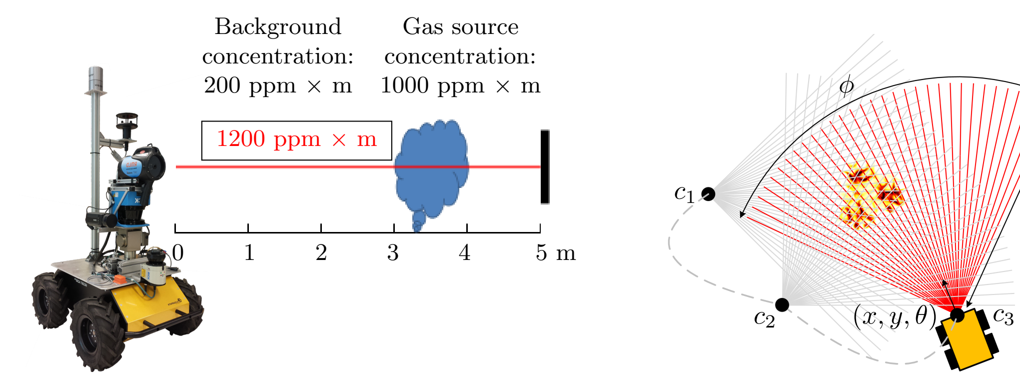
Sensor Planning Strategies for Robot Emission Monitoring with Remote Gas Sensor

1 Introduction

A surveillance task for the gas emission monitoring includes sensing coverage to detect gas leaks and building a gas distribution model to accurately locate the gas concentrations in the environment. This information can be useful to make better strategic decisions in order to mitigate the gas emissions.

We perform the gas emission monitoring task using a mobile robot equipped with a spectroscopy-based remote gas sensor (Fig. 1(a)). In particular, we use a Tunable Diode Laser Absorption Spectroscopy (TDLAS), which can collect integral concentrations along the line-of-sight. In our setup, the remote gas sensor installed on the mobile robot is actuated using a pan-tilt unit. This means it can project optical beams in different directions, and therefore, a large circular sector (r, ϕ) can be sampled at a particular pose (x, y, θ) in the environment, which we refer as a *sensing configuration* (c).



(a) A gas-sensitive mobile robot

(b) Sensing configuration

Figure 1: (a) The robot is equipped with an actuated TDLAS sensor, which reports integral concentration of methane along its line-of-sight. (b) A sensing configuration c is sampling a circular sector (r, ϕ) by emitting s optical beams at pose (x, y, θ).

A robotic solution for the surveillance task is a tour of selected sensing configurations $\{c_1, c_2, .., c_n\}$ to sample the environment. An efficient plan consists of least number of sensing configurations and minimum traveling distance, and yet provides a surveillance that result into maximum sensing coverage and high quality reconstructions of gas distribution.

2 Adaptive Sensor Planning for Exploration and Exploitation

A gas emission monitoring strategy must provide solutions for the exploration and exploitation of the environment. The exploration is to detect gas leaks in the environment and exploitation is to accurately locate the gas distributions. The exploration and the exploitation can be conducted either step-wise in two different robotic tours, or in a combination of a single tour. In the step-wise scheme, first the environment is explored for the leak detections by providing full sensing coverage, and then an intensive sensing coverage is provided in the areas of interests to refine the reconstruction of gas distributions. In the combination of the both, the emission monitoring is started with a task of exploration of gas detection, meanwhile the local areas of high gas concentrations are exploited with a focused sensing coverage whenever a gas leak is detected. The first scheme identifies better the areas of interest to exploit as the exploration is conducted beforehand, hence an optimal list of sensor configurations can be found. However, the overall solution of the step-wise scheme is tend to be more expensive than the single-tour scheme as both the steps are performed in two different robotic tours. The single-tour scheme on the other hand, may provide little expensive exploitation solutions due to high entropy of the areas of interest but the overall solution is less expensive as both the tasks are performed in a single robotic tour.

To solve the problem, we represent the environment in a Cartesian grid of occupied and unoccupied cells. The candidate sensing configurations are placed in the middle of an unoccupied cell, and their sensing coverage can be captured in a binary matrix V of size number of candidate sensing configurations times the cells to be covered $\mathcal{S}$.

Algorithm 1 *cxvt*-SPP

Find π_{detect} for the initial $\mathcal{S}$;
while $\pi_{\mathsf{detect}} \neq \emptyset$ **do**
  Execute the configuration $c_1 \in \pi_{\mathsf{detect}}$;
  $\pi_{\mathsf{detect}} \mapsfrom (\pi_{\mathsf{detect}} - c_1)$, and $\mathcal{S} \mapsfrom (\mathcal{S} - \mathcal{S}c_1)$;
  if High concentration is reported **then**
    Estimate $\mathcal{H}_c$;
    Find π_{tomo} for $\mathcal{H}_c$;
    while $\pi_{\mathsf{tomo}} \neq \emptyset$ **do**
      Execute the configuration $c_1 \in \pi_{\mathsf{tomo}}$;
      $\pi_{\mathsf{tomo}} \mapsfrom (\pi_{\mathsf{tomo}} - c_1)$, and $\mathcal{S} \mapsfrom (\mathcal{S} - \mathcal{S}c_1)$;
      Re-estimate $\mathcal{H}_c$ and replan π_{tomo} accordingly;
    end while
    Find new π_{detect} for the updated $\mathcal{S}$;
  end if
end while

A sensor planning solution for exploration is π_{detect}, which is a list of sensing configurations that provides the desired sensing coverage. The solution π_{detect} is a result of an optimization problem in Eq. 1. Where C is a binary decision vector of candidate sensing configurations, and $\mathcal{C}$ is the sensing coverage, which is equals to or above a set threshold $\mathfrak{n}$.

$$\pi_{\mathsf{detect}} = \text{argmin } |C| \text{ s.t. } \mathcal{C} \geq \mathfrak{n} \tag{1}$$

For the desired sensing coverage less than 100% ($\mathfrak{n} < 1$), first we solve the optimization problem for the full sensing coverage ($\mathfrak{n} \geq 1$) and then iteratively reduce the configurations in the list π_{detect} until the minimum desired sensing coverage can not be guaranteed. Finally, π_{detect} is sorted for the minimum traveling distance between the configurations to execute.

Similarly, a sensor planning solution for the exploitation is π_{tomo}, which aims to provide better expected reconstruction quality (ERQ) of gas distributions in a local area. ERQ is an arbitrary quantity, which is inversely proportional to the reconstruction error, i.e. the error between the reconstruction and the true gas distributions in the environment. The areas of interests need to be sampled from different view points and the sensing configurations need to be placed in a way that the desired sensing overlaps are obtained. Eq. 2 is the optimization problem for the exploitation, where $\mathcal{Q}$ is ERQ.

$$\pi_{\mathsf{tomo}} = \text{argmin } |C| \text{ s.t. } \mathcal{Q} \geq \mathfrak{n} \tag{2}$$

Given the above solutions for the exploration and exploitation, our single-tour sensor planning strategy is summarized in Algorithm 1. We find the initial solution π_{detect} for all the unoccupied cells to be covered $\mathcal{S}$, and sample the environment by executing the first configuration in the list. If a high gas concentration is detected, then π_{tomo} is computed for all the hotspots in the local area. The plan π_{tomo} is iteratively executed and improved for the each selected configuration. At the end of any local exploitation process, an updated π_{detect} is computed for exploration of the remaining uncovered area. This process continues until no configuration is left in the exploration list π_{detect}.

3 Experimental Evaluation

We have evaluated our sensor planning solutions for gas emission monitoring in large environments, and conducted experiments in an indoor complex environment of size 000 × 00 m. Our robotic platform, as shown in Fig. 1, is Husky-200 which is running Robot Operating System (ROS), and equipped with an RMLD remote methane sensor and a pan-tilt unit. It is also equipped with the other sensors to navigation through the environment. In all the experiments, gas sampling was performed using sensing configurations of parameters $\phi = 270°$, and $r = 15$ m.

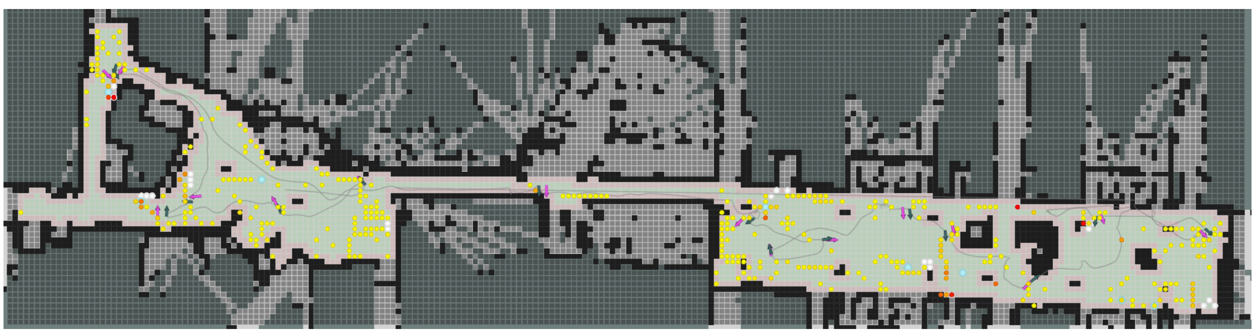


Figure 2: A simulation scenario (to be replaced)

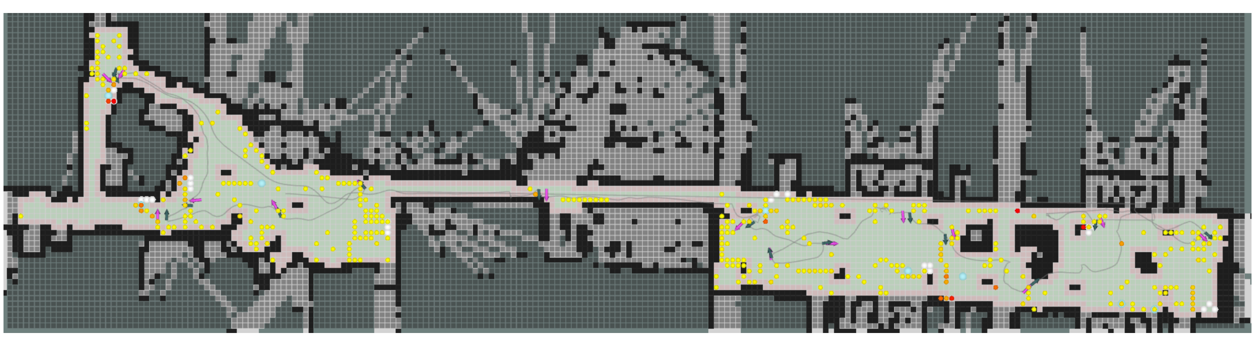


Figure 3: A real-world scenario (to be replaced)

Fig. 1 shows the complete inspection process in a simulation scenario: the initial plan for the exploration task is shown in blue, which was later updated by an exploitation plan (in red) due to the detection of high gas concentrations present in the environment. In particular, configuration c_1 was executed for the exploration task, and c_2 and c_3 for the reconstruction purpose. After the exploitation process was completed at c_3, a new exploration plan was computed (in gray) and c_4 and c_5 were executed. The measurements collected for c_5 indicated another high concentration area, for which the exploitation was carried out by executing c_6

and c_7. Finally, an updated plan of $c_8, ..., c_n$ was adapted for the exploration of the remaining uncovered area. It can noticed that the initially planned to the final executed configurations deviate from x to y, as the initial planned inspections was only for the exploration, and the new plans were adapted to exploit the environment while the inspection was carried out. Therefore, the final inspection resulted not only a desired sensing coverage but also a high quality reconstruction of gas distributions.

Fig. 2 is an inspection of a real-world scenario, where configuration-poses are indicated with arrows. The configurations for the exploration and exploitation are marked in two different colors, and the final reconstruction of gas distribution is shown in yellow-to-red circles for low-to-high concentrations.