

# Toxic Plume Source Localization in Urban Environments Using Collaborating Robots

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## Abstract

The research work presented herein is part of a large effort in R&D of a physics-based approach to develop networks of mobile sensing agents for monitoring, tracking, reporting and responding to hazardous conditions such as those resulting from the release of a WMD. We present the development of an efficient and robust distributed collaborative search algorithm for a team of unmanned robots that must locate the emitter of a toxic plume in an urban setting. We aim to provide a scientific, yet practical, approach to the design and analysis of rapidly deployable, scalable, adaptive, cost-effective groups of autonomous robots to replace or complement humans in the hazardous task of localizing the source of toxic chemical, biological or radiological plumes. In our approach, the robot group coordination and control are based on a physics-based framework called *physicomimetics*, and the collaborative search algorithm, called *fluxotaxis*, is based on fluid mechanics.

## 1. Introduction

Physicomimetics [1, 2] or artificial physics (AP) is a physics-based framework for distributed multi-agent coordination and control that assumes several simple, inexpensive mobile robotic agents with limited processing power and a small set of on-board sensors. The basic AP framework is elegantly simple. Virtual forces drive the multi-robot system to a desired configuration or state. The desired state is one that minimizes overall system potential energy. Using AP, the robots configure into adaptive geometric formations (e.g., lattices) that are preserved as they navigate around obstacles in search of the toxic plume source location.

Fluxotaxis [3] is a distributed, plume tracing algorithm based on formal fluid mechanics principles. The robots sense the ambient plume

velocity and chemical concentration, and calculate derivatives to estimate the local flow divergence collectively. The algorithm drives the group of robots to the source of the toxic plume, where measures can be taken to disable the source emitter. This algorithm has been proven superior (i.e., faster source localization and more robust) to the existing plume tracing approaches, which use dominant fluid velocity direction or plume concentration gradient [4, 5].

## 2. Methodology

This research is being performed using two levels of abstraction (i.e., mathematical modeling and sensor-based simulations) and real robots experiments. In section 2.1, we summarize the concepts and mathematical frameworks of physicomimetics and fluxotaxis as applied to the toxic plume source localization problem.

### 2.1 Mathematical Abstraction

We use mathematical abstractions to develop both the distributed control of the robots and the plume source localization algorithm.

#### *Physicomimetics for Distributed Control of Autonomous Robots*

The basic physicomimetics or AP framework is as follows. In essence the multi-robot system acts as a particle physics simulation. Each particle has position  $\mathbf{X}$  and velocity  $\mathbf{v}$ . We use a discrete-time approximation to describe the continuous behavior of the system, with time-step  $\Delta t$ . At each time step, the position of each particle (i.e., robot) undergoes a perturbation  $\Delta X$ , which depends on the current velocity of the robot, i.e.,  $\Delta X = \mathbf{v}\Delta t$ . The velocity of each robot at each time step also changes by  $\Delta v$ . The change in velocity is controlled by the total force on the robot, i.e.,  $\Delta v = F\Delta t/m$ , where  $m$  is the mass of that robot and  $F$  is the total force on the

robot. A frictional force is included, for self-stabilization. This is modeled as a viscous friction term, i.e., the product of a viscosity coefficient and the robot's velocity. We have also included a parameter  $F_{max}$ , which restricts the maximum force felt by a robot. This provides a necessary restriction on the acceleration a robot can achieve. Also, a parameter  $v_{max}$  restricts the velocity of the robot, which is necessary for modeling real robots.

We have created a force law (profile) that generates attractive and repulsive forces between any two robots based on the distance separating the robots. With such a force profile, the resulting group configuration is a lattice that navigates the environment while maintaining its lattice integrity. The lattice configuration is necessary for the fluxotaxis algorithm.

### *Fluxotaxis for Cooperative Toxic Plume Source Localization*

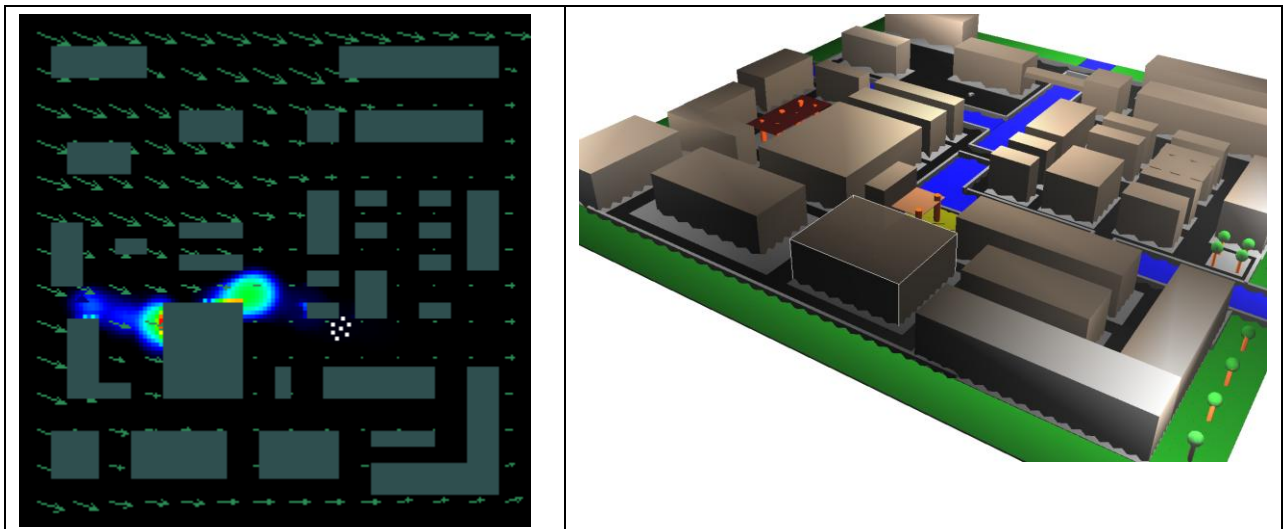
We use computational fluid dynamics methods, focusing on the conservation form of the fluid. In particular, the algorithm performs a time-domain analysis of the mass flux within a volume spatially fixed in the plume flow field [6] to infer the direction of mass flux (i.e., inflow or outflow). The conservation of mass is written as follows.

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{V}) \quad (1)$$

In Equation (1),  $\rho$  is the mass density of the chemical in the air,  $\mathbf{V}$  is the wind velocity vector, and  $t$  is time. The divergence of mass flux within the differential volume is a convenient way to quantify its change in space. For the current application, we are only concerned with 2D changes of the mass flux. We express the mass flux divergence in 2D Cartesian coordinates as follows.

$$\nabla \cdot (\rho \mathbf{V}) = V_x \frac{\partial \rho}{\partial x} + \rho \frac{\partial V_x}{\partial x} + V_y \frac{\partial \rho}{\partial y} + \rho \frac{\partial V_y}{\partial y} \quad (2)$$

In Equation (2),  $V_x$  and  $V_y$  are the components of  $\mathbf{V}$  in the  $x$  and  $y$  coordinate directions, respectively. A volume containing a source (e.g., emitter) will have a positive mass flux divergence, while a volume containing a sink will have a negative mass flux divergence. This consideration serves as the basis of the fluxotaxis algorithm. With this algorithm, the robotic lattice computes the local divergence of mass flux, and follows its gradient (i.e., the direction of steepest increase of mass flux). Each individual robot independently calculates this flux gradient. Due to the virtual (physicomimetic) cohesive forces holding the lattice together, the whole group of robots moves in the flux gradient direction determined by the majority.



(a)

(b)

Figure 1: (a) 2D simulation of an urban environment with a toxic plume. Arrows represent local wind velocities; seven white dots represent the robots. (b) Physics-based 3D simulation of the same setting.

## 2.2 Simulation

We are using 2D and 3D simulation abstractions to develop the toxic plume localization algorithm. Each simulation abstraction has some advantages and disadvantages.

### *2D Point Simulation*

This simulation abstraction is computationally efficient, fast, and can quickly provide results for first order analysis. Figure 1a shows a 2D image of cluttered urban environment. A toxic plume source is simulated in the lower left area of the environment and the robots are released in the lower area at the start of the simulation. It is worth noticing that the highest concentrations of plume are not at the source. This is a result of the complex behavior of the plume as it encounters obstacles in the environment (e.g., accumulations and high concentrations near wall surfaces). Seven robots are shown in the lower area in a lattice configuration.

### *3D Sensor-Based Simulation*

We use Webots for 3D simulation. Webots is a three-dimensional, sensor-based mobile robot simulator. It allows the user to model and simulate complex physical robotic platforms and environments. Robots interact with each other and with the environment through onboard sensors and simulated RF communications. Webots is more computationally intensive than the 2D point simulation, but the Webots simulation is physics-based and, therefore, more realistic. Figure 1b shows the 3D equivalent of the 2D environment of Figure 1a.

## 3. On-going & Future Work

The early simulation results have tested and verified the efficiency of the fluxotaxis algorithm in the urban environment of Figure 1. More complex flow configurations are currently being investigated. Finally, we are planning for the implementation of the algorithm on a fleet of ground robots equipped with electronic sensors to detect a series of chemical compounds of interest.

### **Acknowledgment**

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