2012 International Conference on Intelligent Systems Design and Engineering Application

Validation of an Odor Source Identification Algorithm via an Underwater Vehicle

Xiaodong Kang[1,2], Wei Li[1,3], Hongli Xu[1], Xisheng Feng[1], Yiping Li[1]

[1]State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences
Liaoning Province, 110016, China
[2]Graduate School of the Chinese Academy of Sciences, Beijing 100049, China
[3]Department of Computer Engineering and Science
California State University, Bakersfield, CA 93311, USA
wli@csub.edu

***Abstract*—This paper systemically discusses a procedure for evaluating and validating an odor source identification algorithm derived from moth-inspired plume tracing strategies. We evaluate and validate the proposed source identification algorithm as follows. First, we identify the source of a virtual chemical plume with significant filament intermittency and meander via a simulated underwater vehicle. Second, we validate the source identification algorithm using the virtual chemical plume and a real underwater vehicle in a swimming pool. Finally, we run in-water tests to trace a Rhodamine dye plume developed in near-shore ocean environments characterized by turbulence, tides and waves, and to identify its source via the underwater vehicle at Da Lian Bay in China.**

Keywords- Insect-inspired robots; chemical plume tracing; underwater vehicle; odor source identification

I. INTRODUCTION

Olfactory-based mechanisms have been hypothesized for biological behaviors, e.g., foraging by lobsters [1], foraging by blue crabs [2], mate seeking and foraging by moths [3]. Koehl et al. [4] further reported how lobster olfactory antennules hydro-dynamically alter the spatiotemporal patterns of concentration in turbulent odor plumes. Recently there has been interest in developing autonomous vehicles capable of chemical plume tracing (CPT) [5]. Vergassola et al. [6] generalized CPT issue as "'infotaxis' searching without gradients". Belanger and Willis [7] presented plume tracing strategies, including counter-turning strategies, intended to mimic moth behavior and analyzed the performance in a computer simulation. Li et al. [8] evaluated and optimized the moth-inspired plume tracing strategies in a simulated plume with significant meander and intermittency of plume puffs. Grasso et al. [9] evaluated biomimetic strategies and challenged theoretical assumptions of the strategies by implementing biomimetic strategies on their robot lobster. Russell [10] included robotic implementation of algorithms that estimate statistics of the plume such as the plume centroid and experiments where the chemical is constrained to a multiple-duct tunnel system. Marques et al. [11] performed plume tracing tests using mobile robots in laboratory environments. Recently, Li [12] used six robots to localize an odor source in a laboratory environment. Figure 1 shows our recent in-water CPT mission for odor source identification in near-shore ocean environments at Da Lian Bay China.

Figure 1. A field test run of plume source identification via an underwater vehicle at Da Lian Bay on October 10, 2010

Autonomous underwater vehicles (AUVs) with CPT capabilities would be valuable for searching for deep-sea hydrothermal vents, finding unexploded ordnance in near-shore environments, and monitoring pollutants or localizing sources of hazardous chemicals in harbor. The strategies proposed in [8] were implemented on a REMUS underwater vehicle with a single chemical sensor for the in-water test runs in November and April 2002 at the San Clemente Island of California and in June 2003 in Duck, North Carolina [13][14]. The field experiments successfully demonstrated tracking of chemical plumes over 100 m and source identification on the order of tens of meters in the near shore, oceanic fluid flow environments, where plumes were developed under turbulence, tides and waves. The most recent CPT in-water tests via an AUV at Da Lian Bay in China were documented in [15] to validate the moth-inspired CPT strategies.

This paper systemically discusses a methodology for validating source identification algorithms, which are abstracted from the moth-inspired plume tracing strategies based on a single chemical sensor. First, we identify the source of a virtual chemical plume with significant filament intermittency and meander via a simulated underwater

978-0-7695-4608-7/12 $26.00 © 2012 IEEE
DOI 10.1109/ISdea.2012.485

vehicle. Second, we validate the source identification algorithm using the virtual chemical plume and a physical underwater vehicle in a swimming pool. Finally, we run in-water tests to identify a Rhodamine dye plume source via the underwater vehicle at Da Lian Bay in China.

II. SOURCE IDENTIFICATION ALGORITHM

A. Last chemical detection point (LCDP)

We derive a source identification algorithm from the two moth-inspired plume tracing behaviors: Maintain-Plume and Reacquire-Plume. Maintain-Plume is broken down into Track-In and Track-Out activities because of intermittency of a chemical plume transported in a fluid flow environment [8]. The Reacquire-Plume behavior is to reacquire contact with the plume in the situation where chemical has not been detected for at least a few seconds. A cloverleaf-shaped trajectory or its variant [13][14] was used to implement the Reacquire-Plume behavior for casting the lost chemical plume. We choose the length of each leaf by considering that the minimum value is constrained to be larger than the tracer turning radius, e.g., 10–15 meters for the REMUS vehicle. Note that one leaf is aligned with the down-flow direction for the tracer to rediscover the chemical when it has passed the source location.

A chemical detection point at which the tracer loses contact with the chemical plume for λ seconds is defined as a LCDP, e.g., point (x_{last} , y_{last}) in Figure 2. During a Reacquire-Plume activity, the tracer either detects the chemical or completes the cloverleaf trajectory N_{re} times (N_{re} = 2 or 3 for the in-water tests). If N_{re} repetitions are completed without a chemical detection, the tracer reverts to Find-Plume [13]. In the moth-inspired CPT strategies, the chemical sensor works as a "binary detector". The Boolean value is "1" if the chemical concentration is above the threshold.

B. Patterns for source identification

The LCDPs are separated along the axis of the plume when the tracer is far from the source location, while the LCDPs are clustered in the vicinity of the source when the tracer is approaching the source location. The tracer usually exits the plume and moves up flow from the source when it traces the plume to the source location. When this situation occurs, the tracer also activates Reacquire-Plume to rediscover the plume on a cloverleaf trajectory. As a result of the frequent switching between Maintain-Plume and Reacquire-Plume, the tracer generates a pattern with a number of cloverleaf trajectories in the vicinity of the source location, as shown in Figure 2. Such a distribution of the LCDPs is employed to facilitate development of the source identification algorithm.

The tracer detects a new LCDP and inserts its node into the priority queue when it switches its behavior from Maintain-Plume to Reacquire-Plume. The queue sorts the LCDP nodes in a new coordinate system, defined in order of the current up-flow direction, $f_{dir} + 180^\circ$. Its x-axis is aligned with the f_{dir} direction, and its origin is located at (x_{last} , y_{last}).

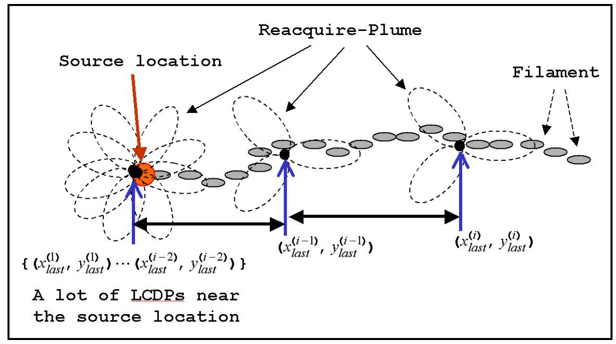

Figure 2. Patterns for identifying the odor source using the LCDPs.

Table I: Pseudo Code for SIZ_F algorithm

```
ALGORITHM SIZ_F ( Q[1,… N_all] )
  //Identifying the source location by SIZ_F algorithm
  //Input: Priority queue Q[1,… N_all]
  //Output: Status of source identification
  if ( N_all ≥ N_ini )
     Sort Q in the order of the current up-flow direction
     L[1,… N_all] ← Q[1,… N_all] ; n1 ← N_all  // L is a list
     status ← false
    while n1 ≥ N_min do
      Calculate (x_last^(m), y_last^(m)) of all LCDPs in the queue;
      Find p_max with D_max in Eq. (2)
      if D_max > ε_F
        remove p_max from L; n1←n1-1
      else
         status ← true; break
      if status = true
         return (x_last^f(1), y_last^f(1)) as the source location
      else
         return no source location identified
  else
     return no source location identified
```

C. SIZ_F algorithm

The SIZ_F algorithm maintains ***all*** LCDPs in the order of the current up-flow direction using the priority queue. SIZ_F holds a constant size, ε_F , and makes the source identification by the following iterative construct: First, SIZ_F calculates ($x_{last}^{(m)}$, $y_{last}^{(m)}$) of all the LCDPs; Second, SIZ_F find the point, $p_{\max}$, with the largest distance to ($x_{last}^{(m)}$, $y_{last}^{(m)}$)

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

$$(i = 1, 2, \cdots N_{all})$$

from the priority queue, where a superscript f indicates that the LCDPs are sorted in the order of the most recent up-flow direction, and N_{all} is the total number of LCDPs detected during a CPT mission. If $D_{\max}$ is greater than ε_F, SIZ_F removes the LCDP with $p_{\max}$ from the set of LCDPs. These calculations repeat until all remaining LCDPs are close enough to ($x_{last}^{(m)}$, $y_{last}^{(m)}$). If the number of the remaining LCDPs is greater than N_{min}, SIZ_F identifies its most up-flow LCDP as the odor source. Table I lists the pseudo code of the SIZ_F algorithm with three parameters: the SIZ_F size, ε_F, the initial value, N_{ini}, and the integer, N_{min}, which indicates the minimum number of LCDPs remaining inside SIZ_F for the source identification. The SIZ_F algorithm also has two the adjustable parameters ε_F and N_{min}. The SIZ_F algorithm uses an iterative construct to cluster LCDPs inside SIZ_F. The parameter, N_{ini}, defined in the algorithms works as a filter to block some invalid LCPDs, only when N_{min} is very small.

III. Algorithm Evaluation and Validation

A. *Virtual plume and simulated unerwater vehicle*

We evaluate the SIZ_F source identification algorithm via an underwater vehicle in a simulated fluid-advected environment [17], which upgrades the version [18] by expanding the filament-based plume model from two-dimensions to three dimensions. The upgraded version allows us conveniently to define multiple vehicles and plume sources, as shown in Figure 3. This plume model addresses the major characters that challenge CPT algorithms, such as significant intermittency between chemical filaments, significant plume meander, noise and uncertainty of sensors, and magnitude and direction variation of flow fluid at time and location. The operation area is specified by [0,100] × [-50, 50] in meters. The filament release rate is 5 filaments per second, the simulation time step is 0.01 s, and the mean fluid velocity is 1.0 m/s. The measured fluid flow is corrupted by additive noise that is white normal random process. The plume source is located at (10, 0) in meters, which is unknown to the vehicles fleet. The home location is defined as (110, 40) in meters outside the operation area.

For evaluation studies, we implement the dynamics of an underwater vehicle developed by State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences for our evaluation studies [15]. Simulations continue 1000 CPT test runs without duplications of the trajectory, the odor-hit points, and the LCDPs. We define a CPT test run as a cycle the vehicle starts at its home location and returns the home location. The test run fails (in this case, the vehicle returns the home location with record "over-time" test run) if the vehicle cannot identify the source location within the time limit $T_{\max}$=1000.0 s (this limit can be used to measure CPT performance in simulation studies and viewed as the energy remaining for vehicle back home in the field tests). The optimized algorithm achieves the mean identification time in about 3 minutes and the success rate about 90%.

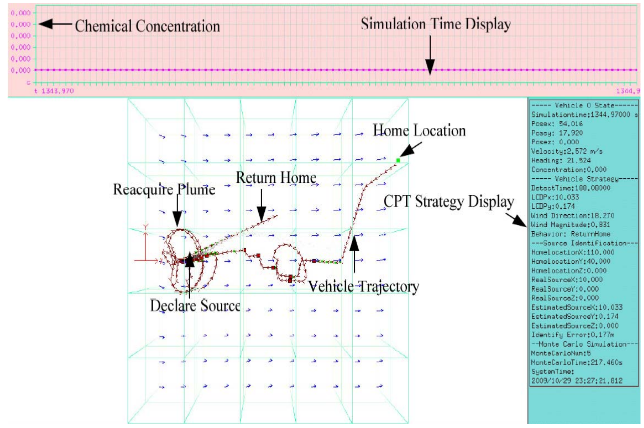

Figure 3. Olfactory-based chemical plume tracing and source identification in a simulated fluid-advected environment

B. *Virtual plume and real underwater vehicle*

Before our in-water test runs, we need to investigate the effect of sensor noise and vehicle dynamics on chemical source identification, so we validate the proposed algorithm using the virtual chemical plume and the underwater vehicle that run in a swimming pool. The simulated chemical sensor and fluid detector detect the chemical concentration, and fluid direction and magnitude in the simulated flow fluid environment. Our plume tracing algorithm generates the vehicle commands which control the real vehicle maneuver in the swimming pool. Figure 4 shows a test run of tracing the virtual plume via the underwater vehicle in swimming pool. The study shows that the average accuracy of the source identification is about 0.18m.

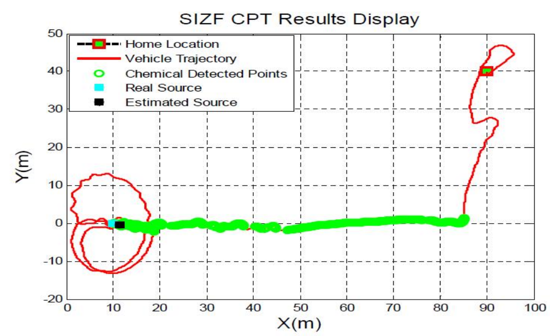

Figure 4. Chemical plume tracing and source identification using a virtual plume and a real underwater vehicle

C. *Rhodamine dye plume and real underwater vehicle*

The underwater vehicle for our field tests is equipped with multiple sensor sensors, including an underwater fluorometer to detect the Rhodamine plume and a Doppler Velocity Log (DVL) to measure vehicle's velocity relative to the sea bottom and the reference water layer which is 2 m below the sensor head with sample rate 2-3 Hz.

We perform our in-water test rum to validate the proposed source identification algorithm at Da Lian Bay on

October 10, 2010. Figure 5 displays the trajectory of an underwater vehicle activity during plume tracing and source identification. We conduct five CPT missions to identify the source location of the Rhodamine dye plume shown in Figure 6. Missions 4 and 5 identified the source locations with accuracy 8.38 meters and 29.42 meters relative to the nominal source location, respectively.

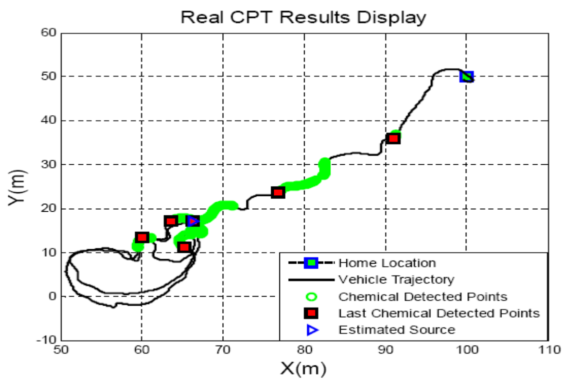

Figure 5. An in-water test of chemical plume tracing and source identification via the underwater vehicle

Figure 6. Rhodamine dye plume developed in near-shore ocean environment at Da Lian Bay

IV. CONCLUSIONS

We validate the SIZ_F algorithm in near-shore ocean environments. The in-water tests achieve source declaration accuracy relative to the source location on the order of tens of meters, which is similar to the test results provided in [13]. The first three CPT missions fail due to the following reasons: First, shifts of the boat which releases Rhodamine dye heavily affect distribution of the Rhodamine dye. Second, tuning algorithms of processing the data measured by DVL. Finally, the parameter ε_F of SIZ_F algorithm is selected too small. Our further research will address chemical plume tracing and source identification in 3-D dimensions.

ACKNOWLEDGMENT

The work of this paper is in part supported by the Chinese National 863 Plan Program under grant 2007AA09Z207, National Science Foundation under grant 60805050, and State Key Laboratory of Robotics at Shenyang Institute of Automation under grant 2009-Z03. The authors would like to thank collaborators in the Department of Underwater Vehicle, Shenyang Institute of Automation, Chinese Academy of Sciences, for their support in the field experiments.

REFERENCES

[1] J. Basil, and J. Atema, "Lobster orientation in turbulent odor plumes: Simultaneous measurements of tracking behavior and temporal odor patterns," *Biological Bulletin*, vol.187, pp. 272–273, 1994.

[2] M. J. Weissburg, and R. K. Zimmer-Faust, "Odor plumes and how blue crabs use them in finding prey," *Journal of Experimental Biology,* vol. 197, pp. 349–375, 1994.

[3] R. T. Cardé, "Odour plumes and odour-mediated flight in insects. In olfaction in mosquito-host interactions," *CIBA Found. Symp*, 200: John Wiley & Sons, pp.54-66, 1996.

[4] M. A. R. Koehl, et al, "Lobster Sniffing: Antennule Design and Hydrodynamic Filtering of Information in an Odor Plume," *Science*, vol. 294, no. 5548, pp. 1948-1951, 2001.

[5] E. A. Cowen, K. B Ward, "Chemical plume tracing," *Fluid Mech. Environ,* vol.2, no.1–2, pp.1–7. 2002.

[6] M. Vergassola, E. Villermaux & B. I. Shraiman "'Infotaxis' as a strategy for searching without gradients," *Nature,* vol. 445, no.25, pp. 406-409, 2007.

[7] J. H. Belanger, and M. A. Willis, "Adaptive control of chemical – guided location: Behavioral flexibility as an antidote to environmental unpredictability," *Adaptive Behavior*, vol. 4, pp. 217-253, 1998.

[8] W. Li, J. A. Farrell, and RT Cardé, "Tracking of fluid-advected chemical plumes: Strategies inspired by insect orientation to pheromone," *Adaptive Behavior*, vol.9, pp.14-170. 2001.

[9] F. W. Grasso, T. Consi, D. Mountain, and J. Atema, "Locating chemical sources in turbulence with a lobster inspired robot," *From Animals to Animats 4: Proceedings of the Fourth International Conference on Simulation of Adaptive Behavior* (P. Maes, M. J. Mataric, J.-A. Meyer, J. Pollack, and S. W. Wilson, Eds), MIT Press, pp. 104-112, 1996.

[10] R. A. Russell, "Tracking chemical plumes in constrained environments," *Robotica*, vol.19, pp.451–458, 2001.

[11] L. Marques, U. Nunes U, A. T. de Almeida, "Olfaction-based mobile robot navigation," *Thin Solid Films*. vol. 418, pp.51–58, 2002.

[12] F. Li, "Multi-robot odor-source localization in turbulence dominated airflow environments," [Ph. D. Dissertation]. [Tianjin (China)]: School of Electrical Engineering and Automation, Tianjin University, 2009.

[13] 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.

[14] J. A. Farrell, S. Pang, and W. Li, "Chemical plume tracing via an autonomous underwater vehicle," *IEEE Journal of Ocean Engineering*, vol.30, pp.428-442, 2005.

[15] X. D. Kang, "Research on chemical plume exploration via multiple AUVs with formation-keeping," [Ph. D. Dissertation]. [Shenyang (China)]: Shenyang Institute of Automation, Chinese Academy of Sciences, 2010.

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

[17] J. Sutton, and W. Li, "Development of CPT_M3D for multiple chemical plume tracing and source identification," *Seventh International Conference on Machine Learning and Applications*, pp.470-475, 2008.

[18] J. A. Farrell, J. Murlis, X. Long, W. Li, and R. T. Cardé, "Filament-based atmospheric dispersion model to achieve short time-scale structure of odor plumes," *Environmental Fluid Mechanics*, vol.2, pp.143-169, 2002.