Moth-Inspired Plume Tracing via Autonomous Underwater Vehicle with only a pair of Separated Chemical Sensors

Conference Paper · October 2015

Wei Li
California State University, Bakersfield

Fumin Zhang
Georgia Institute of Technology

Moth-Inspired Plume Tracing via Autonomous Underwaer Vehcle with only a pair of Separated Chemical Sensors

Yu Tian[1], Wei Li[1,2], Fumin Zhang[1,3]

1. State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China

2. Department of Computer and Electrical Engineering and Computer Science, California State University, Bakersfield, CA 93311, USA

3. School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

tiany@sia.cn, wli@csub.edu, fumin@gatech.edu

***Abstract*— Effective chemical plume tracing strategies are important for autonomous underwater vehicles (AUVs) to perform a variety of missions of searching for underwater targets, such as oil spill sources and deep-sea hydrothermal vents. In such circumstances where fluid flow direction cannot be measured by AUVs or fluid flow direction provides little or wrong information about the distribution of a dynamic chemical plume or its source location, chemical plume tracing strategies that rely on information of fluid flow direction may not work effectively. In this paper, a modified moth-inspired chemical plume tracing strategy is presented, which could trace a turbulent chemical plume without need of information of flow direction. The strategy estimates the direction of plume centerline based on information from a pair of spatially separated chemical sensors symmetrically mounted on an AUV's nose together with the AUV's zigzag plume-tracing trajectory, and employs the estimated direction of plume centerline to implement the plume tracing. The proposed strategy is implemented in a computer simulation environment and the simulation results demonstrate that with the strategy an AUV could track a turbulent chemical plume over a long distance and finally localize the plume source.**

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

Introduction

Autonomous underwater vehicles (AUVs) are important tools being employed in a variety of missions of searching for underwater targets. In a number of these missions, the interested natural or artificial targets such as deep-sea hydrothermal vents, oil spill sources, and underwater unexploded ordnances, release chemical substances into the seawater, which are advected by ocean currents and develop into chemical plumes. Chemical plumes have larger spatial scales than their sources (the targets) and provide significant information about the locations of the targets, thus finding the plumes and then tracking the plumes to theirs sources is an effective approach to discovering these targets and pinpointing their locations. Therefore, endowing an AUV with the chemical plume tracing capability is of significance for AUVs to perform these searching tasks. And a key issue of endowing an AUV with the chemical plume tracing capability is to design and implement a chemical plume tracing 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.

A number of approaches have been employed to design chemical plume tracing strategies for robots or autonomous vehicles to track a chemical plume and localize the plume source [1, 2]. In natural world, long-range chemical plume tracing by animals and insects has been observed and documented. Inspired by the remarkable chemical plume tracing capabilities, many researches try to replicate the chemical plume tracing behaviors of animals or insects in robots and autonomous vehicles and develop biomimetic chemical plume tracing strategies. Inspired by the moth plume-tracing behavior, Li *et al*. [3] and Farrell *et al*. [4] developed complete chemical plume tracing strategies for an AUV to find a plume, track the plume up-flow toward the plume source and finally identify the source location. The strategies were implemented on a REMUS AUV with a flow sensor and 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 meters in the near shore, oceanic fluid flow environments [3, 4]. In addition, Shenyang Institute of Automation, Chinese Academy of Sciences also performed experiments on the moth-inspired chemical plume tracing with an AUV equipped with a flow sensor and a single chemical sensor in Dalian Bay, China in October 2010 [5]. The experiments also demonstrated that the AUV could track a Rhodamine dye plume developed under turbulence, tides and surface waves over a long distance.

The moth-inspired chemical plume tracing strategy described above navigates an AUV to track a chemical plume along the up-flow direction measured by a flow sensor. However, in some circumstances, the flow speed and direction cannot be accurately measured by an AUV or the flow information provides little or wrong information about the distribution of a dynamic chemical plume or its source location (e.g., in tidal environments in some time periods the flow speed is rather slow and the measured flow direction may change chaotically, or in some applications the plume source moves continuously so that the flow direction provides little or wrong clues on the distribution of the dynamic plume and its source location). Consequently, the moth-inspired chemical plume tracing strategy relying on flow direction cannot work efficiently in these circumstances.

To enable an AUV to efficiently track a turbulent chemical plume when information of flow direction cannot be used, we modify the moth-inspired chemical plume tracing strategy proposed by Li *et al*. [3] to trace a turbulent chemical plume without need of information of flow direction. Inspired by insects and animals with double antennae, we mount a pair of spatially separated chemical sensors on an AUV's nose. And we modify the chemical plume tracing strategy to incorporate estimation of the direction of plume centerline and to trace a turbulent chemical plume along the estimated direction of plume centerline instead of flow direction. This paper presents the modified moth-inspired chemical plume tracing strategy and is organized as follows. In section II, we give a brief description the moth-inspired chemical plume tracing strategy proposed by Li *et al*. [3]. In section III, we present the modified moth-inspired chemical plume tracing strategy that uses only a pair of spatially separated chemical sensors, which features estimation of the direction of plume centerline with information from a pair of chemical sensors and AUV's zigzag plume-tracing trajectory. In section IV, we present computer simulation results of the strategy to demonstrate its performance, using our developed simulation environment. In section V, we draw some conclusions.

Moth-Inspired Chemical Plume Tracing Strategy

For chemical plume tracing tasks, the location of pheromone-emitting females by flying male moths is considered to be a remarkable case. Inspired-by the moth plume-tracing behavior, Li *et al*. [3] developed a behavior-based planning strategy for tracking turbulent chemical plumes with an AUV in two dimensions. The strategy takes the information from a chemical sensor and a flow sensor as input, and outputs the commanded AUV heading ψ_c and speed v_c. 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 $\psi_c = f_{\text{dir}}(t,x,y) + \text{sign}(\eta)\Delta\psi(t)$, which is an offset to the computed flow direction f_{dir} at time t and the AUV location (x,y). $\eta = 0.5(Y_{\max} + Y_{\min}) - y$ and its sign will be ± 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 [3].

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:

$$\begin{cases} \psi_c = f_{\text{dir}}(t,x,y) + 180° + \Delta\psi(t)_{\text{Track-In}} \\ v_c = v_{\text{Track-In}} \end{cases} \text{t} \in T_{\text{Track-In}} \quad (1)$$

$$\begin{cases} \psi_c = f_{\text{dir}}(t,x,y) + 180° + \Delta\psi(t)_{\text{Track-Out}} \\ v_c = v_{\text{Track-Out}} \end{cases} \text{t} \in T_{\text{Track-Out}} \quad (2)$$

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 $\text{t} \in T_{\text{Track-In}}$ and $\text{t} \in T_{\text{Track-Out}}$ 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 chemical 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 [4] 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: $\psi_c = \text{atan2}(y_i - y, x_i - x)$, where (x_i, y_i) is the sub-goal located on the cloverleaf, whose center is located on the most recent chemical detected location $(x_{\text{last}}, y_{\text{last}})$.

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 an AUV 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 closely 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 were proposed and evaluated, and their detailed implementation and discussion are addressed in [6].

Modified Moth-Inspired Strategy using only a pair of Spatially Separated Chemical Sensors

The moth-inspired chemical plume tracing strategy using a flow sensor and a single chemical sensor described in section II maneuvers an AUV to track a chemical plume along the up-flow direction $f_{\text{dir}}(t,x,y)$+180°. In such circumstances where flow direction cannot be measured by an AUV or the flow direction provides little or wrong information about the distribution of a dynamic chemical plume or its source location, this strategy that relies on flow direction $f_{\text{dir}}(t,x,y)$ may not work effectively. In this paper, we propose to mount an AUV with a pair of spatially separated chemical sensors on its nose and we modify the moth-inspired strategy to enable an AUV to track a turbulent chemical plume with only chemical sensors and without need of information of flow direction.

For chemical plume tracing researches, a number of plume tracing strategies employing sensor array or multiple chemical sensors have been developed and tested, e.g. a recent research in [7]. The data from multiple chemical sensors could be utilized to estimate information about the plume distribution such as concentration gradient, plume boundary, or plume centerline, etc., which is then employed alone or together with flow information to guide a plume tracing robot or vehicle to move along a plume to its source location. In this paper, we use the data from two chemical sensors mounted on an AUV together with the AUV's zigzag plume-tracing trajectory to estimate the direction of plume centerline. Thereby an AUV could track a turbulent chemical plume along the estimated direction of plume centerline instead of flow direction.

Fig. 1 shows an illustration of chemical plume tracing with an AUV mounted with a pair of spatially separated chemical sensors. As shown in Fig. 1, a chemical plume develops along the flow direction and the dashed line represents the centerline of the plume. An AUV is equipped with a pair of spatially separated chemical sensors on the nose, with the left chemical sensor and its reading being denoted by S_L and $C(S_L)$ and the right chemical sensor and its reading being denoted by S_R and $C(S_R)$ in this paper.

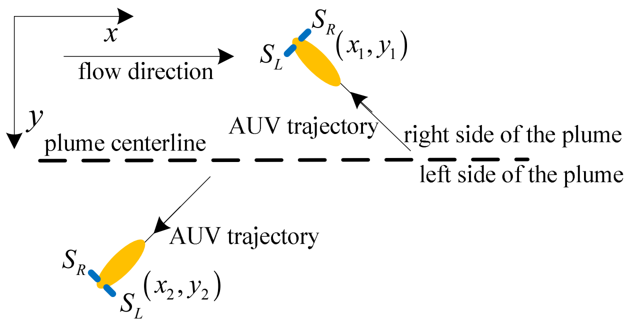

Fig. 1. Illustration of chemical plume tracing with an AUV mounted with a pair of spatially separated chemical sensors.

With the moth-inspired chemical plume tracing strategy, when the AUV detects chemical the AUV switches to Track-In behavior and tracks the plume with an offset angle relative to the opposite direction of plume development. When the AUV tracks the plume in the cross-plume direction of left to right and arrives at the right side of the plume centerline (as shown in Fig. 1), then at locations on the AUV's trajectory (e.g. (x_1, y_1)) S_L is located both closer to the up-flow source and the plume centerline than S_R, thus the probability of $C(S_L)$ being higher than $C(S_R)$) should be larger than the probability of $C(S_L)$ being lower than $C(S_R)$, considering that the plume distribution conforms to the Gaussian plume model. Likewise, when the AUV tracks the plume in the cross-plume direction of right to left and arrives at the left side of the plume centerline, then at locations on the AUV's trajectory (e.g. (x_2, y_2)) S_R is located both closer to the up-flow source and the plume centerline than S_L, thus the probability of $C(S_R) > C(S_L)$ should be larger than the probability of $C(S_R) < C(S_L)$. Therefore, based on the AUV's cross-plume movement direction and statistics of the readings of the two chemical sensors, we can estimate on which side of the plume centerline the AUV is located.

While in the Track-In behavior, once the AUV has estimated on which side of the plume centerline it arrived, we could control the AUV to switch its cross-plume movement direction to enable the AUV to cross the plume centerline and to arrive at the other side of the plume centerline. By repeating this process, while tracking the plume the AUV could also move back and forth relative to the plume centerline and exhibits a zigzag trajectory covering the plume centerline. Then the plume centerline could be estimated by using the AUV's zigzag plume-tracing trajectory that covers the plume centerline.

Based on the above idea, we modify the moth-inspired chemical plume tracing strategy to incorporate the estimation of the direction of plume centerline and to track the plume along the estimated direction of plume centerline. And the implementation of the Find-Plume, Track-In, Track-Out, Reacquire-Plume, and Declare-Source behaviors are as follows:

A. *Find-Plume*

The Find-Plume behavior implements a "zigzag" maneuver to search for the entire predefined operational area, as describe in Section II. In this paper, the operational area is designed to contain the plume to be tracked and the x axis is defined to be parallel with the assumed direction of plume development based on priori information. Then the direction of x axis is employed as the mean flow direction in the Find-Plume behavior. When the AUV detects the chemical with either one or both of the chemical sensors, the AUV switches to Track-In behavior.

Most of AUVs in practical applications are underactuated, as these AUVs have no capability to directly control their transversal movement. Thus, due to disturbances such as currents and waves, an underactuated AUV's heading may not be the direction of the AUV'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 AUV's movement accurately (e.g., controlling the direction of the AUV's movement to have an offset angle with a referenced direction such as the direction of plume centerline), we have developed a path-following guidance algorithm which could maneuver an underactuated AUV to follow a given three dimensional path thus could maneuver the direction of the AUV's movement [8]. The path-following guidance algorithm takes the desired AUV path as input and outputs the commanded heading and pitch angles of the AUV to its motion control.

In the Find-Plume and other behaviors described below, we employ the path-following guidance algorithm to calculate the commanded heading ψ_c of the AUV to control the AUV's movement direction and to enable the AUV to realize the planned plume-tracing paths in these behaviors. And in all the behaviors in this paper, the commanded speed v_c of the AUV is set as a constant value.

B. *Track-In*

The Track-In behavior in the modified chemical plume tracing strategy implements the estimation of the direction of plume centerline CL_{dir} and navigates an AUV to track the plume using a zigzag trajectory along the estimated direction of plume centerline $\widetilde{CL}_{\text{dir}}$, while chemical is detected by either one or both of the two chemical sensors. The Track-In behavior is illustrated in Fig. 2.

In Track-In behavior, we define two sub-behaviors: Track-In-to-Right and Track-In-to-Left. Track-In-to-Right employs the path-following guidance to navigate an AUV to track a plume along a straight line, with the starting point of the line being set as the location where the AUV switches to this behavior, and with the direction of the line (also the AUV' movement direction) being set to have an offset angle θ_{TR} ($\theta_{TR} > 0$) relative to $\widetilde{CL}_{\text{dir}}$ to enable the AUV to move in the cross-$\widetilde{CL}_{\mathrm{dir}}$ direction of left to right. Likewise, Track-In-to-Left navigates an AUV to track a plume with a straight-line with an offset angle θ_{TL} ($\theta_{TL} < 0$) relative to $\widetilde{CL}_{\mathrm{dir}}$ to enable the AUV to move in the cross-$\widetilde{CL}_{\mathrm{dir}}$ direction of right to left.

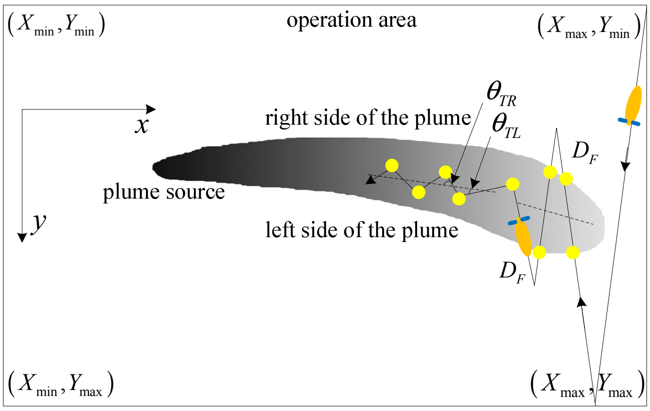

Fig. 2. Illustration of the Track-In behavior. The dashed lines represent estimatied plume centerlines.

When the AUV switches from Find-Plume behavior to Track-In behavior, for the Track-In-to-Right or Track-In-to-Left to work an initial estimated direction of plume centerline is needed. If an initial estimated CL_{dir} could not be given before the plume-tracing mission based on some priori information about the plume development, an adaptive plume mapping sub-behavior is also proposed in the Track-In behavior to generate an initial estimate of CL_{dir}. The mapping behavior continues the zigzag motion pattern as the Find-Plume behavior does and contains two plume-mapping tracklines. In the first trackline, when the AUV has left the plume for a predefined distance D_F from one side of the plume, the AUV reverses its cross-plume movement direction to return to the plume and continues the second trackline. When the two tracklines are completed, four points on the plume boundary could be obtained as shown in Fig. 2. Then an initial plume centerline is estimated as the straight line that fits the four points, using the method of least square.

When the plume mapping and initial estimation of CL_{dir} are completed, one of the behaviors of Track-In-to-Right and Track-In-to-Left is activated based on the AUV's cross-plume tracking direction to enable the AUV to continue moving into the plume, as illustrated in Fig. 2, and the θ_{TR} and θ_{TL} for the first Track-In-to-Right and Track-In-to-Left are predefined parameters in the Track-In behavior.

When Track-In-to-Right or Track-In-to-Left activates, the AUV starts recording sensor readings $C(S_R)$ and $C(S_L)$ of the two chemical sensors for s seconds, which is a design parameter in the Track-In behavior. And when the AUV remains in these behaviors over s seconds, the AUV records the sensor readings of the most recent s seconds. Then for each chemical sensor $s \times f$ sensor readings are saved, where f is the sampling frequency of the chemical sensors, and $\sum_{i=1}^{s\times f}[C(S_L)_i > C(S_R)_i]$ or $\sum_{i=1}^{s\times f}[C(S_R)_i > C(S_L)_i]$ is calculated. When the AUV is tracking the plume with the Track-In-to-Right behavior and if $\sum_{i=1}^{s\times f}[C(S_L)_i > C(S_R)_i] > [(s \times f)/p_T]$ (p_T is a design parameter in Track-In behavior and $1 < p_T < 2$) is satisfied ($\sum_{i=1}^{s\times f}[C(S_L)_i > C(S_R)_i] > [(s \times f)/p_T]$ indicates that $C(S_L) > C(S_R)$ occurs on over half of the AUV trajectory of last s seconds (denoting the trajectory by Tr_s))), then the probability of complete or part of Tr_s being in the right side of the plume centerline is higher than the probability of complete Tr_s being in the left side of the plume centerline and thus the current AUV location is estimated on the right side of the plume centerline. Likewise, when the AUV is tracking the plume in the Track-In-to-Left behavior and if $\sum_{i=1}^{s\times f}[C(S_R)_i > C(S_L)_i] > [(s \times f)/p_T]$ is satisfied, the current AUV location is estimated on the left side of the plume centerline.

When in Track-In-to-Right behavior and the AUV estimates that it is located on the right side of the plume centerline, the AUV switches to Track-In-to-Left behavior; and when in Track-In-to-Left behavior and the AUV estimates that it is located on the left side of the plume centerline, the AUV switches to Track-In-to-Right behavior. With this strategy, the AUV will exhibit a zigzag plume-tracing trajectory, which should partly or completely cover the plume centerline. Therefore, based on the zigzag plume-tracing trajectory in the Track-In behavior, the plume centerline could be estimated. And when a new segment of the zigzag plume-tracing trajectory is generated by the Track-In-to-Right behavior or the Track-In-to-Right behavior, the estimation of the plume centerline and its direction could be updated.

In this paper, we estimate the plume centerline as the straight line that fits the points on the AUV's zigzag trajectory where a switch of Track-In-to-Right and Track-In-to-Left occurs, as the left five points on the AUV trajectory shown in Fig.2. When a switch of Track-In-to-Right and Track-In-to-Left occurs, the AUV's location is recorded as (x_{bs}, y_{bs}). And a list of points L_T including these points of (x_{bs}, y_{bs}) and the four boundary points generated by the plume mapping is maintained. When a switch of the behaviors occurs and a new point is added in the list L_T, the plume centerline is estimated. And the straight line that fits the most recent added n ($n \geq 4$) points in the list is estimated as the plume centerline by the method of least square (Due to that the plume distribution is dynamic and the plume centerline maybe meandrous, n should be set as a small number to make the estimation locally accurate in the vicinity of the current AUV location), and the centerline's slope k is estimated as follows:

$$k = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} \quad (3)$$

In the chemical plume tracing mission in this paper as shown in Fig.2, the plume is assumed to develop mainly along the x axis and the AUV tracks the plume along the opposite direction of x axis, then we define the estimated direction of plume centerline $\widetilde{CL}_{\mathrm{dir}}$ for the chemical plume tracing mission in this paper as:

$$\widetilde{CL}_{\mathrm{dir}} = \mathrm{atan2}(k, 1) + 180° \quad (4)$$

In addition to estimate on which side of the plume centerline the AUV is located, we could further use $\sum_{i=1}^{s\times f}[C(S_L)_i > C(S_R)_i]$ and $\sum_{i=1}^{s\times f}[C(S_R)_i > C(S_L)_i]$ and the AUV trajectories in the last Track-In-to-Right and Track-In-to-Left to estimate the AUV's location relative to the plume centerline, based on which θ_{TL} and θ_{TR} for the following Track-In-to-Left and Track-In-to-Right could be adjusted to enable the AUV to move closely along the plume centerline. The strategy of designing θ_{TL} and θ_{TR} is being under development and in this paper we set θ_{TL} and θ_{TR} as constant values.

It should be noted that the above method of estimating on which side of the plume centerline the AUV is located and the direction of plume centerline cannot guarantee the correctness of the estimated results. However, with above strategy the AUV could stay inside the plume and track the plume along the plume. When chemical is being detected, the AUV keeps in the Track-In behavior. When the AUV has tracked the plume for a distance of D_T from the most recent chemical detected location without plume detection by both of the chemical sensors, the AUV may has left the plume due to tracking along an incorrect $\widetilde{CL}_{\mathrm{dir}}$ or some other reasons such as the plume centerline meander or plume intermittency, then the Track-Out behavior is activated to navigate the AUV back into the plume (D_T is a parameter of Track-In behavior and should be selected larger than the mean inter-filament distance of the chemical plume). And when the AUV switches to Track-Out behavior, the most recent chemical detected location is saved as a LCDP.

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.

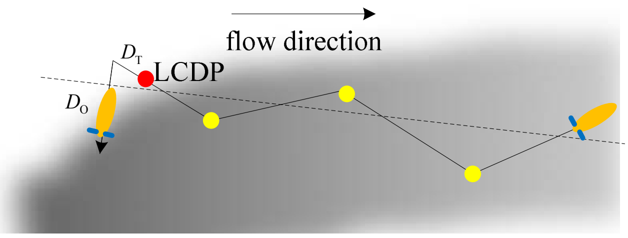

Fig. 3. Illustration of the Track-Out behavior. The dashed line represnts the estimated plume centerline.

When an AUV has not detected chemical for D_T in Track-In, probably the AUV has left the chemical plume from one side of the plume as shown in Fig. 3. In order to rapidly re-contact the chemical plume, Track-Out uses the path-following guidance to control the AUV to follow a straight line, whose starting point is set as the location where the AUV switches its behavior from Track-In to Track-Out and direction is set as the cross-$\widetilde{CL}_{\mathrm{dir}}$ direction of 90° or $-90°$ that enables the AUV to return to the plume (90° or $-90°$ is selected to be the opposite cross-$\widetilde{CL}_{\mathrm{dir}}$ direction in last Track-In behavior, as shown in Fig. 3).

If the AUV detects the plume, then it switches to Track-In. And the cross-$\widetilde{CL}_{\mathrm{dir}}$ direction of the following Track-In is the same with the cross-$\widetilde{CL}_{\mathrm{dir}}$ direction in the Track-Out behavior. If the AUV has moved a distance of D_O without plume detection, then the AUV switches to Reacquire-Plume behavior. D_O is a design parameter of the Track-Out behavior, and should be set large enough to ensure that the AUV could come back into the interior of the plume (D_O should be larger than $D_T \times sin(\theta_{TR})$ and $D_T \times sin(\theta_{TL})$; in addition, its selection should consider the plume centerline meander and the plume intermittency).

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 LCDP, as a moth does with the casting behavior. Considering the path-following capability of the AUV, we design the search pattern as a rectangle as illustrated in Fig. 4, with D_R being a design parameter that should be larger than $D_T \times cos(\theta_{TR})$ and $D_T \times cos(\theta_{TR})$ to make the rectangle cover the LCDP. The Reacquire-Plume uses the path-following guidance to enable the AUV to implement this trajectory.

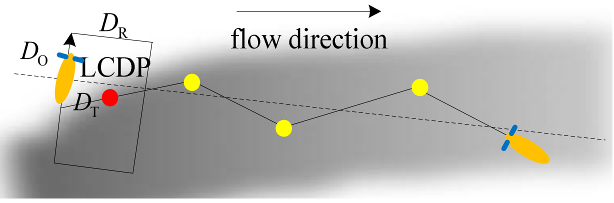

Fig. 4. Illustration of the Reacquire-Plume behavior. The dashed line represents the estimated plume centerline.

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 estimation error of the direction of plume centerline or the plume meander, the AUV does not leave the plume from the expected direction and thus Track-Out drives the AUV further leave the plume as shown in Fig. 4. 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 rectangular search path for successive N_R times without plume detection, then the AUV switches to Find-Plume behavior (The plume shape and location has changed dramatically due to varying flow). If the AUV detects the plume with the Reacquire-Plume behavior, then the AUV switches to Track-In. And if the AUV detects the plume on the left side of the centerline of the rectangle, which is the straight line that is parallel with the estimated plume centerline and passes LCDP, then in the following Track-In the AUV tracks the plume in the cross-$\widetilde{CL}_{\mathrm{dir}}$ direction of right to left; otherwise, the AUV tracks the plume in the cross-$\widetilde{CL}_{\mathrm{dir}}$ direction of left to right. By this strategy, the AUV could track the plume into the plume interior, with the consideration that most LCDPs are usually located on the boundary of a chemical plume.

In addition to the coordinate system defined for the chemical plume tracing mission as shown in Fig. 1, we also define a local coordinate system for estimating the source location, whose direction of the x axis is $\widetilde{CL}_{\mathrm{dir}} - 180°$. If the AUV implements the rectangular search trajectory and detects the plume on the right side of LCDP along the x axis direction in the local coordinate system but does not detect the plume on the left side of LCDP, the LCDP may be in the vicinity of the plume source (Plumes could only be detected down flow of the source along the plume centerline). Then this LCDP is saved as LCDP-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 LCDP-S is a location that a plume source may be in the vicinity. Thus LCDP-Ss provide information on the plume source location. If a cluster of LCDP-Ss is accumulated within a small area with the scale on the order of the plume source diameter, then it could be concluded that no plume exists up flow of this area while there exists plume down flow this area (In the vicinity of a plume source, the plume centerline will be parallel with the flow direction), 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 LCDP-S is generated, the Declare-Source behavior activates. The Declare-Source behavior arranges the obtained LCDP-S in the local coordinate system. Then in the x axis direction of the local coordinate system if the distance between the most left LCDP-S and its right N_Dth LCDP-S is small than a predefined parameter D_D, then the source is declared (Selecting D_D should consider the scale of the plume source's diameter, and N_D should be selected large enough to make the source declaration be correct and robust). And the source location could be estimated as the center of the cluster of N_D LCDP-Ss or the most left of the LCDP-S in the local coordinate system.

SIMULATION DEMONSTRATION

Due to the costs and complexities of in water tests, computer simulation is a key alternative approach to evaluating and validating chemical plume tracing strategies. To support the research on chemical plume tracing with AUVs, we have developed a computer simulation environment using C++ programming language [9]. In the simulation environment, a numerical turbulent plume is generated by a Lagrangian particle random walk based turbulent plume model, which captures the key features of a turbulent chemical plume to complicate the plume tracing problem [10]. We have implemented the proposed chemical plume tracing strategy in the simulation environment and the simulation results demonstrate that with the strategy an AUV could effectively track a turbulent plume and localize the plume source. In the following, we give some of the simulation results to demonstrate the performance of the strategy.

In the simulation demonstration, the operational area of the chemical plume tracing mission $[X_{\min}, X_{\max}] \times [Y_{\min}, Y_{\max}]$ is set as [0, 500] m×[-250, 250] m, and the plume source is located at (50, 0) m with its diameter 1 m. The AUV starts the mission with the Find-Plume behavior at (500, -250) m and after the AUV has localized the plume source the AUV returns to (0, 0) m. A pair of chemical sensors is mounted symmetrically on the right and left side of the AUV's nose location and the distance between the two sensors is set as 0.2 m, and the sampling frequency of both of the chemical sensors is set as 10 Hz. The mission planning and motion control cycles of the AUV are both set as 0.1 s, the AUV's speed is set as 2.0 m/s during the entire chemical plume tracing mission. And the REMUS AUV's dynamic model is adopted [11] for simulating the AUV's dynamics.

Fig. 5 shows a result of a simulation run. In this chemical plume tracing mission, a plume is generated by a uniform and steady flow field and develops along the x axis direction. The dots on the AUV plume-tracing trajectory indicate that at corresponding location the chemical is detected by either one or both of the two chemical sensors of the AUV. And the red points near the plume source are LCDP-Ss generated in the Reacquire-Plume behavior.

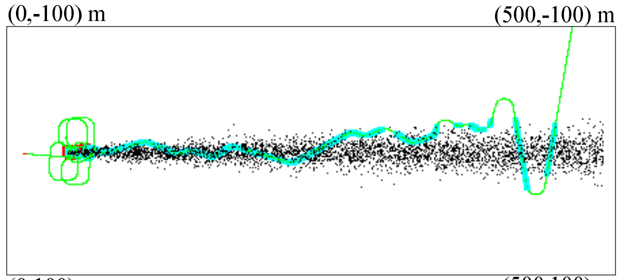

Fig. 5. A simulation result of tracking of a straight turbulent plume.

In this mission, the AUV starts with the Find-Plume behavior to search the operational using the zigzag search pattern, and the AUV's movement direction relative to the up-flow direction for the up-flow search is set as 80 degrees. During the search, the AUV detects the chemical at (452.6, -21.3) m and at simulation time of 120 s. After the plume detection, the AUV switches to Track-In behavior, which first implements the plume mapping and estimates the direction of plume centerline with four boundary points as 4.96 degrees (D_F is set as 10 m). Then the Track-In-to-Right and Track-In-to-Left are activated to track the plume along the estimated direction of plume centerline, with the offset angles θ_{TR} and θ_{TL} being set as 25 degrees and -25 degrees, respectively. Track-In-to-Right and Track-In-to-left use $\sum_{i=1}^{50}[C(S_L)_i > C(S_R)_i] > 30$ and $\sum_{i=1}^{50}[C(S_R)_i > C(S_L)_i] > 30$ (s is set as 5 s and Tr_s is 10 m) to estimate that the AUV arrives on the right or left side of the plume centerline, respectively. When a switch of the Track-In-to-Right and Track-In-to-Left occurs and a new (x_{bs}, y_{bs}) is generated and added in L_T, the Track-In behavior uses the most recent four points in the list to update the estimation of the direction of plume centerline. When the AUV has not detected chemical from the most recent plume detected location for a distance of D_T=5 m in Track-In behavior, Track-Out behavior activates to navigate the AUV back into the plume. If Track-Out behavior fails to detect the chemical for a distance of D_T=15 m, Reacquire-Plume behavior activates to search the plume in the vicinity of LCDP. When a LCDP-S is generated in Reacquire-Plume behavior, the Declare-Source behavior activates. And if the distance between the most left LCDP-S and its right 4th LCDP-S is less than D_D=20 m in the x axis direction of defined local coordinate system, the plume source is declared. And the source location $(x_s, y_s)$is estimated as:

$$x_s = x_{\min} \tag{5}$$

$$y_s = (y_{\max} + y_{\min})/2 \tag{6}$$

where $(x_{\min}, y_{\min})$ and $(x_{\max}, y_{\max})$ are the minimum and maximum x and y coordinate values of the four LCDP-S expressed in the defined local coordinate system. With this method in this simulation run the plume source is estimated at (50.2, -1.2) m at simulation time of 572 s.

Fig. 6 shows the estimated direction of plume centerline during the chemical plume tracing mission. As shown in Fig. 6, the estimated direction of plume centerline converges to 0.77 degrees when the mission is completed. Fig. 7 shows the AUV's heading during the simulation run, which shows that the AUV zigzags along the plume centerline to the plume source, as also shown by the AUV's trajectory in Fig. 5.

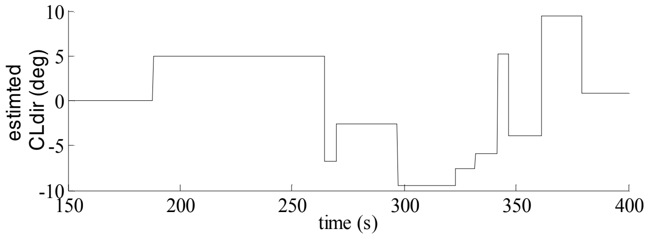

Fig. 6. Estimated direction of plme centerline in the plume tracing run in Fig. 5.

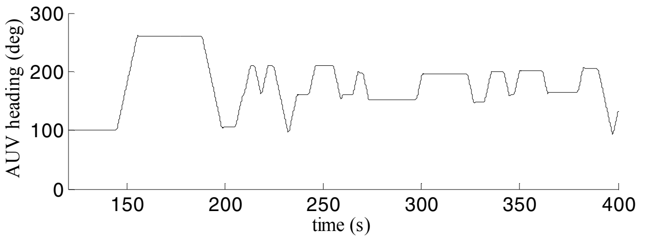

Fig. 7. AUV's heading in the plume tracing run in Fig. 5.

Fig. 8 shows a simulation result of tracking of a turbulent plume whose centerline is meandrous. For demonstration of tracing of a meandrous plume, the plume in this simulation run is set as static without evolving. The settings of the parameters in the mission and the chemical plume tracing strategy is the same with the above simulation run. In this simulation run, the AUV first detects chemical at location (435.2, 77.4) m and at simulation time of 170 s. And at simulation time of 632 s, the AUV declares the plume source and the estimated source location is (51.9, 1.2) m. Fig 9 shows the estimated direction of plume centerline during the simulation run, which changes from 36.5 degrees that is estimated by the plume mapping behavior to -24.4 degrees when the plume source is declared.

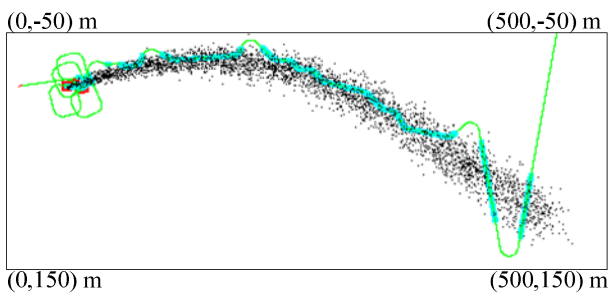

Fig. 8. A simulation result of tracking of a turbulent plume whose centerline is meandrous.

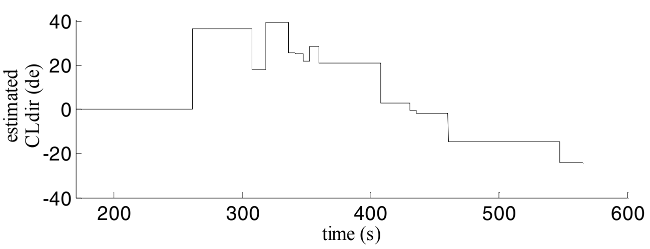

Fig. 9. Estimated direction of plme centerline in the plume tracing run in Fig. 8.

Fig. 10 shows a simulation result of tracking of a dynamic turbulent plume. The parameters in the chemical plume tracing strategy are the same with above two simulation runs. However, to challenge the chemical plume tracing strategy, the plume in this mission is set to be more intermittent, and the plume location changes rapidly with the varying flow field. The three sub-figures show the simulation results at simulation time of 126.9 s, 317.6 s and 889.9 s, respectively.

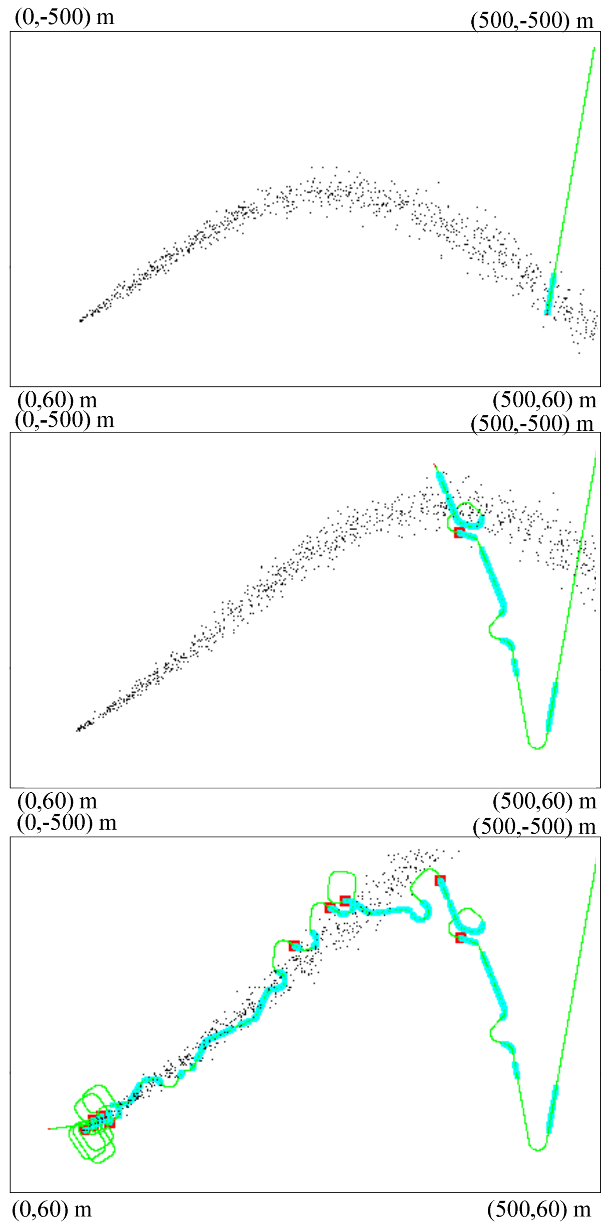

Fig. 10. A simulation result of tracking of a dynamic turbulent plume.

In this mission, the AUV first detects chemical at (455.8, -39.6) m at simulation time of 110.7 s, then the AUV switches to Track-In behavior and by the mapping sub-behavior estimates the direction of plume centerline as 43.1 degrees. Due to the meander and varying of the plume centerline, the AUV leaves the plume by tracking the plume along the estimated direction of plume centerline of the right part of the plume. Then with the Track-Out behavior and the Reacquire-Plume behavior, the AUV reacquires the plume and Track-In behavior activates and a number of (x_{bs}, y_{bs})s are generated, with which the estimated direction of plume centerline is continually updated to -33.5 degrees (as shown in Fig. 11), which is close to the direction of the plume centerline of the left part of the plume. At simulation time of

870.3 s, the source is declared and the estimated source location is (52.2, -4.0) m.

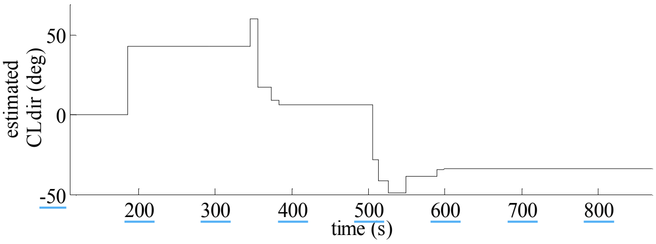

Fig. 11. Estimated direction of plme centerline in the plume tracing run in Fig. 10.

CONLCUSION

This paper presents a modified moth-inspired chemical plume tracing strategy, which is proposed to aim to enable an AUV to track a turbulent chemical plume and localize the plume source when no effective information of flow direction is available for a chemical plume tracing mission. The strategy employs only a pair of chemical sensors mounted on an AUV's nose for plume tracing, and works under the conditions that the two chemical sensors are accurately calibrated and in the cross-plume direction a location with shorter distance to the plume centerline has higher mean chemical concentration. Then the strategy uses the readings from the two chemical sensors and the AUV's zigzag plume-tracing trajectory to estimate the direction of plume centerline. And the estimated direction of plume centerline is employed in the strategy for an AUV to track the plume, thus the strategy works without need of information of flow direction. The strategy is implemented in our developed simulation environment and the simulation results demonstrate that with the proposed strategy an AUV could effectively track a meandrous turbulent plume over a long distance and finally localize the source.

In following work, we will test the proposed strategy via field experiments with an AUV and Rhodamine dye plumes, and develop methods of adjusting the offset angles of θ_{TL} and θ_{TR} in Track-In behavior based on chemical sensor readings and AUV's plume-tracing trajectory to enable an AUV to track closely along the plume centerline thus the performance of the strategy could be improved.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (Grand No. 41376110), the State Key Laboratory of Robotics in China (Grand No. 2012-Z04), and China Scholarship Council (Grant No. 20143012).

REFERENCES

[1] W. Naeem, R. Sutton, and J. Chudley, "Chemical plume tracing and odour source localisation by autonomous vehicles," The Journal of Navigation, Vol. 60, No. 2, pp. 173-190, 2007.

[2] G. Kowadlo, and R. A. Russell, "Robot odor localization: A taxonomy and sruvey," The International Journal of Robotics Research, 2008, 27(8), 869-894.

[3] W. Li, J. A. Farrell, S. Pang, and R. M. Arrieta, "Moth-inspired chemical plume tracing on an autonomous underwater vehicle," IEEE Transactions on Robotics, vol. 22, no. 2, pp. 292-307, 2006.

[4] J. A. Farrell, S. Pang, and W. Li, "Chemical plume tracing via an autonomous underwater vehicle," IEEE Journal of Oceanic Engineering, vol. 30, no. 2, pp. 428-442, 2005.

[5] Y. Tian, W. Li, A. Zhang, J. Yu, Q. Zhang, and Y. Li, "From simulation to validation: Moth-inspired chemical plume tracing with an autonomous underwater vehicle," Proceedings of OCEANS 2014 St. John's, pp. 1-10, 2014.

[6] W. Li, "Identifying an odour source in fluid-advected environments, algorithms abstracted from moth-inspired plume tracing strategies," Applied Bionics and Biomechanics, vol. 7, no. 1, pp. 3-17, 2010.

[7] J. Yuan, D. Oswald, and W. Li, "Autonomous tracking of chemical plumes developed in both difusive and turbulent airflow environments using Petrinets," Expert Systems with Applications, vol. 42, no. 1, pp. 527-538, 2015.

[8] Y. Tian, and A. Zhang, "Development of a guidance and control system for an underwater plume exploring AUV," Proceedings of the 8th World Congress on Intelligent Control and Automation, pp. 6666-6670, 2010.

[9] Y. Tian, W. Li, and A. Zhang, "A simulation environment for deepsea hydrothermal plume tracing with autonomous underwater vehicles," Robot, vol.34, no. 2, pp. 159-169, 196, 2012.

[10] Y. Tian, W. Li, and A. Zhang, "A Lagrangian particle random walk model for simulating a deep-sea hydrothermal plume with both buoyant and non-buoyant features," China Ocean Engineering, vol. 27, no. 2, pp. 215-230, 2013.

[11] P. Timothy, "Verification of a six-degree of freedom simulation model for the REMUS autonomous underwater vehicle," Master thesis, MIT-WHOI, 2001.