From Simulation to Validation: Moth-Inspired Chemical Plume Tracing with an Autonomous Underwater Vehicle

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Abstract— Chemical plume tracing capability is important for autonomous underwater vehicles (AUVs) to perform a variety of ocean exploration and exploitation missions. For studying and validating moth-inspired chemical plume tracing algorithms, Shenyang Institute of Automation, Chinese Academy of Sciences developed an AUV equipped with multiple sensors, including an underwater fluorometer and a Doppler velocity log (DVL). Based on the AUV’s dynamics and its path-following capability, a path-following based algorithm implementation of the moth-inspired chemical plume tracing strategy was developed. To validate the algorithm, computer simulation and field experiments were conducted. This paper presents the path-following based algorithm of the moth-inspired chemical plume tracing strategy and the systematic study on the algorithm, from computer simulation via proper numerical plumes, to field experiments with the AUV and Rhodamine dye plumes performed at Dalian Bay, China in 2010.

Keywords—autonomous underwater vehicle; chemical plume tracing; odor source localization; behavior-based planning; bio-inspired robot

I. INTRODUCTION

Autonomous underwater vehicles (AUVs) are significant tools in ocean survey, exploration and exploitation missions. In a number of these missions, such as discovering deep-sea hydrothermal vents, searching for unexploded ordnance, finding oil spill sources, and localizing sources of hazardous chemicals, etc., AUVs’ capability of chemical plume tracing is important for efficient accomplishment of these missions. In ocean environments, the development of chemical plumes are under the influence of turbulence, varying currents and tides, and surface or internal waves, etc., resulting in that the instantaneous plume distribution being irregular and non-uniform, the plume filament being intermittent, the plume centerline being meandering, and the flow in the plume not always directing to the plume source location, which complicate the chemical plume tracing problem. Therefore, designing an effective AUV chemical plume tracing strategy, i.e., designing a control strategy that navigates an AUV in response to real-time sensor information to find a chemical plume, to track the plume toward its source, and finally to reliably and accurately pinpoint the source location, is challenging and has been directed a lot of research interests.

For the potential applications of chemical plume tracing with autonomous robots and vehicles, during last two decades enormous efforts have been made to design chemical plume tracing strategies for autonomous robots and vehicles, and a variety of strategies have been proposed using different approaches. In natural world, long-range chemical plume tracing by animals and insects for homing, foraging, host or mate seeking, etc. has been observed and documented. Inspired by the remarkable chemical plume tracing capabilities, many researchers try to replicate the chemical plume tracing behaviors of animals and insects in robots and vehicles and develop biomimetic chemical plume tracing strategies. Fundamental aspects of these research efforts include sensing the chemical with a single sensor or a sensor array, sensing or estimating the fluid flow, and generating a sequence of robot speed and heading commands based on the instantaneous or very recent sensor information such that the resulting robot motion is likely to approach the chemical source, and typical maneuvers include: sprinting up flow upon chemical detection and moving cross flow when not detecting; manipulating the relative orientation of a multiple sensor array, either to follow an estimated plume boundary or to maintain the maximum mean reading near the central sensor.

However, most of the bio-inspired chemical plume tracing researches did not discuss the problem of the plume meander as they discussed the plume tracing issue with scales of several centimeters to a few meters, and experimental studies described in most of the existing literature have occurred in structured laboratory environments. In addition, most of work did not consider the complete mission behaviors including the plume finding, plume tracing and plume source identification which are required for field applications. In order to develop effective strategies for tracking the plume at distance from the source where it is possible that neither the plume centerline nor the flow direction point to the source, Li et al. [1] developed, evaluated and optimized both passive and active chemical plume tracing strategies inspired by moth plume tracing behavior. Based on these strategies, Li et al. [2] and Farrell et al. [3] developed complete chemical plume tracing strategies for chemical plume tracing experiments in ocean environments with an AUV. The strategies were implemented on a REMUS AUV with a single chemical sensor for the experiments in November and April 2002 at the San Clemente Island of California and in June 2003 in Duck, North Carolina. The field experiments successfully demonstrated tracking of Rhodamine dye plumes over 100 m in the near shore, oceanic fluid flow environments. The moth-inspired chemical plume tracing strategies in [2, 3] provide an effective approach to chemical plume tracing with AUVs in complicated ocean environments.

In this paper, we present further field experiments on the moth-inspired chemical plume tracing strategy [2, 3] with Rhodamine dye plumes and an AUV with a single chemical
sensor. Different from the field experiments reported in [2, 3], in these experiments the Rhodamine dye plumes were developed on the water surface instead of near the sea bottom, and a different type of AUV with better maneuverability and path-following capability was employed, which was developed by Shenyang Institute of Automation (SIA), Chinese Academy of Sciences for the field experiments. In addition, considering the AUV's dynamics and the AUV’s path-following capability, we implement the chemical plume tracing strategy based on the path-following algorithm, for better realization of the moth-inspired chemical plume tracing strategy on the AUV. Since computer simulation evaluation and validation is a key step before field experiments, we perform simulation runs of chemical plume tracing with numerical plumes generated by a proper chemical plume model (The model captures the key features of chemical plumes in natural environments including significant plume meander and intermittency between plume puffs), and with a virtual AUV and the real AUV, respectively. This paper presents the path-following algorithm and the path-following based algorithm implementation of the chemical plume tracing strategy, and reports the systematical study on the moth-inspired chemical plume tracing with the AUV, including computer simulation and field experiments.

This paper is organized as follows. In section II, we describe the moth-inspired chemical plume tracing strategy. In section III, we present the path-following guidance algorithm. In section IV, we describe the path-following based algorithm implementation of the chemical plume tracing strategy. In section V, we validate the chemical plume tracing strategy with numerical plumes generated by a proper plume simulation model. In section VI, we describe the experiments on virtual plume tracing with real AUV. In section VII, we report the Rhodamine dye plume tracing experiments with the AUV, which were performed at Dalian Bay, China in 2010. In section VIII, we draw some conclusions.

II. MOT-INSPIRED CHEMICAL PLUME TRACING STRATEGY

Chemical plume tracing is significant in the life of animals and insects, such as homing, foraging, host-seeking, and mate-seeking. For chemical plume tracing tasks, the location of pheromone-emitting females by flying male moths is considered to be a remarkable case. The chemical plume tracing behaviors exhibited by moths could be summarized as follows. When a moth detects pheromone, it tries to maintain contact with the plume and to move upward toward the source location, with the maneuver being a short sprint predominantly in the upward 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 upward movement and performs 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. If the moth fails to detect pheromone again, it may return to the Find-Plume behavior used initially for location of the plume.

Inspired-by the moth plume-tracing behavior, Li et al. [2] developed a behavior-based planning strategy for tracking turbulent chemical plumes with an AUV in two dimensions. The strategy takes the information from the chemical sensor and the flow sensor as input, and outputs the commanded AUV heading $\psi_c$ and speed $v_f$. The strategy considers the full spectrum of field behaviors for conducting chemical plume tracing missions in near-shore ocean environments, and consists of four fundamental behaviors coordinated in a subsumption architecture: finding the plume (Find-Plume), maintaining the plume (Maintain-Plume), re-acquiring the plume (Reacquire-Plume), and identifying the source location (Declare-Source).

The Find-Plume behavior is designed to dominantly implement a cross-flow search for the entire predefined operational area without any assumptions about the location of the plume source. The commanded heading is defined as $\psi(t) = f_{\psi}((&x, &y) + \text{sign}(&\eta) \Delta \psi(t), t)$, which is an offset to the computed flow direction $f_{\psi}$ at time $t$ and the AUV location $(x, y)$, $\eta = 0.5((Y_{min} + Y_{max}) - y$ and its sign will be $\pm 1$, where $[X_{min}, X_{max}] \times [Y_{min}, Y_{max}]$ specifies the plume-tracing operational area. The variable $\Delta \psi(t)$ is an offset angle used for up-flow or down-flow search, and can only take on one of the two constant values $\Delta \psi(t)_{\text{up}}$ (for up-flow search) or $\Delta \psi(t)_{\text{down}}$ (for down-flow search). How to choose an initial direction to start the Find-Plume behavior is discussed in [2].

The Maintain-Plume and Reacquire-Plume are inspired by the behaviors hypothesized from observations of pheromone plume-tracing moths. The Maintain-Plume replicates the behavior of moths to track a plume and includes Track-In and Track-Out activities. Track-In tries to make rapid progress toward the source while chemical is being detected. Track-Out manipulates the AUV to rapidly re-contact the plume immediately following the loss of chemical detection. Track-In and Track-Out are described by:

$$
\begin{align}
\psi &= f_{\psi}((&x, &y) + 180^0 \pm \Delta \psi(t)_{\text{Track-In}}, t \in T_{\text{Track-In}}) \\
\eta &= v_{\text{Track-In}}
\end{align}
$$

$$
\begin{align}
\psi &= f_{\psi}((&x, &y) + 180^0 \pm \Delta \psi(t)_{\text{Track-Out}}, t \in T_{\text{Track-Out}}) \\
\eta &= v_{\text{Track-Out}}
\end{align}
$$

where $\Delta \psi(t)_{\text{Track-In}}$ and $\Delta \psi(t)_{\text{Track-Out}}$ are the offset angles for Track-In and Track-Out, $v_{\text{Track-In}}$ and $v_{\text{Track-Out}}$, and $T_{\text{Track-In}}$ and $T_{\text{Track-Out}}$ are commanded AUV speeds and durations for Track-In and Track-Out, respectively.

If Track-Out fails to detect chemical plumes within a given period of time, then the AUV switches to Reacquire-Plume behavior which maneuvers the AUV to search for the plume in the vicinity of the most recent chemical detected location, as a moth does with the casting behavior. A cloverleaf shaped trajectory or its variant [3] was used to implement the Reacquire-Plume behavior to cast for the lost chemical plume. The commanded AUV heading is calculated using the line of sight guidance method: $\psi_c = \text{atan} 2((y, y, x) - x)$, where $(x, y)$ is the sub-goal located on the cloverleaf, whose center is located on the most recent chemical detected location $(x_{last}, y_{last})$.

The Declare-Source behavior implements an algorithm to identify the plume source location. The algorithm utilizes the...
last chemical detected points (LCDPs) that are generated during the Maintain-Plume and Require-Plume process for source identification (A LCDP is defined as a chemical detection point at which a vehicle loses contact with the chemical plume for certain seconds). LCDPs provide very important information about plume traversal distances between Reacquire-Plume activities. The LCDPs are separated along the axis of the plume when the AUV is far from the source location; while the LCDPs get closer when the AUV is approaching the chemical source, thus a weekly distributed LCDPs indicate that the source is in the vicinity. Two algorithms including SIZ_F and SIZ_T that use a cluster of closely distributed LCDPs to estimate the source location are proposed and evaluated, and their detailed implementation and discussion are addressed in [4].

III. PATH-FOLLOWING GUIDANCE

Most of AUVs in practical use are underactuated, as these vehicles have no capability to directly control its transversal movement. Thus, due to the effects of disturbances such as currents and waves, an underactuated AUV’s heading may not be the direction of the vehicle’s movement. In order to control an underactuated AUV to implement the chemical plume tracing strategy efficiently, which requires to control the direction of the vehicle’s movement accurately (e.g., control the direction of the AUV’s movement to have a defined offset angle with the flow direction), we designed a path-following guidance algorithm FollowPath( ) which could maneuver an underactuated AUV to follow a given predefined three dimensional path (thus could maneuver the direction of the vehicle’s movement).

FollowPath( ) takes the desired AUV path as the input and outputs the desired heading and pitch of the AUV to implement the motion control. As in [5], we derive the kinematic model of the AUV path following error in the Serret-Frenet (SF) coordinate frame. Let \{SF\} be the SF frame attached to a point moving along the given path, \textbf{T}, \textbf{N}, and \textbf{B} be its tangent, normal, and binormal unity vector respectively. Let \(s\) be the length along the path, \(\tau\) and \(\kappa\) be its torsion and curvature respectively. Let \((l_r,l_l,l_t)\) be the path following error expressed in SF frame, and \((i_r,i_l,i_t)\) be the changing velocity. We have:

\[
R(\psi_{as},\theta_{as},\psi_{ns}) \begin{bmatrix} V_r \\ \dot{s} \\ l_r \\ i_r \\ l_l \\ i_l \\ l_t \\ i_t \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\]

\[
(3)
\]

where \(R(\psi_{as},\theta_{as},\psi_{ns})\) is the rotation matrix from the AUV’s velocity frame to SF frame, \((\psi_{as},\theta_{as},\psi_{ns})\) is the corresponding Euler angles, \([V_r,0,0]^T\) is the AUV’s velocity expressed in the velocity frame, \([\dot{s},0,0]^T\) is the moving velocity of the SF frame’s origin expressed in SF frame, and \([i_r,i_l,i_t]^T\) is the SF frame’s angular velocity.

Expanding and rearranging (3), we get:

\[
\begin{aligned}
\dot{l}_r &= \cos \psi_{as} \cos \theta_{as} V_r - s(1 - \kappa l_t) \\
\dot{l}_l &= \sin \psi_{as} \cos \theta_{as} V_r - s(\kappa l_r - \tau l_t) \\
\dot{l}_t &= -\sin \theta_{as} V_r - \tau l_t
\end{aligned}
\]

(4)

In order to specify the transient motion performance of the AUV as it is approaching the desired path, we design the approach angles for heading \(\psi\), and pitch \(\theta\), as follows:

\[
\begin{aligned}
\psi_r &= -\text{sign}(V_r) \left( \frac{2.0}{1.0 + e^{-\frac{4}{V}} - 1.0} \right) \\
\theta_r &= \text{sign}(V_r) \left( \frac{2.0}{1.0 + e^{-\frac{4}{V}} - 1.0} \right)
\end{aligned}
\]

(5)

where \(k_s > 0\), \(k_s > 0\), \(0 \leq \psi_r \leq \pi/2\), and \(0 \leq \theta_r \leq \pi/2\) are constant design parameters, which are determined based on vehicle’s dynamics and the designer’s requirements.

In order to avoid the singularity of \(\dot{s}\) at \(l_t = 1/\kappa\), we adopt the analysis in [5] and choose the Lyapunov candidate:

\[
V_e = \frac{1}{2}(i_r^2 + i_l^2 + i_t^2)
\]

(6)

Substituting (4) into its time derivative \(\dot{V}_e\), and choosing:

\[
\dot{s} = V_r \cos \psi_{as} \cos \theta_{as} + k_l \]

(7)

where \(k_l\) is a positive constant design parameter, we can get:

\[
\dot{V}_e = -K(i_r^2 + i_l^2) \sin \psi_{as} \cos \theta_{as} - V_l i_s \sin \theta_{as}
\]

(8)

If our designed controllers guarantee that \(\psi_{as}\) and \(\theta_{as}\) converge asymptotically to approach angles \(\psi_r\) and \(\theta_r\), respectively, then we can get:

\[
\dot{V}_e = -k_r i_r^2 + V_l i_s \sin \psi_r \cos \theta_r - V_l i_s \sin \theta_r \leq 0
\]

(9)

From above, the AUV can follow the given desired path, that is, the difference between the vehicle’s center of mass and the origin of the SF frame, and the angular difference between the vehicle’s velocity vector and the SF frame’s \textbf{T} vector both converge to zero asymptotically.

For most AUVs, roll is not controlled and kept a small value by design. Then the commanded heading and pitch angles outputted from the FollowPath( ) guidance algorithm are:

\[
\begin{aligned}
\psi_r &= \text{FollowPath}(P,t) = \psi - \psi_{as} + \psi \\
\theta_r &= \text{FollowPath}(P,t) = \theta - \theta_{as} + \theta
\end{aligned}
\]

(10)

where \(\psi\) and \(\theta\) are AUV’s heading and pitch angles, respectively.

IV. IMPLEMENTATION OF THE BEHAVIORLS

For the field experiments, a small AUV as shown in Figure 1 was developed at SIA. The AUV is controlled by six thrusters. In the field experiments, the two vertical thrusters are used to keep the AUV’s depth, the two forward horizontal thrusters control the AUV’s heading, and the two afterward horizontal thrusters control the AUV’s speed. The vehicle’s ideal speed is about 0.5 m/s. (The AUV is equipped with multiple sensors, including navigation sensors such as a depth sensor, an electronic compass, in addition, the vehicle
is equipped with an underwater fluorometer (Cyclops-7) to detect the Rhodamine dye, and a Doppler velocity log (DVL) (Workhorse Navigator 1200 kHz) to measure the AUV’ velocities relative to the sea bottom and the reference water layer.

![Image](image.png)

**Fig. 1.** The AUV employed in the experiments, equipped with the Workhorse Navigator 1200 kHz DVL and Cyclops-7 fluorometer.

As mentioned above, the speed of the AUV is relatively slow. And by using the two horizontal thrusters to control the heading of the AUV, the maneuverability of the vehicle is better (The turning radius of the vehicle is on the order of several meters) than AUVs with a main thruster and a rudder such as the REMUS AUV. And when the speed of the vehicle is slow enough, the AUV could even change its heading without much variation of its position.

Because of the better maneuverability, the AUV could achieve expected complicated maneuvers. Thus we can even neglect the turning radius of the AUV when designing the plume tracing maneuvers for plumes with relatively large scales. Therefore, based on the AUV’s dynamics and the above designed path-following algorithm, we develop another algorithm implementation of the chemical plume tracing strategy, which is described as follows.

### A. Find-Plume

The Find-Plume behavior implements a “zigzag” maneuver to search for the entire predefined operational area until the AUV contacts a chemical plume [2]. Find-Plume behavior uses the path-following guidance $\text{FollowPath}(\cdot)$ to control the AUV to follow the “zigzag” path.

### B. Track-In

The Maintain-Plume behavior includes Track-In and Track-Out activities, which together enable the AUV to track a chemical plume up flow with the zigzag movement pattern. Track-In is illustrated in Figure 2.

![Image](image.png)

**Fig. 2.** Illustration of Track-In.

Track-In is to replicate the moth’s behavior to track a chemical plume up flow with an offset angle $\theta_s$, which is a design parameter of this behavior. Track-In uses the path-following $\text{FollowPath}(\cdot)$ to control the AUV to follow a straight line, with the starting location as $(x, y)$ at which the AUV switches its behavior from other behaviors to Track-In, and with the angle $\theta_s$, as shown in Figure 2. When the AUV switches from Find-Plume behavior or Track-Out to Track-In behavior, $\psi + \beta - f_{\omega}$ is computed, in which $\beta$ is the AUV’s angle of attack. If $\psi + \beta - f_{\omega} < \pi$, indicating that the AUV is moving from the left side of the plume to the right side (as shown in Figure 2), then $\text{sign}(\theta_s)$ is selected to enable the AUV to continue to track the plume in this direction. If $\psi + \beta - f_{\omega} > \pi$, indicating that the AUV is moving from the right side of the plume to the left side, then $\text{sign}(\theta_s)$ is set to enable the AUV to continue to track the plume in the right-left direction. With above setting of $\text{sign}(\theta_s)$, when the AUV switches to Track-In, the AUV could track the plume from outside of the plume to the interior of the plume.

In order to enable the AUV to track the plume in the expected direction (Thus the AUV could leave the plume from the right side of left side as expected), $\theta_s$ should be selected larger than the flow direction measurement error (the difference between the real flow direction and the measured flow direction), and should be larger than the $\theta_{diff}$, which is the angle difference between the flow direction and the direction of the plume centerline (Due to the integrated effect of the varying currents, the plume centerline is not always parallel to the flow direction). Detailed discussion of the parameter $\theta_s$ on effective plume tracking is addressed in [6].

While the AUV detects the chemical plume in Track-In, the AUV keeps Track-In to track the plume up flow. If the AUV does not detect the plume in Track-In, the AUV may not be outside of the plume, because the plume is intermittent and non-detection of the plume is reasonable. To ensure that the AUV has indeed left the plume from the right side or left side of the plume with Track-In, the AUV needs to track a distance $D_r$ from the most recent plume detected location, where $D_r$ is another parameter of Track-In and should be selected larger than the mean inter-filament distance of the chemical plume. If the AUV has moved $D_r$ without plume detection, then the AUV switches from Track-In to Track-Out, and saves the most recent plume detected location as LTDL (Last Tracer Detected Location).

### C. Track-Out

Track-Out maneuvers the AUV to rapidly re-contact the chemical plume immediately following Track-In. Track-Out is illustrated in Figure 3.

![Image](image.png)

**Fig. 3.** Illustration of Track-Out.

Track-Out uses the path-following $\text{FollowPath}(\cdot)$ to control the AUV to follow a straight line, with the starting point as the $(x, y)$ where the AUV switches its behavior from Track-In, and with the cross-flow direction that enables the AUV to return to the plume (the opposite tracking direction of Track-In). If the AUV detects the plume, then it switches to Track-In. If the AUV has moved a distance $D_o$ without plume detection, then the AUV switches to Reacquire-Plume behavior. $D_o$ is a design parameter of this behavior, and...
should be set large enough ( $D_o$ should be larger than $D_x \times \sin(\theta_r)$, in addition, its selection should consider the plume centerline meander and the plume intermittency) to ensure that the AUV could come back into the interior of the plume.

D. Reacquire-Plume

If Track-Out fails to detect the plume, then the AUV switches to Reacquire-Plume behavior to search for the plume in the vicinity of LTDL, as a moth does with the casting behavior. The Reacquire-Plume behavior is illustrated in Figure 4.

![Illustration of the Reacquire-Plume behavior.](image1)

Considering the dynamics of the AUV, we design the search pattern as a rectangle, with $D_x$ being a design parameter that should be larger than $D_x \times \cos(\theta_r)$ to make the rectangle cover the LTDL. And the Reacquire-Plume uses the FollowPath() to enable the AUV to implement this trajectory. When Track-Out fails to detect the plume, following three scenarios may occur. First, due to the plume intermittency, the AUV does not detect the plume, but the AUV comes back into the plume. Second, due to the flow measurement error or the plume meander, the AUV does not leave the plume from the expected direction, thus Track-Out drives the AUV further leave the plume. Third, the AUV has moved up flow of the plume source. Whichever scenario occurs, the designed Reacquire-Plume behavior could enable the AUV to find the plume again.

If the AUV implements the rectangle search for successive $N_x$ times without plume detection (The plume shape and location has changed dramatically due to varying flow), then the AUV switches to Find-Plume behavior. If the AUV detects the plume with the Reacquire-Plume behavior, then the AUV switches to Track-In. If the AUV detects the plume on the left side of LTDL, then in the following Track-In, the AUV tracks the plume in the right-left direction; otherwise, the AUV tracks the plume in the left-right direction. With this setting, the AUV could track the plume into the plume interior (with the assumption that most LTDLs are usually located on the boundary of a chemical plume).

Meanwhile, if the AUV detects the plume down flow of the LTDL but does not detects the plume up flow of the LTDL, then the LTDL may be in the vicinity of the plume source (Plumes could only be detected down flow of the source). Then this LTDL is saved as LTDL-S and will be used by the Declare-Source behavior.

E. Declare-Source

The Declare-Source behavior is designed to identify the plume source and estimate the source location.

A LTDL-S is a location that a plume source may be in the vicinity. Thus LTDL-Ss provide information on the plume source location. If a cluster of LTDL-Ss is accumulated within a small area with the scale on the order of the plume source diameter, then it could be concluded that up flow of this area, no plume exists while there exists plume down flow of this area, and thus the plume source is within this small area.

In our implementation, when the AUV switches from Reacquire-Plume behavior to other behaviors and a new LTDL-S is generated, the Declare-Source behavior activates. The Declare-Source behavior arranges the obtained LTDL-S down flow of it is small than a predefined parameter $D_o$ ($D_o$ is selected on the order of the plume source diameter, and $N_o$ should be selected large enough to make the source declaration be correct and robust), then the source is declared. And the source location could be estimated as the center of the cluster of LTDL-Ss or the most up flow of the LTDL-S.

F. AUV Control Architecture

Figure 5 shows the control architecture for chemical plume tracing. As in [2, 3], in each planning cycle $T$, the strategy uses only the flow direction and logical information instead of the intensity values of the chemical plume tracers to implement the planning, and computes and outputs the commanded signals of the AUV heading and speed to the motion control.

![The control architecture for chemical plume tracing.](image2)

V. COMPUTER SIMULATION

A. Simulation Environment

Due to the costs and complexities of in water experiments, computer simulation is a key step before chemical plume tracing field experiments.

To support the computer simulation evaluation and validation of chemical plume tracing strategies, we have developed a turbulent plume simulation model [7], which captures the key features of a chemical plume to complicate the plume tracing problem, and have developed a simulation environment using the C++ programming language that implements the plume model [8].

Figure 6 shows a screen display of the developed simulation environment. The scale of the simulated flow field is 2000 m x 2000 m. Thus we can test the performance of plume tracing at long distance. (In the simulation shown in Figure 6, we simulate three plumes with different characteristics. The upper one is more intermittent. The lower one is narrower in the plume width. With such a simulation environment, we can test the performance of the strategy for tracing plumes with different characteristics (the plume intermittency, the plume scale and the plume meander))
Compared with the simulation environment in [9], this simulation environment has better visual effect. The higher the color is, the higher the chemical concentration value is. The visual effect is achieved by using the OpenGL texture mapping technique. We map a picture shown in figure 6 to each plume particle on the computer screen, with the color value and scale of the picture be proportional to the concentration value and scale of the corresponding simulated plume particle. In addition we open the OpenGL’s blending function and the colors of the plume particles are superimposed to simulate the superimposition of the concentration of the simulated plume particles. Thus the red color values of the plume can represent the concentration values directly.

B. Simulation Result

We have not identify the hydrodynamic coefficients relating to the dynamics model of the AUV used in the field experiments, therefore, we adopt the REMUS AUV’s dynamics model [10] for the simulation validation of the above developed chemical plume tracing algorithm.

Figure 7 shows a simulation result of chemical plume tracing run on the above simulation environment. The cycle of the flow variation with time is set as 2000 seconds. The mean flow speed is set as 0.5 m/s, and the mean flow direction is set as 0 degree. The plume source is located at (500, 0) m. And in the simulation the flow sensor and the plume sensor are assumed to be ideal without noise; and we treat the plume sensor as a binary detector in the plume tracing algorithm with a threshold of 0.1. The mean speed of the AUV is set as 2.5 m/s, and the planning and motion control cycles of the AUV are both set as 0.1 s.

VI. VIRTUAL PLUME TRACING

As stated above, we have no parameters relating to the AUV’s dynamics model, and in the simulation we use the REMUS AUV’s dynamics model. Thus the parameters related to the plume tracing algorithm are tuned based on the dynamics of the REMUS AUV. So for the experiments with the AUV used for our experiments, the parameters relating to the chemical plume tracing algorithm should be tuned based on the real AUV’s dynamics. Due to the costs and complexities of plume tracing experiments with real Rhodamine dye plumes, in the parameter tuning stage, we perform virtual plume tracing experiments. That is, the AUV is real; however, the flow and plume sensors’ data are simulated via the plume simulation run on the AUV control system. Using this approach, we can save the cost of releasing Rhodamine dye plumes.

A. Path-Following

Before virtual plume tracing experiments, we tuned the motion controllers of the AUV, and validated the path-following guidance algorithm.
Figure 8 shows experimental results of AUV following circle and quinquefoliate paths, respectively, which validate the designed path-following guidance algorithm. In both of the path-following experiments, the AUV starts following the path from the location of (0, 0) m.

B. Virtual Plume Tracing

Based on the AUV’s dynamics and motion control performance, we tuned the parameters of the chemical plume tracing algorithm and performed virtual plume tracing experiments. Figure 9 shows an experimental result of the virtual plume tracing experiments. The AUV finds the plume, traces the plume and finally declares the plume source. (Because in this experiment, the AUV’s was tethered with a cable, thus the movement of the AUV was disturbed and the plume tracing path was not as ideal as in computer simulation).

The water depth at the experimental site is about 8-9 m. The flow in this experimental site varies with both time and location and, especially, is tidally dominated with the cycle of about 12 hours. And during the experiments, the maximum flow speed was 16 cm/s which is estimated via the data collected by the DVL equipped on the AUV.

Since there are no proper natural plumes available for the experiments, generating the Rhodamine dye plumes is an important step to perform the chemical plume tracing experiments. For the field experiments conducted in November and April 2002 at the San Clemente Island of California and in June 2003 in Duck, North Carolina [2, 3], a Rhodamine dye plume was generated in near-shore ocean environments by pumping the dye in the sea water at a release rate of 1-2 g/min. The plume source is located at the sea bottom, thus the resulting plumes developed near the sea bottom. Due to the poor natural luminance below the sea surface, the plume distribution cannot be visually observed. Figure 11 (a) only shows the Rhodamine dye plume about a few meters in the vicinity of its source location, which was taken by a video camera in the water focusing on the chemical source using an additional light system.

In the experimental result shown in figure 9, the AUV starts the mission from (300, -20) m, and navigates to the operational area (280, 0) m, then performs the plume finding using the zigzag search pattern. After the declaration of the plume source, the AUV goes to the (0, 0) m. In this mission, the mean depth of the AUV is 1.4 m, the mean altitude of the AUV relative to the sea bottom is 4 m, and the mean speed of the AUV is 0.474 m/s. The offset angle $\theta_{i}$ of Track-In is set as 20 degrees, and the distance $D_{i}$ in Track-In based on which the AUV switches from Track-In to track-Out is set as 10 m. And the distance $D_{0}$ in Track-Out is set as $15+10\times\sin(D_{1})$ m. The mission time is 1451 s.

Using the virtual plume tracing approach, we could tune the parameters of the chemical plume tracing algorithm based on the AUV’s dynamics and performance of the vehicle’s motion control, especially without real chemical plumes. The virtual plume tracing experimental result validates the developed chemical plume tracing algorithm.

VII. RHODAMINE DYE PLUME TRACING

A. Rhodamine Dye Plumes Generated in the Experiments

We choose the Dalian Bay, China, as our experimental site, as shown in the rectangle in Figure 10.

The water depth at the experimental site is about 8-9 m. The flow in this experimental site varies with both time and location and, especially, is tidally dominated with the cycle of about 12 hours. And during the experiments, the maximum flow speed was 16 cm/s which is estimated via the data collected by the DVL equipped on the AUV.

Since there are no proper natural plumes available for the experiments, generating the Rhodamine dye plumes is an important step to perform the chemical plume tracing experiments. For the field experiments conducted in November and April 2002 at the San Clemente Island of California and in June 2003 in Duck, North Carolina [2, 3], a Rhodamine dye plume was generated in near-shore ocean environments by pumping the dye in the sea water at a release rate of 1-2 g/min. The plume source is located at the sea bottom, thus the resulting plumes developed near the sea bottom. Due to the poor natural luminance below the sea surface, the plume distribution cannot be visually observed. Figure 11 (a) only shows the Rhodamine dye plume about a few meters in the vicinity of its source location, which was taken by a video camera in the water focusing on the chemical source using an additional light system.

For better understanding of the plume nature via visual observation, for the experiments conducted in October 2010 at Dalian Bay, China, an alternative strategy is adopted to develop a Rhodamine dye plume. The pump releasing the Rhodamine dye was placed at a small anchored boat, instead of at the sea bottom. The Rhodamine dye was then pumped up to the sea surface through a wound drainage plastic pipe, with its size 1.0 m× 0.5 m. The plume source was submerged below the sea surface about 1.5 m and the release rate of the Rhodamine dye was controlled at 1-2 g/min. The plume then developed near the sea surface and its shape and distribution could be visually observed. Figure 11(b) shows a picture of the plume source. As demonstrated in Figure 11, the Rhodamine dye plume centerline directs to its source location within a few meters to the plume source, thus it is interpretable that the tracking of the plume in the vicinity of the source location does not challenge the plume tracing algorithm very much.

Figure 12 shows a snapshot of a chemical plume developed during the field experiments at Dalian Bay, with the plume length about 350 m. As shown in Figure 12, a significant plume meander (a snakelike path) appears when the plume is propagated over a long distance, resulting from the varying fluid flow. Because the fluid flow direction and
magnitude change, spatially and temporally, the instantaneous fluid flow direction within the plume often will not point toward the plume’s source nor be coincident with the plume’s centerline.

The meander and lack of correlation between the fluid flow direction and the plume longitudinal axis significantly complicate the plume tracing process. To our knowledge, most of existing plume tracing algorithms do not explicitly discuss how to deal with the plume meander issue. Figure 12 also shows that the Rhodamine dye concentration distribution is not uniform and has many local extrema and sharp spatial gradients (The chemical concentration at some locations where the plume looks like broken is very low, but at other locations with a large dye area the deep red color is very high), due to turbulence and the beating of waves. The problem with local concentration maxima significantly challenges source declaration algorithms which are investigated in laboratory environments by searching for the maximum proximity of a plume with a uniform concentration distribution.

B. Rhodamine Dye Plume Mapping

In the plume tracing missions, the AUV uses the fluorometer to detect the Rhodamine dye plume, and uses the DVL to measure the flow speed and direction.

For our field experiments, we set the sampling rate of the fluorometer as 10 Hz and choose the 0-10 ug/L (ppb) measurement scale with which the fluorometer outputs 5 VDC when the detected Rhodamine concentration reaches 10 ug/L. There is noise in the sensor outputs, that is, when there is no Rhodamine detection, the output of the sensor is not zero. In addition to the noise of the sensor’s own, the hardware of the AUV for sampling the voltage of the sensor output also introduces some noise. So when processing the experimental data of the Rhodamine dye concentration, the noise should be subtracted to obtain the absolute concentration value of the Rhodamine plume.

The DVL is mounted on the forward part of the AUV as shown in Figure 1. This location allows a clear path for all the four acoustic beams of the DVL, and the AUV will not interfere with the DVL measurements. The DVL measures the AUV speed relative to the sea bottom (the DVL’s sample rate was set as 2-3 Hz.), based on which we use the dead reckoning method to estimate the AUV position. In addition, the DVL measures the AUV speed relative to a reference water layer. In our field experiments, we select the flow layer 1-3 m below the DVL. The flow speed at this layer is the same with or very close to the speed of the layer that contains the AUV and the plume. The flow speed is obtained by the relation: the AUV relative speed to the sea bottom = the AUV relative speed to a reference water layer + the fluid speed at the reference layer relative to the sea bottom. However, using this method, the flow speed data has noise and should be filtered.

In order to understand the plume distribution and nature, and the fluorometer and the DVL’s noise characteristics, we conduct Rhodamine dye plume mapping missions before the plume tracing missions.

Figure 13 shows an experimental result of the adaptive lawn-mower plume mapping mission (When the AUV has left the plume for a prescribed distance, then it ends the current trackline and goes on to the next trackline, thus maps the area that contains the plume). The short lines on the AUV trajectory show the flow direction and magnitude on the corresponding location. For better expression of the experimental results, we define a local coordinate system for each plume mapping and tracing mission. The origin of the local coordinate system is defined as the location where we launch the AUV in these missions, which is usually a location near the plume source. The longitudinal axis of the coordinate system is north, east, south, or west which is close to the mean flow direction, which is also the direction of the longitudinal axis of the plume. And the transversal axis is defined by the right hand rule. With the aid of the GPS, we can transform the local coordinate system to the longitude-latitude coordinate system via the rotation matrix. This local coordinate system is easy for us to implement the strategies and analyze the experimental results, as the AUV always traces the plume from the downward of the x axis to the upward (near the origin of the coordinate system).

In this experiment, the plume source is located near the origin of the local coordinate system. The AUV starts the mission from (0, 0) m, and first navigates to (20, -20) m, then detects the Rhodamine dye plume. The AUV ends this mission at (62, 21) m, and the mission lasts for 850 s. The space between two tracklines is set as 10 m. The mean depth of the AUV is kept as 1.6 m, and the mean speed of the AUV is 0.45 m/s. For the convenient of the mission implementation, we control the AUV to perform the mission from the up-flow to the down-flow direction. From Figure 13, we can obtain the plume width at 30, 40, 50, 60 meter being 15.51, 22.38, 29.7 and 43.685 m, respectively. In addition, from the centerline data of the plume, the direction of the plume centerline could be calculated, being 27.8802, 11.9057, and 11.6951 degrees, between 30-40, 40-50 and 50-60 m, respectively.

Figure 14 shows the time series plot of the Rhodamine dye concentration measured by the AUV during the mission. Based on this result, we set a threshold of 0.35 (large enough to surpass the sensor’ noise) for the fluorometer data, that is,
the AUV assumes that it does not detect the Rhodamine dye plume if the output of the fluorometer is lower than 0.35.

![Fig. 14. Time series plot of the Rhodamine dye concentration measured by the AUV during the mission.](image)

There is noise in the flow speed data by using the above DVL measurement method. Figure 15 shows a histogram of a sample of the noise data. Based on the analysis of the statistics of the noise data shown in Figure 15, we can conclude that the distribution of the noise could be assumed by zero mean Gaussian white noise. Therefore, we average 100 s flow speed data to filter the noise. At last, we use the filtered flow speed data to compute the flow direction. And we use the filtered flow speed and flow direction in the plume mapping and plume tracing experiments. Figure 13 and Figure 16 show the filtered flow speed and direction data.

![Fig. 15. Time series plot of the flow speed and flow direction measure by the AUV during the mission.](image)

From the plume mapping experiments, we can see that the plume is intermittent, the plume width grows with the distance away the plume source, the plume centerline is not a straight line, and the mean flow direction is consistent with the direction of the longitudinal axis of the plume (which validates the flow measurement via the DVL, thus we can use the flow data to perform the plume tracing missions). And in the vicinity of the plume source, the concentration value of the Rhodamine dye has beyond the plume sensor’s measurement scale. Thus, a strategy that uses the concentration value to identify the plume source with such sensors that cannot measure the accurate concentration value of the plume will be problematic.

C. Rhodamine Dye Plume Tracing

After plume mapping missions and tuning the sensor parameters, we performed the real plume tracing experiments. We have performed many real plume tracing missions (the planning and control cycle of the AUV are both set as 0.1 s), however, due to the consideration of the safety of the AUV (the AUV may collide with the plume source), we did not perform the plume source declaration and estimation experiments. In many of the missions, the AUV could track the plumes over 100 m.

Figure 17 shows a plume tracing experimental result. The dots on the AUV trajectory shown in Figure 17 show that the AUV detects the Rhodamine at corresponding location; the short lines on the trajectory show the flow speed and direction at the corresponding location. The red dot shows the plume source location.

![Fig. 17. An experimental result of Rhodamine dye plume tracing (expressed in a defined local coordinate system).](image)

Figure 18 shows the time series plots of the flow direction and fluorometer sensor data measured by the AUV during the experiment, respectively.

![Fig. 18. Time series plots of the flow direction and Rhodamine dye concentration measured by the AUV during the plume tracing mission.](image)

In this mission, the AUV starts the mission at (297.0, -98.0) m, and searches for the plume in the defined operational area [0 200 -100 100], then the AUV detects the plume at (200.6, 24.4) m and switches from the Finding-Plume behavior to Track-In. Track-In navigates the AUV up flow with a defined angle $\theta$ relative to the upflow direction. In this experiment, the angle $\theta$ is set as 20 degrees. When the AUV has not detect the plume for a defined distance $D_t$ which is
set as 10 m), the AUV switches from Track-In to Track-Out. Track-Out navigates the AUV across the plume ($D_1$ in Track-Out is set as $15+10 \times \sin(D_1)$ m), and if the AUV detects the plume, the AUV switches from Track-Out to Track-In.

In this mission, the AUV ends the mission at (2.28, 71.36) m. Based on the GPS data, the plume source is at (-68.86, 98.62) m. In this mission, the mean AUV depth is 1.7 m, the mean AUV speed is 0.434 m/s, and the mission lasts for 1302 s. Based on the first plume detected location (202.25, 25.99) m and the last plume detected location (2.28, 71.36) m in this mission, the distance between these two locations is calculated as 204.81 meter.

The plume tracing experiments demonstrate that the AUV could track a Rhodamine dye plume to its source in complicated near-shore ocean environments using the developed moth-inspired plume tracing algorithm.

VIII. CONCLUSIONS

This paper presents the path-following based algorithm implementation of the moth-inspired chemical plume tracing strategy and the systematic study on the algorithm.

For computer simulation study, we have developed a computer simulation environment with better visual effect, which also supports multiple plumes tracing. Due to the costs and complexities of in-water tests, a simulation environment is a powerful complementary tool for the evaluating and validating of the chemical plume tracing algorithms. And with the plume simulation reflecting the key features of plumes to complicate the plume tracing problem, the algorithms that perform well in simulation will be also effective in real world. Another important function of the plume simulation is to aid the in-water tests of the chemical plume tracing algorithms. In the initial tuning stage of field experiments, virtual plume tracing experiments could be conducted, that is, the plume and flow sensors' data are simulated via the plume simulation running on the AUV control system. By this approach, mission operators could tune the parameters relating to the algorithm for the dynamics of the experimental AUV and test the performance of the algorithm's parameters without need for real plumes, which could reduce the costs of in-water plume tracing experiments via artificial plumes.

For field experiments, we have developed an AUV with better maneuverability and path-following capability. And different from the field experiments in [2, 3], the experiments presented herein have following advantages: (1) The Rhodamine dye plume developed in ocean environments under turbulence, tides and waves is visible over a few hundred meters for better understanding of the plume nature of intermittency and significant meander; (2) The AUV missions can be visually observed, and more importantly manual control would stop the AUV missions during the AUV tuning stage; (3) The experiments are less cost than the ones presented in [2, 3] as there is no divers needed to inspect the AUV maneuvers under the sea in depth about 20 m; (4) GPS signals are directly available to calibrate the DVL-based AUV localization algorithms.

The systematic study presented in this paper, including computer simulation, virtual plume tracing and Rhodamine plume tracing, demonstrate that the developed plume tracing algorithm is effective for the tracking of plumes developed in complicated ocean environments with currents, tides and waves. The algorithm requires less computational resources and does not require the AUV to be positioned accurately. The parameters relating to the algorithm are easy to design and tune based on the characteristics of the plume, flow and the AUV's performance. However, a fundamental aspect of the plume tracing strategy is that the mean flow direction points to the up flow source. Therefore, selecting the mission time when the mean flow direction points to the up flow source is a key prerequisite for the strategy to be effective, as in some environments this assumption is not always feasible (for example, in the time between the flood and ebb the flow field is chaotic to some extent). In such cases, the adaptive lawn-mower strategy could be an effective strategy for plume mapping and source identification as it does not require the real time flow information, and this strategy is more effective than the common lawn-mower which covers the whole operational area.

In future work, we will develop and validate strategies and algorithms for mapping and tracing buoyant plumes and plumes without continuous sources with the simulation environment and real AUVs.

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