

# A Simulation Framework for Plume-Tracing Research

Zhenzhang Liu  
The University of Adelaide  
zhenzhang.liu@student.adelaide.edu.au  
Tien-Fu Lu  
The University of Adelaide  
tien-fu.lu@adelaide.edu.au

## Abstract

The recent increasing threat of chemical weapon technologies has highlighted the need for an efficient detection of hazardous emission sources. One promising area of technological development is odour source detection using plume-tracing mobile robots. Using plume-tracing mobile robots has the potential to detect emissions caused by dangerous sources such as early stage fire, toxic gas and explosives, without endangering human life during the detection and source localisation process. Simulation has been popular and useful for researchers in various researches. Similarly, simulation is also good for developing and testing plume-tracing algorithms before being realised in real robots. This study presents the development of a simulation framework for plume-tracing research. This simulation framework integrated the plume data produced using Computational Fluid Dynamics (CFD) software with a simulated mobile robot in Matlab to simulate a more realistic scenario for plume-tracing research. Preliminary simulation had been conducted in this framework and it demonstrated this simulation framework is appropriate to be used for the simulation of plume-tracing research.

## 1 Introduction

In the past decade, plume-tracing mobile robots have been used to localize odour source and today odour source localization using this kind of mobile robot is still a topic that continues to attract research attention. A robot which is capable of odour plume tracing can be deployed for various applications, such as the detection of toxic gas, fire at its early stage and explosives. It is reasonable to develop and test a plume-tracing algorithm through simulation because it replaces the need for fabrication of prototype robot for the purpose of algorithm development. Based on the outcomes of simulation, researchers are able to improve their plume-tracing algorithms and test them in simulated environments until the performance of the algorithms are satisfactory and then the algorithms can be

realised using real robots. A flowchart of the development of plume-tracing algorithm is illustrated in Figure 1.

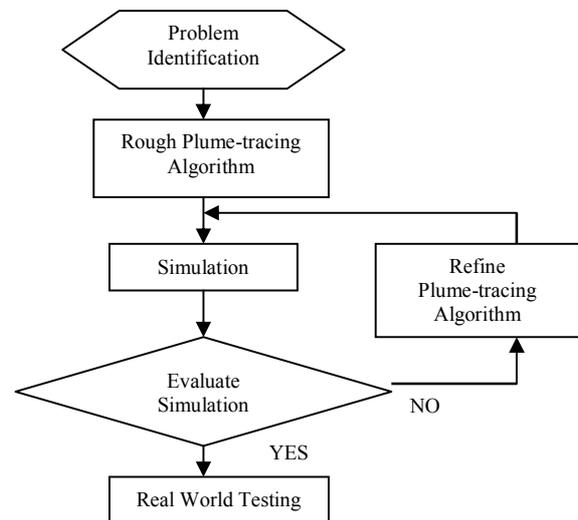


Figure 1 A flowchart of the development of plume-tracing algorithm for mobile robot.

There are many kinds of simulator that are available for mobile robot study and research; however, to date there is no completed robotic simulator can be used for mobile robot plume-tracing research. The difficulty of constructing a robotic simulator for plume-tracing research is that the simulator should present realistic gas/odour plumes in virtual environments. Various researchers have conducted plume-tracing algorithm simulations before real robot testing. [Hayes et al., 2002; Zarzhitsky et al., 2005; Farrell et al., 2003] had performed mobile robot plume-tracing simulations in their research. The gas/odour plume model they adopted was developed by [Farrell et al., 2002], which is the first and a popular plume model for plume-tracing research using mobile robot. This plume model was named the filament-based atmospheric dispersion model. It included a continuous wind field which covered the region of interests and the wind vectors varied with location and time in this region.

The odour plume was represented by a sequence of puffs and each puff was composed of a number of filaments. The shape of the filament was predefined and the size and location of the filament were determined by the wind field. Therefore, a sequence of filaments with different size and location form a plume varied by time in the simulated region. This plume model was a simplified plume model for plume-tracing research; therefore it did not need so much computation during the simulation, however, the simulated robot could only detect the local plume concentration by sensing the centre of the filament which made this model quite different from real plume propagation process.

Gas/odour plume propagation includes two processes: advection and diffusion. Advection indicates a gas/odour particle is purely shifted from one place to another by airflow. Diffusion indicates during the plume propagation there will be net diffusive flux from those locations with high concentrations to locations with low concentrations [Holzbecher, 2007]. However, there were no concentration gradients between the filaments centre in the filament-based atmospheric dispersion model and this was the reason that a simulated robot could only detect the local plume concentration by sensing the centre of the filament. Therefore, this model only simulated the advection process but did not simulate the diffusion process very well.

The aim of this study was to develop a simulation framework for mobile robot plume-tracing research. The gas/odour plume in this framework was expected to overcome the limitation of the filament-based atmospheric dispersion model. The plume was simulated using computational fluid dynamics (CFD) software, Fluent (Fluent, Inc.). The plume data produced by Fluent were imported into Matlab (Mathworks, Inc.) and integrated with a simulated mobile robot for plume-tracing behaviour simulation.

This paper is organized as follows: a brief description of plume generation using CFD approach is given in section 2. Section 3 introduces the integration of gas/odour plume with a simulated mobile robot using Matlab. The preliminary simulation results are given in section 4. Conclusions and future works of this study are given in section 5.

## 2 Gas/odour Plume for the Framework

In this study, a numerical approach was adopted to produce gas/odour plume for the simulation framework. Computational Fluid Dynamics (CFD) is used to generate the flow. It iteratively solves conservation equations for mass, momentum and energy in a finite volume for fluid dynamics problems. [Lin et al., 2007] successfully used a commercial CFD software package to simulate the effect of windbreaks on the odour dispersion. [Riddle et al., 2003] demonstrated that CFD software package is

appropriate for gas dispersion simulation which involves complex geometry. [Lee et al., 2002] and [Chang, 2006] both demonstrated that CFD is quite a good approach to simulate contaminant dispersions in realistic environments.

Compared with the filament-based plume model, the simulated plume in CFD is more precise because the airflow velocity and odour concentrations are estimated throughout the space of interest. Therefore, the plume diffusion process can be simulated based on specific fluid dynamics equations for the whole space of interest rather than just giving estimated plume concentrations at the "centre of filaments" as mentioned in the filament-based atmospheric dispersion model. As a result, CFD handles the plume diffusion process better than the filament-based dispersion model.

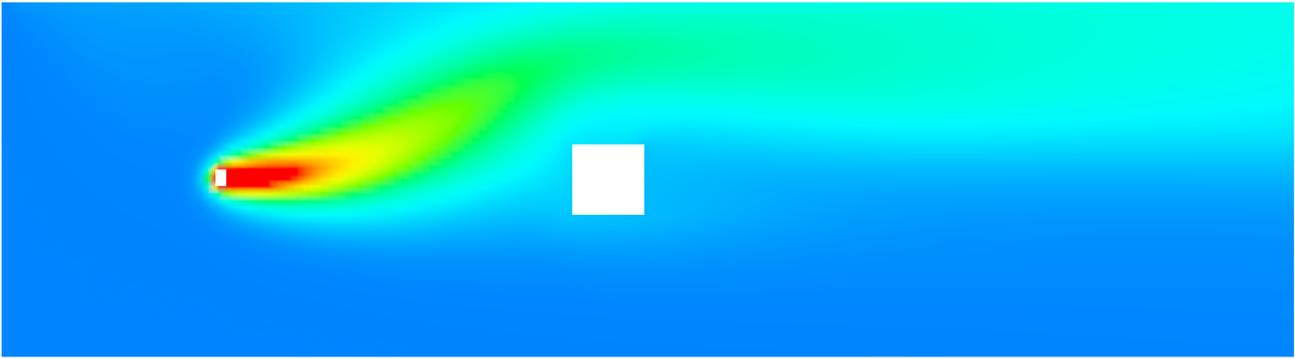
Fluent (Fluent Inc.), one kind of commercial CFD software package was adopted in this study to simulate gas/odour plume and generate plume data for the framework. Steps to simulate gas/odour plume using Fluent are given as follows:

### (A) Define the simulated domain.

Firstly, the size and the geometry of the simulated domain are defined for the plume simulation using Fluent. The robot will trace a plume in this domain and the location of an odour/gas source which is also defined in the domain. In this study, we assumed the simulated domain was a 2D environment. After the simulated domain was defined, it was imported into Fluent for further processing. In this study, Gambit (Fluent Inc.) which is a pre-processor for Fluent was used to define the simulated domain.

### (B) Choose solver for the simulation.

Fluent provides two solvers for plume simulation: the segregated solver and the coupled solver. These two solvers have different approaches to solve the governing integral equations for the conservation of mass, momentum and chemical species. In this study, a point source was located in a simulated domain and it released gas/odour to form a plume in the air, therefore it was a fluid species transport (without chemical reaction) problem. It was assumed that there were only two kinds of fluid species existing in the simulated environment, which were the gas/odour and the air. In this simple situation, the segregated solver was chosen to simulate gas/odour plume.



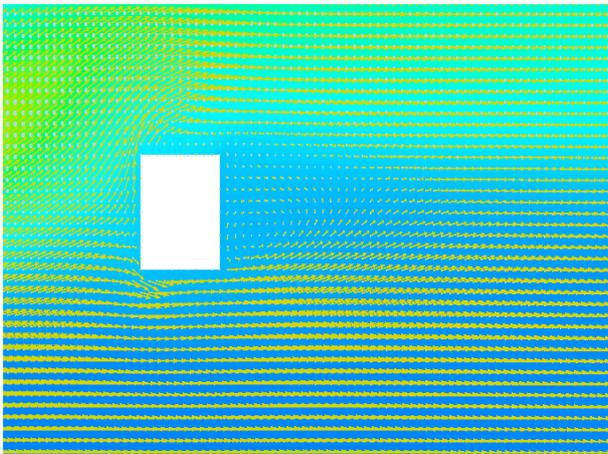
**Figure 2.** One snapshot of the simulated plume in Fluent. The unstable airflow entered into the left-hand side of the simulation domain and exited from the right-hand side of the simulation domain. A small white block indicates the position of the point source and the big white block is an obstacle.

(C) Designate fluid species material for the simulation.

Two kinds of fluid species material were chosen in this study for plume simulation based on the research done by [Lin et al., 2007]. One kind of the fluid species was air and the other was hydrogen-sulphide ( $H_2S$ ) to be the gas/odour. A point source released  $H_2S$  in the air and  $H_2S$  plume was formed.

(D) Set boundary conditions, run the simulation and save the simulation data.

Then the boundary conditions for the simulated domain, e.g. the airflow inlet, airflow outlet and the wall boundary conditions were set. Results were obtained by specifying the numbers of time step for the simulation and then running the plume simulations. During the simulation, plume data (gas/odour concentration, airflow vectors) were stored in files for further processing. Files in ASCII format occupy less hard-disk and memory space; therefore, all plume data produced by Fluent were stored in ASCII format. The simulated domain, the simulated  $H_2S$  plume and the local airflow vectors can be seen in Figure 2 and Figure 3. Detailed information for using Fluent to simulate plumes can be found at [Fluent Inc., 2003].



**Figure 3.** Local airflow vectors around the obstacle (the white block) in the simulation domain.

### 3 Integration of Gas/odour Plume and a Simulated Mobile Robot

An advantage of a CFD software package is that it can simulate plumes precisely. A disadvantage of CFD is: we can not simulate a mobile robot in the CFD simulation environment. Compromise was made between the advantage and the disadvantage of using CFD software. In this study, CFD was only responsible for plume simulation and plume data export. The plume data were then imported into Matlab for being integrated with a simulated mobile robot.

The construction of a simulated mobile robot was based on [Petrić et al., 2006; Hrabec, 2001]. The robot in this simulation framework was a two-wheel circular shape mobile robot with an unactuated ground contact provided by a ball bearing located in front of the robot's central axis. The robot totally had four simulated ultrasonic sensors to detect obstacles around it. Every sensor covered 45deg detection angle and four sensors covered totally 180deg in front of the robot. In this study, measurement noises of the sensors were not considered. Bresenham's algorithm [Wu and Rokne, 1987] was used to simulate ultrasonic sensors. The virtual environment the robot travelled in was represented by a true colour image and it was assumed that the obstacles in the image were white in colour. Therefore, once the sensors detected white colour at some place near the robot, they sensed there were obstacles near the robot. Figure 4 shows the coordinate system of the virtual environment and the robot. The robot's heading is represented by a line with orientation angle.

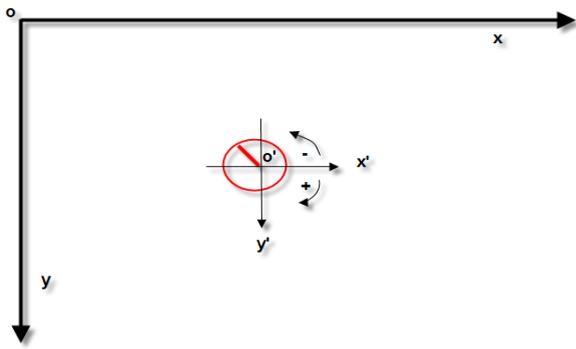


Figure 4. Coordinate system of the virtual environment and the robot.  $XOY$  is the coordinate system of the virtual environment and  $X'O'Y'$  is the coordinate system of the robot. Arrows show the direction of positive and negative angle increase of the robot heading.

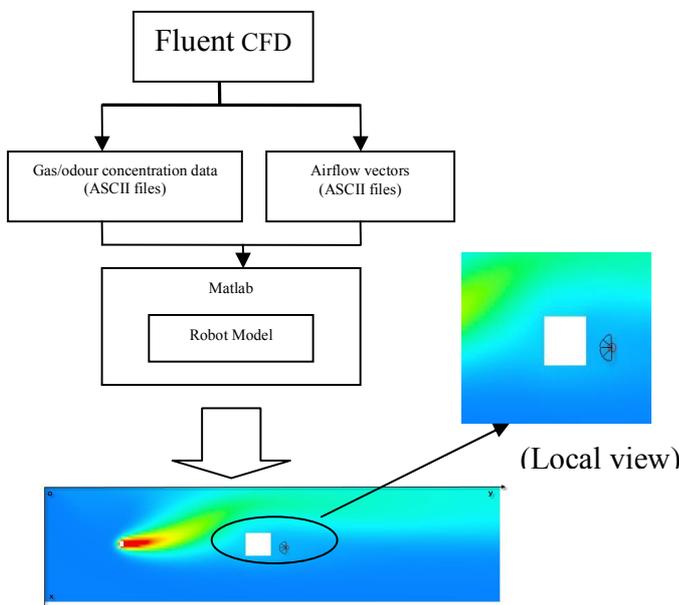


Figure 5. Illustration of the combination of plume simulation data and simulated mobile robot in Matlab.

The simulated mobile robot was then located in a 2D virtual environment which contained a gas/odour plume. The size and the shape of the virtual environment have to be always kept the same as the simulated domain in Fluent. In Figure 5, a simulated mobile robot was shown near an obstacle (the big white block) and the “field-of-view” of the ultrasonic sensors are also indicated. During the simulation, the detection filed of sensors was not visualized in order to save memory space and speed up the simulation process. At this stage, the simulated robot was able to travel in the virtual environment and detected obstacles existing in the virtual environment.

After the preparation of robot simulation had been completed, the plume data from Fluent was integrated with this simulated robot in Matlab. Figure 5 shows the basic idea on the integration. As mentioned in

Section 2, simulation data in Fluent at different time were stored in ASCII format files which contained the plume concentration and airflow vectors information. These files were then imported into Matlab and the gas/odour plume in the 2D virtual environment was reproduced. In Matlab, different gas/odour concentration value was represented by different colour. For example, the red colour in Figure 5 represents the highest concentration value and it is the location where the source is. By analogy, yellow colour in Figure 5 represents lower concentration than the red colour; the green colour represents lower concentration than the yellow colour, and so on. The dark blue colour in the virtual environment in Figure 5 represents that there is no plume in that area. In order to clearly visualize the robot’s plume-tracing behaviour, the airflow vectors were not visualized.

Once the robot had the capability to travel in a plume existed virtual environment, it should also have the capability to “sense” the local plume concentration and airflow. From Figure 5, it is evident that the robot can have access to the ASCII files imported into Matlab, therefore the robot “senses” the plume concentration and local airflow by accessing the ASCII files and searching the corresponding plume concentration value and airflow vectors at its current position. Using this approach, the simulated robot was able to sense the concentrations of the plume, the airflow directions and velocities.

#### 4 Preliminary Simulations and Discussions

A simulated mobile robot was controlled by a simple reactive plume-tracing algorithm, namely anemotaxis to trace a plume in a simulated virtual environment (represented  $5m \times 20m$  real world scenario) to demonstrate the capability of this simulation framework for plume-tracing research. The simulated mobile robot was located in the virtual environment and if the gas/odour concentration it sensed exceeded a predefined threshold it adjusted its heading to face the airflow direction and moved forward for a set distance. If the gas/odour concentration the robot sensed did not exceed the predefined threshold, no action was taken. In this initial development, no casting action was implemented when there was no plume senses.

The plume-tracing algorithm was combined with a simple wall-following collision avoidance algorithm to control the robot to locate an odour source in this study. Once the robot detected obstacles, it switched to the collision avoidance algorithm, and after the robot completed the collision avoidance algorithm, it switched back to the plume-tracing algorithm.

The airflow entered into simulated environment from the left-hand side boundary of the virtual environment and exited from the right-hand side boundary. The mean direction of the airflow shifted between  $+22.5^\circ$  and  $-22.5^\circ$  approximately every 1 second with varying wind velocity ranging from 5 to 10 m/s. Figure 6 shows a series of snapshots while the robot was tracing the  $H_2S$  plume in the virtual environment. The robot’s trajectories are indicated by black lines.

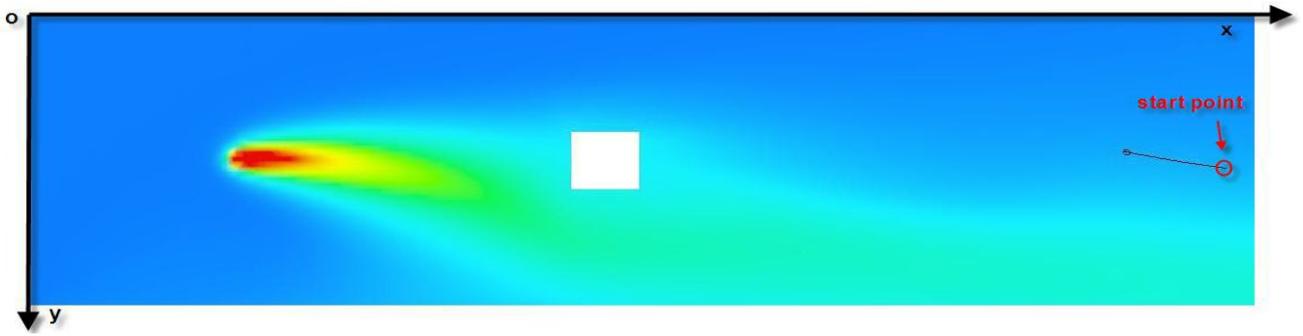


Figure 6 (a) snapshot of the simulation at time-step  $T=268s$

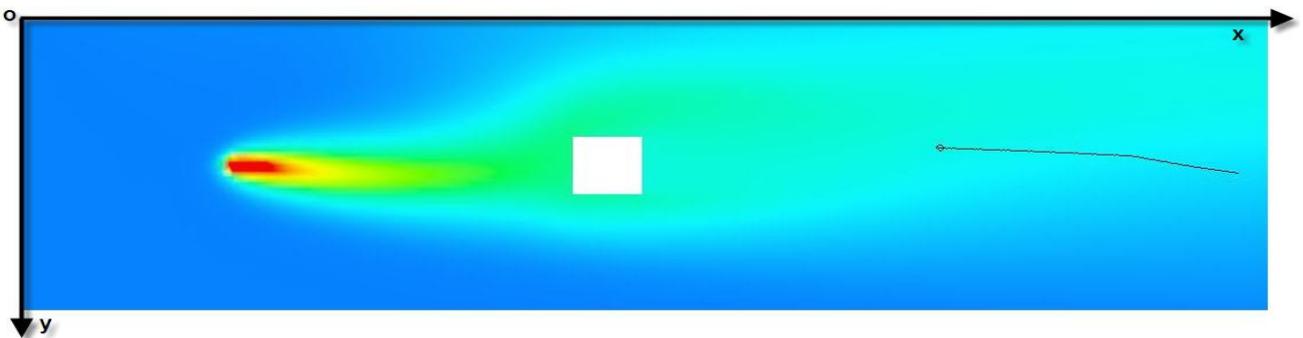


Figure 6 (b) snapshot of the simulation at time-step  $T=536s$

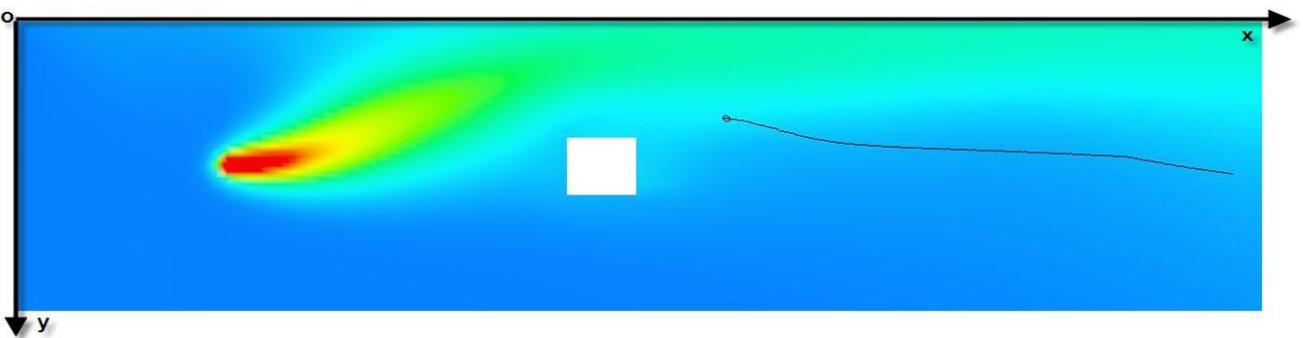


Figure 6 (c) snapshot of the simulation at time-step  $T=804s$

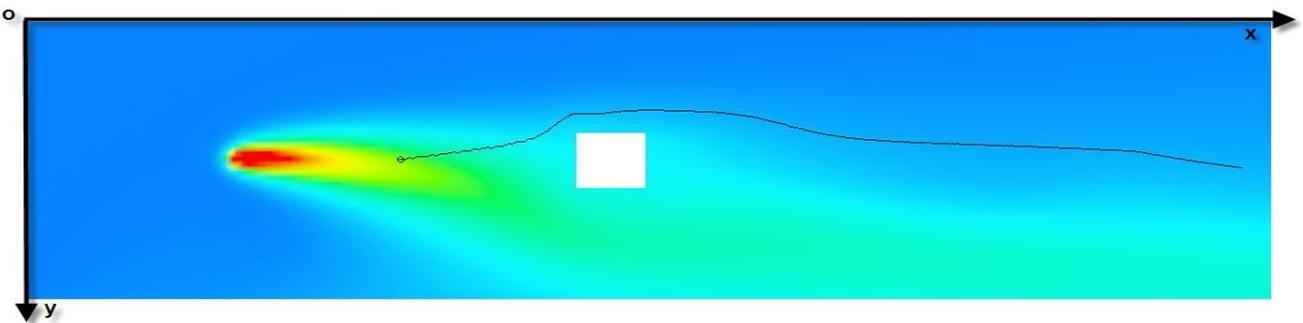


Figure 6 (d) snapshot of the simulation at time-step  $T=1072s$

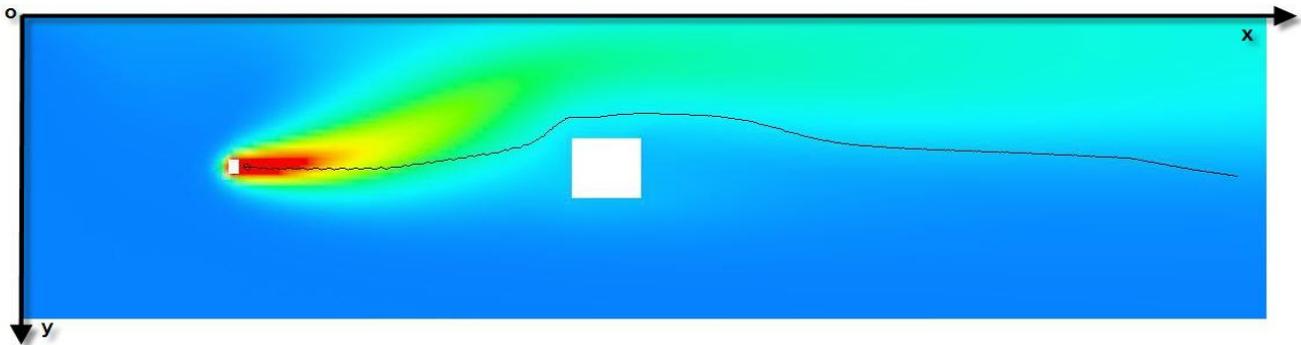


Figure 6 (e) snapshot of the simulation at time-step  $T=1340s$

From Figure 6, it can be seen that the robot in the virtual environment sensed the plume and traced it until it reached the location where the source was. In Figure 6 it can be found that the robot's trajectories are not straight because the robot had to adjust its heading to face the local wind airflow while it was tracing the plume. As the robot was controlled to move 1 pixel (represented 2cm distance in real world) at every 1 second time step, the time for the robot to locate the source was long (approximately 22 minutes). In future, the robot will be controlled to move at a more realistic velocity. Although the plume-tracing algorithm was simple, it demonstrated the simulation framework developed can be used for the research of plume-tracing.

## 5 Conclusions and Future Works

In this study, a CFD numerical method was adopted to produce gas/odour plume for the plume-tracing robotic simulation framework. Using the CFD method together with Matlab to establish a simulation framework for plume-tracing research has both advantages and disadvantages.

The advantages of this framework are: the gas/odour plume reproduced in the virtual environment was more realistic than the filament-based plume model due to the numerical methods adopted by CFD for plume simulation. As gas/odour concentrations were estimated throughout the space of interest, CFD simulated the diffusion problem better than the filament-based model. Additionally, the plume simulation data generated in CFD can be re-used as many times as the researchers prefer; therefore researchers do not need to repeatedly spend time on plume model development and can focus on the development of the plume-tracing algorithms.

There are some limitations of using this simulation framework. First of all, researchers should be familiar with CFD and know the basics about how to simulate plumes using CFD. Secondly, in this study it was assumed that the size and the motion of the mobile robot did not influence the plume propagation while the robot was tracing the plume in the virtual environment. However, this is not really true especially when the size of the robot is relatively big and travels at higher velocities. In this study, the influence of the robot's size and motion on the plume propagation was not considered.

In future, the virtual environment will be extended to show a boarder scenario of the plume propagation. Friendly user interface will be developed for the simulation framework as well.

## Acknowledgements

The authors would like to thank Ms. Dorothy Missingham for her valuable suggestions on this manuscript.

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