

Chapter 14

Chemical Plume Tracing and Mapping via Swarm Robots

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ABSTRACT

This chapter addresses the key issues of chemical plume mapping and tracing via swarm robots. First, the authors present the models of turbulent odor plumes with both non-buoyant and buoyant features, which can efficiently evaluate strategies for tracing plumes, identifying their sources in two or three-dimensions. Second, the authors use the Monte Carlo technique to optimize moth-inspired plume tracing via swarm robots under formation control, which includes a leader to perform plume tracing maneuvers and non-leaders to follow the leader during plume tracing missions. Third, the authors introduce a variety of robot-based plume tracers, including ground-based robots, autonomous underwater vehicles, or unmanned aerial vehicles. Finally, the authors prospect the further research in this area, e.g., applying swarm robots to detect oil or gas leak, or to investigate subsea chemical pollution and greenhouse gases.

INTRODUCTION

A potential application of a swarm robot system is to search for environmentally interesting phenomena, unexploded ordnance, undersea wreckage, and sources of hazardous chemicals or pollutants. Navigating the swarm robot system in response to real-time sensor information to find the plume, trace the plume towards its source, and identify the source location, is referred to as Chemical Plume Tracing (CPT). Factors that complicate CPT include the chemical source concentration being unknown, the advection distance of any detected chemical being unknown, significant filament intermittency and meander of a chemical plume developed in turbulent fluid flow environments, and the flow variation with both location and time.

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Since last decades, there has been a growing interest to apply robot-based chemical plume tracers in environmental monitoring (Dunbabin & Marques, 2012; Oyekan & Hu, 2014) and in searching for sources of hazardous chemicals or pollutants (Cowen and Ward, 2002). Ishida et al. (1996) used an array of sensors to track the plume by estimating the three-dimensional direction toward the odor source. Russell (2001) included robotic implementation of algorithms that estimate statistics of the plume such as the plume centroid. Marques et al. (2002) performed plume-tracing tests using mobile robots in laboratory environments. Li et al. (2001) developed, evaluated and optimized both passive and active plume tracing strategies inspired by moth behavior. The moth-inspired plume tracing strategies were implemented on a REMUS underwater vehicle 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 (Farrell et al., 2005; Li et al., 2006). 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 test run via an autonomous underwater vehicle at Dalian Bay in China (Tian et al., 2014) also validated effectiveness of the moth-inspired CPT strategies.

Animal swarms are typical distributed systems with flexibility and autonomy for homing, foraging or mate-seeking. The swarm robotics inspired from nature is a combination of swarm intelligence and robotics showing a great potential in several aspects (Beni, 2005; Liu et al., 2010; Tan and Zheng, 2013; Brambilla et al, 2013). For example, a multi-robot system inspired by animal swarms suits to CPT missions very well. Hayes et al. (2002) used multiple robots to improve a Spiral Surge Algorithm in the field of swarm intelligence in order to find a plume and to trace the plume to its source location. Zarzhitsky et al. (2004) presented an approach to CPT based on the physics of fluid dynamics, upon source localization using the divergence theorem of vector calculus. Krishnanand and Ghose (2009) addressed the problem of multiple signal source localization via robotic swarms. Kang and Li (2012) expanded moth-inspired plume tracing via a single robot to multiple robots, which included a mechanism determining a leader vehicle to perform moth-inspired plume-tracing maneuvers and a formation algorithm controlling non-leaders to follow the leader during plume-tracing missions. Marjovi and Marques (2014) presented an analytical approach to the problem of odor plume finding by a swarm robot system.

The chapter starts with the models to achieve short time-scale structure of odor plumes. These computational plume models suit to evaluate algorithms for tracing chemical plumes and identifying the chemical sources via a single robot or multiple robots in two or three dimensions. The chapter discusses the Monte Carlo technique for optimizing moth-inspired CPT via multiple autonomous robots with a leader to perform moth-inspired plume-tracing maneuvers and non-leaders to follow the leader during CPT missions. The results demonstrate CPT performance achieved by swarm robots, which automatically switch their roles superior to the single robot. The chapter presents a variety of robot-based chemical plume tracers, including ground-based DaNI robots, autonomous underwater vehicles (AUVs), or unmanned aerial vehicles (UAVs). The chapter also prospects the further research, e.g., applying swarm-robot-based plume tracers into the oil and gas industry.

Background

Olfactory-based mechanisms have been hypothesized for a variety of biological swarm behaviors (Vickers, 2000; Zimmer and Butman, 2000): homing by Pacific salmon (Hassler and Scholz, 1983), foraging by Antarctic procellariiform seabirds (Nevitt, 2000), foraging by lobsters (Basil and Atema, 1994; Devine

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