Integrated Simulation of Gas Dispersion and Mobile Sensing Systems

Victor Hernandez Bennetts[†], Achim J. Lilienthal[†], Erik Schaffernicht[†], Silvia Ferrari[‡], and John Albertson[§]

[†]AASS School of Science and Technology, Örebro University
[‡] Sibley School of Mechanical and Aerospace Engineering, Cornell University
[§] School of Civil and Environmental Engineering, Cornell University

July 9, 2015

Abstract

Accidental or intentional releases of contaminants into the atmosphere pose risks to human health, the environment, the economy, and national security. In some cases there may be a single release from an unknown source, while in other cases there are fugitive emissions from multiple sources. The need to locate and characterize the sources efficiently - whether it be the urgent need to evacuate or the systematic need to cover broad geographical regions with limited resources - is shared among all cases. Efforts have begun to identify leaks with gas analyzers mounted on Mobile Robot Olfaction (MRO) systems, road vehicles, and networks of fixed sensors, such as may be based in urban environments. To test and compare approaches for gas-sensitive robots a truthful gas dispersion simulator is needed. In this paper, we present a unified framework to simulate gas dispersion and to evaluate mobile robotics and gas sensing technologies using ROS. This framework is also key to developing and testing optimization and planning algorithms for determining sensor placement and sensor motion, as well as for fusing and connecting the sensor measurements to the leak locations.

Approach

The generality of a contaminant dispersion problem and simulation stems from the fact that the underlying mechanisms of gas dispersal are of a fluid mechanical nature, connecting sources and downstream sensors. The technical approach to apply fluid mechanics principles to the source localization is sufficiently general so as to be transferable across problems plaguing many sensing applications and technologies [1]. In the proposed simulator, gas dispersion is modeled as a set of particles affected by diffusion, turbulence, advection, and gravity. Wind information is integrated as time snapshots computed with a computational fluid dynamics (CFD) tool (in this work we use OpenFOAM [2]). In addition, response models for gas sensing devices such as Metal Oxide

(MOX) sensors can be integrated in the framework and simulated onboard stationary or mobile platforms.

Instrumented vehicles and MRO systems, for example, can perform automated inspection routines with a high spatial resolution [3–6]. The flexibility of mobile sensors allows for adaptable data collection that in turn can be used to quantify emission levels and to localize emitting gas sources based on measurements collected over time and space. Moreover, mobile robots can be rapidly deployed in emergency situations where hazardous gases, such as methane or hydrogen sulfide, might be present. Validating mobile olfaction technologies and algorithms through physical tests and experiments, however, is complex, time consuming, and, potentially, hazardous. Preparations have to be made at the start and at the end of each trial. This results in a reduced number of trials that do not allow for statistical validation. Repeatability is also an issue since gas dispersion is a complex phenomenon that depends on several factors such as ambient temperature, wind, and topographic conditions. Small changes in source strength, wind pattern or any of the other relevant environmental variables are common and can substantially alter the experimental outcome, sometimes without clear disambiguation of cause and effect. It is thus of high importance to have a reliable simulator that takes into account the dynamic interactions between gas sources, environmental conditions, sensing mechanisms, the mobile platform and constraints through the terrain [7, 8]. Using the proposed simulator, mobile sensing systems and planning algorithms can be developed, tested and evaluated with a large number of trials to produce statistically significant results at the given fidelity of the simulation. In a subsequent step, an implementation of the mobile sensing system should then be evaluated through physical experimental trials in real world scenarios.

This paper presents a modular simulation framework (see Fig. 1) that allows the user to model critical aspects of mobile olfaction systems, such as the robotic platform, the gas sensing mechanisms, the wind flow patterns, the configuration of physical obstacles, the gas dispersion process and properties of the released chemicals. Of particular interest is that the simulator was implemented entirely using the Robot Operating System (ROS), which is commonly used in robotic research. ROS is an open source initiative that aims to implement a flexible framework for writing robot software and it is arguably the most widely used operating system in robotics research. The flexibility of ROS allows the presented framework to simulate aspects beyond gas sensing such as path planning, robot manipulation, sensing mechanisms (e.g. range sensing, odometry) and the physical properties of the robots themselves.

As shown in Fig. 1, the proposed simulation framework comprises four sub modules namely, environment, dispersion, robot and sensor simulator. The inputs used in the simulation process are shown as light blue boxes. The robot model corresponds to the physical configuration of the mobile platform. For example, a URDF file can be used to define the degrees of freedom, joint configuration and physical properties of the robot[1]. The environment model that we currently us is a three dimensional occupancy grid, in which the position of different objects in the environment such as walls and obstacles are represented. Simulation parameters and initial conditions are specified in the launch file. Gas dispersion simulation is carried out in two different stages. First, wind flow is modelled with a computational fluid dynamics tool and integrated as a set of snapshots in which wind flow is specified as a vector field. The snapshots can be computed with any fluid dynamics solver. In this work we used OpenFoam[2].

In the second stage, gas propagation is simulated using an extension of the work presented

[1] `http://wiki.ros.org/urdf`

[2] `http://www.openfoam.com/`

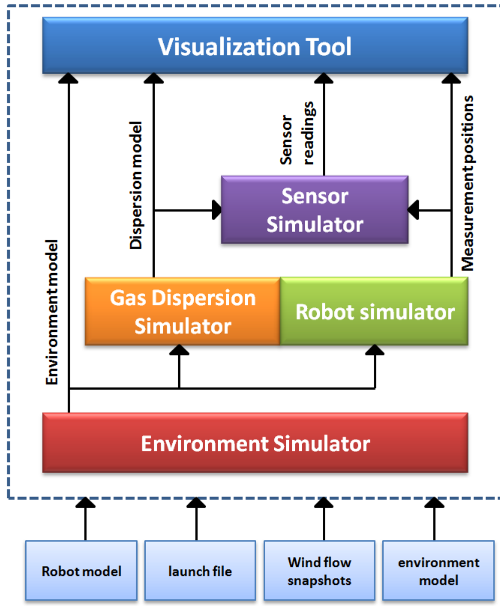

Figure 1: Block diagram of the proposed simulation framework.

by Farrell and co-authors in [9]. In their original work, Farrel et. al. propose a 2-D filament based approach, where gas concentrations are modelled as a collection of particles transported by the given wind flow patterns. In our work, we extended the gas propagation model to three dimensions. Gravitational and buoyancy forces are considered to determine the position of the filaments along the z axis.

The sensor simulation stage models the response of a given gas sensing mechanism exposured to different concentration levels. Currently, *in-situ* devices such as commercial metal oxide sensors and photo ionization detectors or remote sensors such as absorption spectroscopy based devices can be modelled.

In the proposed simulation framework, fluid dynamics simulation (the computation of wind flow snapshots) is carried out offline. Then, the wind flow snapshots are used for the gas propagation simulation, which runs concurrently with robotics algorithms that can use the response of the simulated gas sensors as inputs. In this way, the presented framework can be utilized to evaluate newly developed interdisciplinary olfaction planning algorithms based on information theory, CFD, and robot path planning [10, 11].

Due to the interdisciplinary character of Mobile Robot Olfaction research, the entry threshold for the development of Mobile Robot Olfaction systems is quite high. We believe that the presented gas dispersion simulator unified with ROS will lower this threshold.

References Cited

[1] T. A. Foster-Wittig, E. D. Thoma, and J. D. Albertson, “Estimation of point source fugitive emission rates from a single sensor time series: a conditionally-sampled gaussian plume reconstruction,” *Atmospheric Environment*, 2015.

[2] S. Pashami, S. Asadi, and A. J. Lilienthal, “Integration of openfoam flow simulation and filament-based gas propagation models for gas dispersion simulation,” in *Proceedings of the*

Open Source CFD International Conference, 2010.

[3] M. Trincavelli, M. Reggente, S. Coradeschi, H. Ishida, A. Loutfi, and A. J. Lilienthal, "Towards environmental monitoring with mobile robots," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2008, pp. 2210 – 2215.

[4] V. Hernandez Bennetts, A. Lilienthal, A. A. Khaliq, V. Pomareda Sese, and M. Trincavelli, "Towards real-world gas distribution mapping and leak localization using a mobile robot with 3d and remote gas sensing capabilities," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, 2013, pp. 2327–2332.

[5] V. Hernandez Bennetts, A. J. Lilienthal, P. Neumann, and M. Trincavelli, "Mobile robots for localizing gas emission sources on landfill sites: is bio-inspiration the way to go?" *Frontiers in Neuroengineering*, vol. 4, no. 0, 2012.

[6] V. Hernandez Bennetts, E. Schaffernicht, T. Stoyanov, A. Lilienthal, and M. Trincavelli, "Robot assisted gas tomography localizing methane leaks in outdoor environments," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, 2014, pp. 6362–6367.

[7] G. Cabrita, J. Sousa, and L. Marques, "Plumesim - player/stage plume simulator, in workshop on networked and mobile robot olfaction," in *Workshop on Networked and Mobile Robot Olfaction, IEEE International Conference on Robotics and Automation (ICRA)*, 2010.

[8] J. G. Monroy, J.-L. Blanco, and J. González-Jiménez, "An open source framework for simulating mobile robotics olfaction," in *15th International Symposium on Olfaction and Electronic Nose (ISOEN)*, 2013.

[9] J. A. Farrell, J. Murlis, X. Long, and W. Li, "Filament-based atmospheric dispersion model to achieve short time-scale structure of odour plumes," *Environmental Fluid mechanics*, vol. 2, no. 1, pp. 143–169, 2002.

[10] C. Cai and S. Ferrari, "Information-driven sensor path planning by approximate cell decomposition," *IEEE Transactions on Systems, Man, and Cybernetics - Part B*, vol. 39, no. 2, 2009.

[11] ——, "Comparison of information-theoretic objective functions for decision support in sensor systems," in *Proc. American Control Conference*, New York, NY, 2007, pp. 63–133.