accuracy relative to the nominal source location on the order of tens of meters. However, the source declaration still leaves significant room for improvement.**

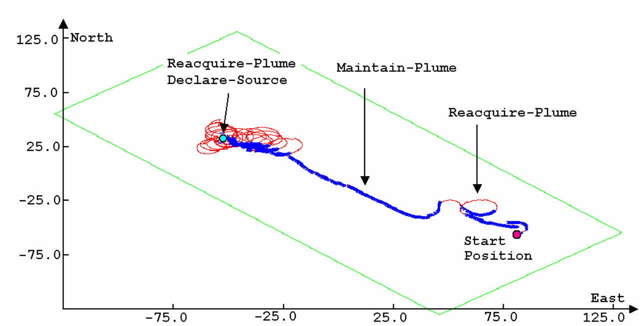
This paper presents two approaches to declaring the odor source location in turbulent fluid environments via an underwater vehicle. The main idea is to use last chemical detection points (`LCDPs`) to construct a source identification zone (`SIZ`) in the order of time series or of the most recent up-flow direction. The performance of the proposed approaches is evaluated using a simulated turbulent fluid environment. The simulation studies show that a success rate in declaring the odor source reaches over 98% and the average error of the declared source locations is less than 1 meter for 1000 CPT test runs in an operation area with length scales of 100 meters.

***Index Terms* — Autonomous underwater vehicles, behavior-based control, chemical plume tracing, odor source declaration.**

I. Introduction

ONE of the greatest challenges to robotics research is to develop autonomous systems capable of rapidly detecting and identifying the sources of hazardous chemicals or pollutants in the real world. This problem, which is referred to as Chemical Plume Tracing (CPT), is of intense interest to homeland security as well as environmental monitoring.

Plume tracing strategies based on both biomimetic [1]-[4] and engineered [7] strategies have been studied and evaluated. Such strategies attempted to solve the CPT problem based on flow information and instantaneous chemical detections. Belanger and Willis [2], [3] presented plume tracing strategies intended to mimic moth behavior and analyzed the performance in a computer simulation. Li et al. [4] developed, evaluated, and optimized both of ***passive*** and ***active*** plume tracing strategies inspired by moth behavior. Grasso et al. [5]-[6] evaluated biomimetic strategies and challenge theoretical assumptions of the strategies by implementing biomimetic strategies on their robot lobster. Robots that replicate simple biological behaviors for plume tracing are also described in [8]-[11]. The works in [12]-[15] tested some insect behavior for plume tracing by using mobile robots in laboratories. All above works mainly addressed the plume tracing issue (travel distance or time cost from finding the plume the first time to a position near the source location). Work in [16] presented a subsumption architecture to integrate certain behaviors for CPT missions, including the issue of source declaration. The ***passive***-based and ***active***-based plume tracing strategies were implemented on a REMUS underwater vehicle and their in-water test runs conducted in November 2002 on San Clemente Island, CA in



(a). A CPT mission for plume tracing and source declaration.

(b). A REMUS vehicle approaching the odor source to identify its location.

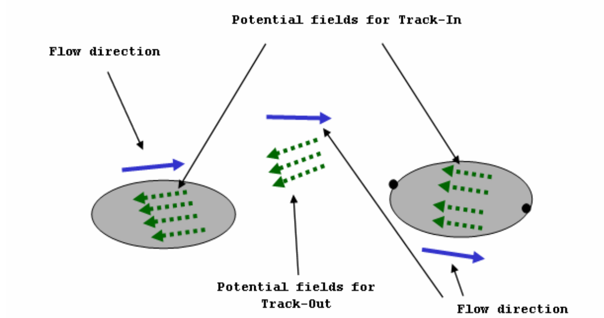
Fig. 1. An in-water test run conducted in November 2002 at San Clemente Island, California, using a plume of Rhodamine dye developed in near shore ocean conditions.

[16]-[17], and in June 2003 at Duck, NC in [18], respectively. The field experiments documented plume tracing distances over 100 m and the source declaration accuracy relative to the nominal source location on the order of tens of meters, as shown in Fig. 1. Although the results demonstrated successful CPT missions in turbulent, near-shore, oceanic fluid flow environments, the source declaration still leaves significant room for improvement.

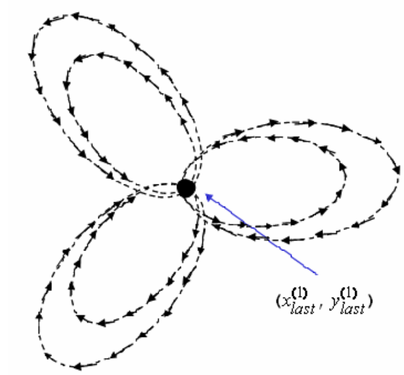
The source identification of the chemical plume in turbulent fluid environments is very difficult, since the advection distance of any detected chemical plume is unknown, and the flow varies with both location and time. The works in [16]-[18] tested the source declaration algorithms based last chemical detection points (**LCDP**s). This paper in detail discusses two **LCDP**-based approaches to declaring the odor source for CPT. The basic idea is to design a source identification zone (**SIZ**) using **LCDP**s which are maintained by a priority queue. The first approach is to construct a **SIZ** in the order of time series, known as **SIZ_T**. The middle of **SIZ_T** is declared as the odor source location, when the **SIZ_T** size becomes small enough during CPT missions; while the second approach is to construct a **SIZ** in the order of the most current up-flow direction, known as **SIZ_F**. **SIZ_F** holds a constant size and chooses the most up-flow **LCDP** as its center. The most up-flow **LCDP** is declared as the odor source location, when **SIZ_T** contains enough **LCDP**s during CPT missions. We evaluate the proposed approaches using a simulated turbulent fluid environment.

II. Moth-Behavior Inspired Plume Tracing

During CPT Missions, the AUV will search for a specific chemical within a specified operation area. If the chemical is detected, the vehicle should trace the chemical plume to its source and accurately declare the source location. In [16]-[18], we proposed a behavior-based strategy for CPT missions, composed of four behaviors: Find-Plume, Maintain-Plume, Reacquire-Plume, and Declare-Source. This paper addresses two approaches to declaring the plume source location. Because the source declaration approaches derived from the reliable plume tracing strategies [4], we briefly review the idea of abstracting the potential fields for Maintain-Plume and Reacquire-Plume from the location of pheromone-emitting females by flying male moths (their more detail discussions can be referenced in [4]). The male moths searching and tracing pheromone are considered a remarkable case of chemical-guided navigation [19]-[23]. These hypothesized behaviors can be summarized as follows. When a moth detects pheromone, it tries to maintain contact with the plume and to move upwind towards the source location. The maneuver is exhibited as a short sprint predominantly in the upwind direction. Repeated pheromone encounters result in the moth progressively approaching the chemical source. When a moth has not detected pheromone for a sufficiently long period of time, it ceases upwind movement and performs



(a). Potential fields for Track-In and Track-Out activities, which depends on the instantaneous flow direction.



(b) Potential fields for the Reacquire-Plume behavior, which generates Cloverleaf-shaped trajectories with the center location $(x_{last}^{(1)}, y_{last}^{(1)})$.

Fig. 2. Potential fields for plume tracing, including Maintain-Plume and Reacquire-Plume. The assumed flow direction is from the left to the right.

progressively widening crosswind excursions, termed 'casting'. In this case, the moth appears to be searching for pheromone near the position where it was last detected. This reacquiring behavior can continue for several seconds until either chemical is again detected or the moth behavior changes.

To maintain contact with the chemical plume at least intermittently during CPT missions via an underwater vehicle, Maintain-Plume is defined by two activities: Track-In and Track-Out. Their potential fields, generating the vehicle commands for the orientation θ and the velocity v, are defined

$$\begin{aligned} \theta &= w_d(t, x, y) + 180^\circ + \Delta\theta(t)_{\mathtt{Track-In}} \\ v &= v_c \\ & \qquad t \in T_{\mathtt{above}} \end{aligned} \quad (1)$$

$$\begin{aligned} \theta &= w_d(t, x, y) + 180^\circ + \Delta\theta(t)_{\mathtt{Track-Out}} \\ v &= v_c \\ & \qquad t \in T_{\mathtt{below}} \end{aligned} \quad , (2)$$

where $w_d(t, x, y)$ is the flow direction, both $\Delta\theta(t)_{\mathtt{Track-In}}$ and $\Delta\theta(t)_{\mathtt{Track-Out}}$ are the offset angles for Track-In and Track-Out activities, $\mathbf{T}_{\mathtt{above}}$ and $\mathbf{T}_{\mathtt{below}}$ are durations for Track-In and Track-Out activities, illustrated in Fig. 2a.

The objective of Reacquire-Plume is to reacquire contact with the plume in the situation where chemical has not been detected for at least a few seconds. The last chemical detection point (**LCDP**), (x_{last}, y_{last}), is recorded, when the AUV switches its behaviors from Maintain-Plume to Reacquire-Plume. **LCDP**s are very important to design both of Reacquire-Plume and Declare-Source. The probability of casing for the plume near the most recent **LCDP**, $(x^{t(1)}_{last}, y^{t(1)}_{last})$, is higher, since $(x^{t(1)}_{last}, y^{t(1)}_{last})$ provides most recent information about the detected chemical plume. Here, **Cloverleaf** functions with the center $(x^{t(1)}_{last}, y^{t(1)}_{last})$ are used to design the potential fields of Reacquire-Plume shown in Fig. 2b. Leaves 1 and 2 (upper left and lower left) of **Cloverleaf** provide significant cross-flow excursions designed to contact the plume in meander situations. Leaf 3 is aligned with the plume centerline in the down-flow direction. This leaf is very important when the vehicle has passed the chemical source location. The attractive fields for this behavior are given

$$\begin{aligned} \theta &= \mathbf{actan\,2}(x_i - x_c, y_i - y_c) \\ v &= v_c \end{aligned} \quad , \qquad (3)$$

where (x_i, y_i) on **Cloverleaf** is chosen as a subgoal, as shown in Fig. 2b, and (x_c, y_c) is a current location of the vehicle. This behavior will stay active until either chemical is detected or the AUV completes the cloverleaf trajectory **N_re** times. If chemical is detected, Maintain-Plume will activate and inhibit Reacquire-Plume.

III. Source Identification Zone Based Approaches

This section discusses how to design the Declare-Source behavior based on the recorded **LCDP**s. The Declare-Source behavior is of importance for CPT missions. Its objective is to estimate and declare the chemical source location. The declaration must be accurate and reliable in the sense that it makes no false declarations. Being different from Maintain-Plume and Reacquire-Plume, the design of Declare-Source is much more difficult, because there is no clear analog to the AUV declare source behavior for male moths. For biological entities (e.g., moths), the conclusion of declaring the pheromone source location may be still mystery. Instead, while the moth plume tracing relies primarily on sensed pheromone, the final determination as to the location of the female moth could be based on data from multiple sensors, which may include vision, tactile, or even auditory cues. However, for CPT using AUVs, the present state of technology requires that we determine the chemical source location based only on the locations of chemical detection events. In our application, available information for making the source declaration includes a set of the detected above-threshold concentration positions during CPT missions and an instantaneous flow direction. Here, we propose two approaches to identifying the odor source location based on a set of the last chemical detection points (**LCDP**s).

Due to the design of the maintain and reacquire behaviors,

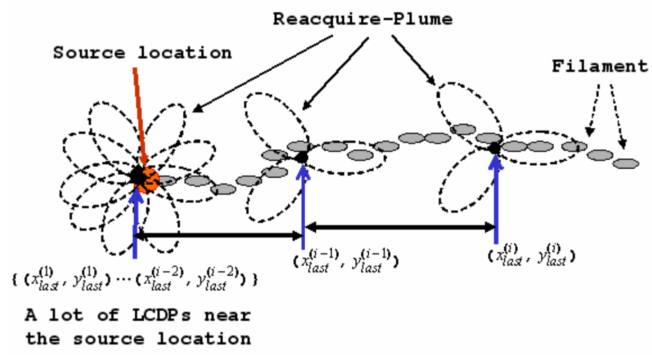


Fig. 3. Pattern for the source identification based on **LCDP**s in the order of the up-flow direction, which is assumed from left to right.

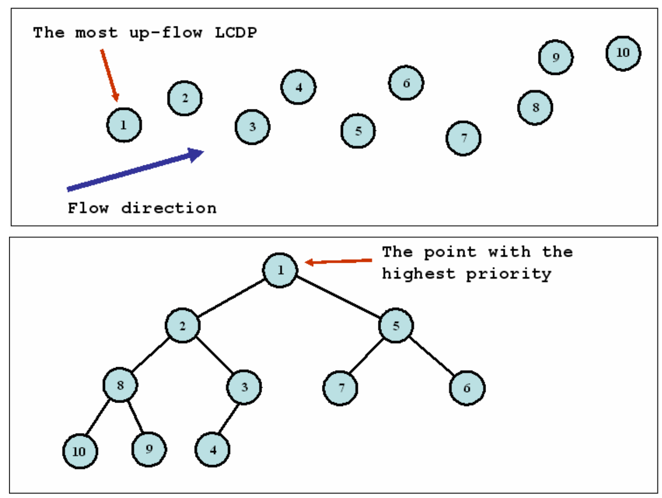


Fig. 4. Maintain the last chemical detection points (**LCDP**s) in the order of the current up-flow direction by a heap-based priority queue.

as verified in Monte Carlo simulation in [4] and in-water studies in [16]-[18], the AUV alternatively utilizes the Maintain-Plume and Reacquire-Plume in making progress towards the source location in the up-flow direction, that means, once the vehicle detects a chemical plume, Maintain-Plume is activated, and when the AUV loses a contact with the chemical plume for a few seconds, it switches to Reacquire-Plume for casting the plume again. The AUV usually exits the plume and move up flow from the source, when it traces the plume to the source location. After the vehicle overshoots the odor source, it activates Reacquire-Plume and usually re-contacts the plume on Leaf 3 of the **Cloverleaf** trajectory since leaves 1 and 2 may be up-flow from the **LCDP**. The important fact is: These **LCDP**s are separated along the axis of the plume, when the AUV is far from the source location; while the **LCDP**s get closer and are located near but down-flow from chemical source location, when the AUV is approaching near the source. Fig. 3 shows the pattern for the distribution of the **LCDP**s during CPT missions. Therefore, a suitably close clustering of the **LCDP**s can be used for the source declaration. In our application, a priority queue is used to maintain this set of the **LCDP**s. The principle operations on a priority queue are finding its item with the highest priority, adding a new item to the set, and deleting the item with the highest priority. A **LCDP**, (x_{last}, y_{last}), is inserted into the priority queue, when the AUV switches its behaviors from Maintain-Plume to Reacquire-Plume. The set of **LCDP**s can be sorted in the order of the time when **LCDP**s are detected or in the order of the current up-flow direction. During the CPT mission, the priority queue accumulates **LCDP**s down-flow from chemical source location. The more **LCDP**s the priority queue accumulates, the more information about the source location the vehicle gathers. Fig. 4 shows an example of a priority queue contains ten **LCDP**s in the order of the instantaneous up-flow direction. Each circle represents a **LCDP** and its number indicates its priority. The smaller the number is, the higher the priority associated with the point is. The following sections describe two approaches to identifying the odor source location based on a source identification zone (**SIZ**).

The first approach is to dynamically monitor the size of a **SIZ_T**. In this approach, the **LCDP**s in the priority queue are sorted in the order of time, and the six most recent **LCDP**s are used to construct **SIZ_T** whose size is determined by

$$\begin{aligned} x_{last}^{(min)} &= \mathbf{min}\{x_{last}^{t(i)}\} \\ x_{last}^{(max)} &= \mathbf{max}\{x_{last}^{t(i)}\} \\ y_{last}^{(min)} &= \mathbf{min}\{y_{last}^{t(i)}\} \\ x_{last}^{(max)} &= \mathbf{max}\{y_{last}^{t(i)}\} \qquad i = 1, \cdots 6 \end{aligned} \quad . \tag{4}$$

where a superscript ***t*** is used to indicate that **LCDP**s are sorted in the order of time series. The important fact is that the size of **SIZ_T** becomes smaller (see discussions above) while the AUV approaches the source location. During CPT missions, the AUV dynamically checks the diameter of **SIZ_T**

$$\sqrt{(x_{last}^{(max)} - x_{last}^{(min)})^2 + (y_{last}^{(max)} - y_{last}^{(min)})^2} \ . \tag{5}$$

When the diameter $\leq \varepsilon_T$, the mean value

$$\begin{aligned} \bar{x}_{last}^{t} &= \sum_{i=1}^{6} x_{last}^{t(i)} \ / \ 6 \\ \bar{y}_{last}^{t} &= \sum_{i=1}^{6} y_{last}^{t(i)} \ / \ 6 \end{aligned} \tag{6}$$

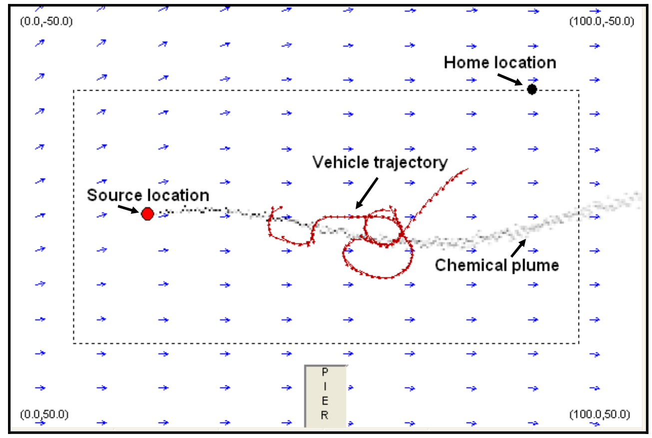
is declared as the source location.

The second approach is to dynamically construct a **SIZ_F** by **LCDP**s that are sorted in the order of the current up-flow direction. **SIZ_F** holds a constant size ε_F, and its center is initialized by the most up flow $(x_{last}^{f(1)}, y_{last}^{f(1)})$. The following iterative construct is used to identify the source location. First, the point $p_{\mathbf{max}}$ with the largest distance to

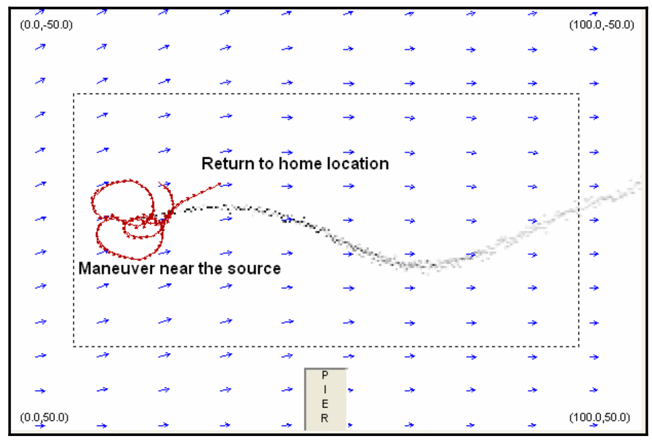
$$D_{\mathbf{max}} = \mathbf{max}\left\{\sqrt{(x_{last}^{f(i)} - x_{last}^{f(1)})^2 + (y_{last}^{f(i)} - y_{last}^{f(1)})^2}\right\} \tag{7}$$

$$(i = 2, \cdots N)$$

is found from the priority queue, where a superscript ***f*** is used



(a). AUV starts its CPT mission from the home location, including plume finding and plume tracing (Maintain-Plume and Reacquire-Plume).



(b) AUV completes its CPT mission and returns the home after declared the source location.

Fig. 5. The chemical source declaration by using **SIZ** based approaches in a simulated turbulent fluid environment. The head-to-tail arrows indicate the vehicle trajectory during a CPT mission. The grayscale indicates above threshold concentration. The arrows in the operation area indicate the magnitude and direction of the local flow vector at the tail of the arrow.

to indicate that **LCDP**s are sorted in the order of the most recent up-flow direction and ***N*** is the number of the **LCDP**s in the queue. Second, the point $p_{\mathbf{max}}$ is removed from the set of **LCDP**s, if $D_{\mathbf{max}}$ is greater than ε_F. This calculation repeats until all the remaining **LCDP**s are close enough to the **SIZ_F** center $(x_{last}^{f(1)}, y_{last}^{f(1)})$, i.e., they all are located inside **SIZ_F**. When this situation occurs, the most up-flow **LCDP** $(x_{last}^{f(1)}, y_{last}^{f(1)})$ in the priority queue is declared as the plume source location, only if the number of the remaining **LCDP**s is greater than $N_{\mathbf{min}}$. The idea of the second approach is to find out a zone in which the most of **LCDP**s are close to each other and to choose the most up-flow **LCDP** as the odor source location.

IV. Results

A number of simulation test runs are performed using a

TABLE I
PERFORMANCE AND ACCURACY OF THE SOURCE DECLARATION APPROACHES

Methods (1000 runs)	Success rate	Spurious declaration / over time	Source declaration error, meters	Error within 2 meters	Error within 2-5 meters	Error within 5-10 meters	Time cost for declaration, seconds
SIZ_T ε_T = 6m 6 **LCDP**s	980 of 1000 (98.0 %)	6 of 1000 / 14 of 1000	$\Delta\bar{x}$=3.27 m $\Delta\bar{y}$=0.00 m	86 of 980 (8.78%)	848 of 980 (86.09%)	38 of 980 (3.86%)	$\bar{T}_D$ = 218.48s
SIZ_F ε_F = 6m N_{min} = 6	984 of 1000 (98.4 %)	10 of 1000 / 6 of 1000	$\Delta\bar{x}$= 0.77 m $\Delta\bar{y}$= 0.00 m	874 of 984 (88.82%)	99 of 984 (10.06%)	10 of 984 (1.02%)	$\bar{T}_D$ =186.79s

simulated turbulent fluid environment to verify the effectiveness of the proposed approach to identifying the plume source location. The operation area is specified by [0,100]×[-50,50] in meter. The filament release rate is 10 filaments s^{-1}, the simulation time step is 0.01 s, and the mean fluid velocity 2m s^{-1}. During the simulation studies, the measured fluid flow is corrupted by additive noise that is white normal random process. The vehicle home location is defined as (80, -30) m in the operation area. The coordinate of a source location is chosen as (20, 0) m, which is just used to check the accuracy of the declared source location, but it is unknown to the AUV during the CTP missions. The operation time is limited within T_{max} =1000 seconds. A CPT mission fails, if the AUV cannot declare the source location within T_{max} ; Otherwise the time cost is recorded and the odor source location is declared. For each CPT mission, the AUV starts at the home location and returns to the home location, when the AUV identifies the source location or reaches its maximum mission time T_{max} . The dynamics model of a REMUS vehicle is used in simulation test runs. The REMUS vehicle is fin controlled. Its velocity range is from 0.25 m to 2.8 m s^{-1}, and it requires a large (5-10 m) turning radius to change orientation. In our simulation studies, the maximum speed command for the vehicle is 2.0 m s^{-1}.

In order to compare the performance of the **SIZ_T** and **SIZ_F** approaches, both approaches are implemented in the same procedure to identify the source location concurrently. This is reasonable because these both **SIZ**-based approaches rely on the same Find-Plume, Maintain-Plume and Reacquire-Plume activities. If one of the approaches declares the source location, the coordinates of the declared source location and the associated time cost are recorded, and then this approach is deactivated. The vehicle continues its CPT mission until the other approach identifies the source location or the operation time reaches its time limit T_{max} .

A successful CPT mission of the vehicle is defined as follows: The vehicle starts from the home location and utilizes Find-Plume, Maintain-Plume and Reacquire-Plume activities to find a chemical plume, trace the chemical plume towards to the source location. The vehicle returns the home location after it declares the odor source location, and then this CPT mission completes, as shown in Fig. 5. A CPT mission fails, if the vehicle could not declare the source location within T_{max} . The time cost for a source declaration activity is defined by the period from the time when the vehicle reaches a point within 10 meters to the source location to the time when the odor source location is identified. In test runs, the parameter ε_T for **SIZ_T** approach is chosen as 6 meters to check the **SIZ_T** size, determined by the six most recent **LCDP**s. The parameters for the **SIZ_F** approach are selected as ε_F =6 meters and N_{min}=6.

The simulation studies continue 1000 CPT test runs which keep changing the chemical plume in a turbulent fluid environment over 130 hours. Table I documents the performance results of the run tests. We evaluate the performance of the both **SIZ**-based approaches in the three aspects: Reliability, accuracy, and time cost. Both approaches achieve a high success rate in declaring the odor source of 98.0%. During 1000 test runs, **SIZ_T** has six spurious declaration and 14 test runs over time limit; while **SIZ_F** has six test runs over time limit and 10 spurious declarations. The accuracy of the source locations declared by **SIZ_F** is higher than that declared by **SIZ_T**. Their average errors are 0.77 meter and 3.27 meters, respectively. Note that, using **SIZ_F**, the average error less than 1 meter in an operation area with length scales of 100 meters is a remarkable. Columns 5-7 in Table I also show a distribution of the declared source locations in three groups: within 2 meters, between 2 and 5 meters, and between 5 and 10 meters. It is clear that the **SIZ_F** approach really reaches a very high accuracy during CPT missions, since 88.82% of the source locations declared by **SIZ_F** are located within 2 meters; while the **SIZ_T** approach just reaches 8.78% within 2 meters. The average time cost for the odor source declarations spent by **SIZ_F** and **SIZ_T** is 186.79 seconds and 218.48 seconds, respectively. This result demonstrates that, in average, the **SIZ_F** approach saves about 14.5% energy in comparison with the **SIZ_T** approach.

V. CONCLUSION

The plume source identification during CPT missions is very difficult, since the advection distance of any detected chemical plume is unknown, and the flow varies with both location and time. Being different from Maintain-Plume and Reacquire-Plume, there is no clear analog to the AUV declare source behavior for biological entities, because the conclusion of declaring the pheromone source location by male moths may be still mystery. Also, the vehicle dynamics must be considered in real application, which makes the source declaration more complicated.

This paper presents two approaches to identifying the odor source location in turbulent fluid environments. Our proposed approaches are based on the last chemical detection points (**LCDP**s), instead of every chemical detection point, during CPT missions. The concept of a **LCDP** is interpreted by the last position where the vehicle has a contact with the chemical plume during a Maintain-Plume activity before the AUV switches its behavior to Reacquire-Plume. The important fact is that the distance between every two **LCDP**s reflects the plume tracing distance in each Maintain-Plume activity. If the vehicle is far from the source location, this distance must be bigger because the vehicle uses mainly Maintain-Plume towards the source location in the up-flow direction. If the vehicle is close to the source location, this distance becomes smaller because the vehicle overshoots the source location, and alternatively activates Reacquire-Plume and Maintain-Plume with a high frequency. That is why the vehicle generates a pattern with a number of **Cloverleaf** trajectories around the source location, shown in Fig. 1 and Fig. 3.

The simulation test runs demonstrate that both approaches achieve high success rates. Especially, the **SIZ_F** approach declares the odor source locations with a very high accuracy and needs much less energy to complete the CPT missions than the **SIZ_T** one. In the future work, the proposed approaches will be tested and verified by using real experimental plume data.

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