# A Probabilistic Gas Patch Path Prediction Approach for Airborne Gas Source Localization in Non-Uniform Wind Fields

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## ABSTRACT
In this paper, we show that a micro unmanned aerial vehicle (UAV) equipped with commercially available gas sensors can address environmental monitoring and gas source localization (GSL) tasks. To account for the challenges of gas sensing under real-world conditions, we present a probabilistic approach for GSL that is based on a particle filter (PF). Simulation and real-world experiments demonstrate the suitability of this algorithm for micro UAV platforms.

## INTRODUCTION
In order to perform GSL tasks in real-world scenarios, gas sensors are mounted on mobile platforms and exposed to a highly dynamic environment. Besides the drawbacks in current sensing technologies (partial selectivity, slow recovery times, response drift) [1], gas sensing in open environments poses several challenges, such as turbulent gas dispersion, non-uniform wind flows, fluctuating environmental conditions and, in the case of gas sensing with quadrocopter-based UAVs, plume disruptions introduced by the rotors. To account for these challenges, robust GSL algorithms have to be developed. In this work, we present a probabilistic GSL approach based on a PF. The approach was first introduced in [2] only as a complement for plume tracking algorithms for a gas-sensitive micro UAV. This paper extends [2] by presenting a thorough performance evaluation of the PF in terms of source localization accuracy; furthermore, the algorithm is tested and analyzed with two different exploration strategies: plume tracking and pre-defined sweeping trajectories. In order to quantify the non-uniformity of natural wind flows, we present a set of experiments were data was collected during several hours with two anemometers placed in an open field.

## NON-UNIFORMITY OF THE WIND FIELD
The GSL problem can be simplified by assuming a uniform wind field. This simplification allows to infer the paths travelled by the gas patches using wind and concentration measurements collected along the exploration path. Li et al. claim in [3] that a time-varying wind field can be regarded as roughly uniform within a circular domain around the robot, when the airflow is not *too weak* (above 0.2 m/s) and the radius of this domain is not too large (less than the distance traveled by the airflow in 10 s). Here, an experiment over a time period of 83 min with two ultrasonic anemometers was performed to ascertain to which degree the assumption of a uniform wind field holds in a realistic scenario. The anemometers were placed in a distance of ≈ 2 m to each other at a height of ≈ 1.35 m and their sampling frequency was set to 1 Hz.

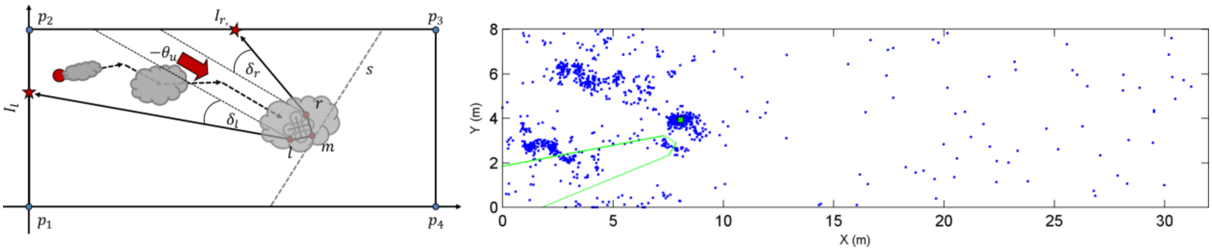


**Figure 1. (a) Construction of the PPE for the micro UAV in real-world environments in non-uniform wind fields. The source location is denoted by the large red dot. (b) PF-based GSL algorithm after 220 iterations using sweeping (blue points = particles and green point = prediction and true gas source location).**

The experimental results show that the claim of a roughly uniform wind field by Li et al. does not hold in the environment considered. This finding is supported by the calculation of the deviations between the two anemometers (up to ≈ 2.5 m/s and ≈ 179°), the Pearson coefficient $r$ for the wind speed ($r$ = 0.11), and the circular-circular correlation index $\rho_{cc}$ for directional data ($\rho_{cc}$ = -0.12).

## PF-BASED GSL ALGORITHM

The presented PF-based GSL algorithm uses gas and wind measurements to reason about the trajectory of a gas patch since it was released by the gas source. Non-uniform wind fields are accounted for by considering a patch path envelope (PPE) that models the likelihood of trajectories along which a sensed gas patch may have moved to the sensor (Fig. 1 (a)). The source is considered to be found (declared), if the location estimate, represented by the particles of the PF, remains within a small region for a defined number of iterations. The advantage of the proposed approach is that it removes the strong assumption of a roughly uniform wind field which in real-world environments rarely holds.

## RESULTS AND DISCUSSION

This work presents a PF-based GSL algorithm for a gas-sensitive micro UAV to estimate the location of a single gas source that is independent of the exploration strategy used. In simulations (Fig. 1 (b)), we optimize for two exploration strategies the meta-parameters of the proposed algorithm for a gas-sensitive, quadrocopter-based UAV. Next, we use the best meta-parameters sets found in simulation for the real-world experiments with this gas-sensitive micro UAV. A total number of 19 trials were performed using plume tracking and predefined sweeping trajectories. The PF-based GSL algorithm was able to locate the gas source with a success rate of 83.3 % (5 of 6 trials succeeded) using plume tracking and 92.3 % (12 of 13 trials succeeded) using predefined sweeping trajectories. The success rate is the ratio of successful localizations with respect to the total number of performed experiments, in which the localization error is less or equal than 1.5 m. The average error of successful localizations is 0.69 m ± 0.35 m and 0.79 m ± 0.38 m, respectively. Furthermore, the results suggest that the different gas sensor technologies used did not have a major impact on the success rate and the localization error. In general, a good correlation between the results from simulation and real-world experiments was found for both exploration strategies.

**Reference**


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