A Feasibility Study of a Leader-Follower Multi-Robot Formation for TDLAS Assisted Methane Detection in Open Spaces

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Abstract. This work deals with the problem of detecting and localizing methane emission sources in open spaces with a mobile robot equipped with a remote gas detector (TDLAS). To reduce the long inspection time of traditional approaches which use the ground as the natural reflector, in this work, we analyze the feasibility of a leader-follower formation, where one robot, the leader, carries the remote gas detector that scans horizontally, parallel to the ground, and a second robot, the follower, that acts as an artificial reflector. We present a visual tracking mechanism for the relative pose estimation of both mobile platforms to extend the measurement range up to 10 m. Results in a 70 m^2 experimental area demonstrate that this approach is effective for a fast location of methane gas sources.

Keywords: mobile robots, relative pose estimation, remote gas sensing, gas distribution mapping, gas source localization

1 Introduction

Methane (CH_4) is both a potent greenhouse gas that significantly contributes to global warming and climate change, and an important energy resource, being the primary component of natural gas and used for heating or electricity generation among other industrial processes. Methane is generated from natural processes, such as wetlands and geological seepage, as well as from human activities like fossil fuel extraction, agriculture, or waste management [16].

Accurate detection and monitoring of outdoor methane emissions are crucial to reducing environmental impacts and harnessing their potential energy for electricity generation and heat production. Yet, methane is an odorless and colorless gas compound lighter than air, making it hard to detect, especially in outdoor environments where large areas must be monitored, and where methane naturally rises, dissipating into the atmosphere.

TDLAS (Tunable Diode Laser Absorption Spectroscopy) represents a powerful and highly sensitive technology for the detection and quantitative measurement of methane gas concentrations [14]. It operates on the principle of laser

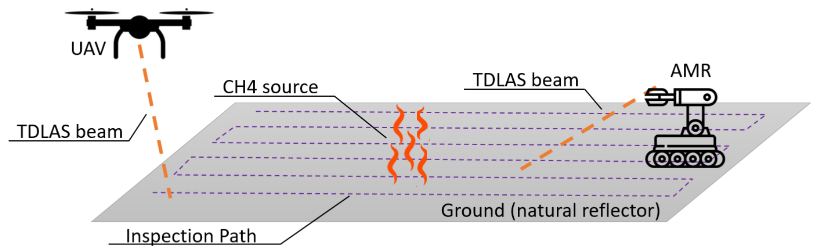

Fig. 1: Conventional top-down inspection approach with TDLAS methane detector. Long inspection paths are required to survey the whole area.

absorption spectroscopy, utilizing electromagnetic radiation in the near-infrared range. Pulsed light is emitted at two wavelengths: one that is easily absorbed by CH_4, and another, in a nearby wavelength, that is not affected by CH_4. This technology finds applications in various industries and settings, like in natural gas pipelines and storage facilities [5].

The advantage of TDLAS when compared with other methane detection technologies lies in its ability to provide real-time, continuous measurements of methane concentrations along a ray path (distributed range measurement) with high sensitivity and selectivity [9]. Other gas sensing technologies, particularly those used in robotics systems (*i.e. MOX, PID*) [6], exclusively offer single-point concentration readings. This not only implies a much longer amount of time to map the distribution of gas throughout the environment but also requires placing the sensor at each location to be sampled, which becomes a serious limitation outdoors given the difficulties of traversing areas that the agent cannot physically reach.

Despite its advantages, the working principle of TDLAS imposes the need for a reflecting background (like any other laser system). Additionally, since each measurement provides the accumulated gas concentration along the ray path (*column density*), multiple readings from different positions and orientations are required to determine the spatial gas distribution or to locate the emission sources [2].

Previous works on methane detection with TDLAS either operate indoors where walls, floor, and ceiling act as reflectors [11], or employ the detector facing down (top-down configuration) to use the terrain as a natural reflector [15,7]. Using the ground as the reflector is the most conventional approach due to the simplicity of setup, only needing one robot with the TDLAS sensor, but requires numerous measurements and long inspection trajectories to cover the work area [1] (see Figure 1). Given the very limited autonomy of unmanned aerial vehicles (UAV) and autonomous mobile robots (AMR), this minimalist approach becomes inefficient and time-consuming, especially for inspecting large open spaces.

In this paper, we describe a dual robot configuration where one robot carries the TDLAS detector (leader), and the other (follower) places the reflector in

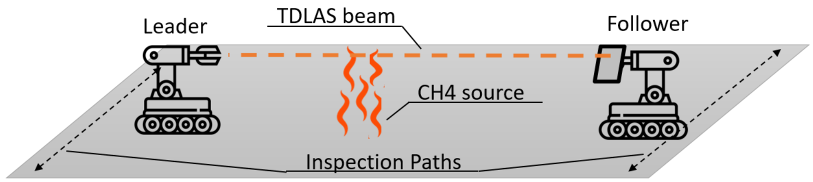

Fig. 2: Dual robot (leader-follower) inspection approach with TDLAS detector. Simple and short inspection paths allow for complete coverage of the working area.

the line of sight of the laser beam. This configuration allows taking range measurements in multiple 3D configurations regardless of the environment structure, reducing the time necessary to survey large areas and consequently improving inspection efficiency. Particularly, we analyze here the option of performing measurements in horizontal sweeps (see Figure 2), which, given the buoyant nature of methane in the air, will allow for fast detection of methane emissions in large areas. As proof of concept, we apply this strategy to wheeled mobile robots, focusing on two specific problems: the synchronization and pose alignment of the emitter-receptor, and the selection of the inspection path.

We propose a leader-follower configuration where the leader (the robot with the TDLAS detector) autonomously navigates a given path to inspect the environment, and where the follower (the robot carrying the reflector) reacts to the leader's movements, ensuring the correct alignment at all measurement times. We evaluate the feasibility of this approach with a set of real experiments, analyzing the results obtained and the potential limitations when extrapolating this solution to larger environments.

The rest of the document is organized as follows. Section 2 introduces the relative pose alignment problem between the emitter and the reflector, while Section 3 describes the probabilistic gas distribution mapping method employed to estimate the presence and location of Methane in the environment. The experimental setup used to validate the proposed approach is detailed in Section 4, followed by the results and discussion in Section 5. Finally, conclusions and future work are stated in Section 6.

2 Relative Pose Alignment for Leader-Follower Formation

The core idea behind TDLAS-assisted methane detection with two mobile robots is to ensure, at measurement time, that the beam emitted by the methane detector from the first robot is properly reflected by the second robot. Assuming each robot is able to localize itself with respect to a common frame (*i.e.* the map reference system), the simplest approach consists of sharing their absolute poses to discern if they are correctly located in the environment (*i.e.* they are properly aligned), or require a correction. Particularly, the leader will be commanded to

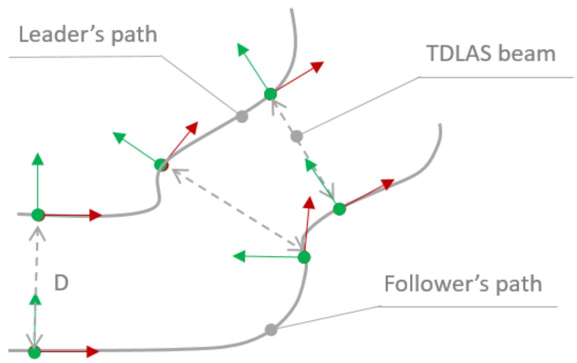

Fig. 3: Illustration of leader's and follower's paths for TDLAS assisted methane inspection of an open area with no natural reflectors. The leader carries the TDLAS detector perpendicular to its forward direction, while the follower (carrying the reflector) must keep a fixed distance D perpendicular to the leader pose to intercept the laser beam.

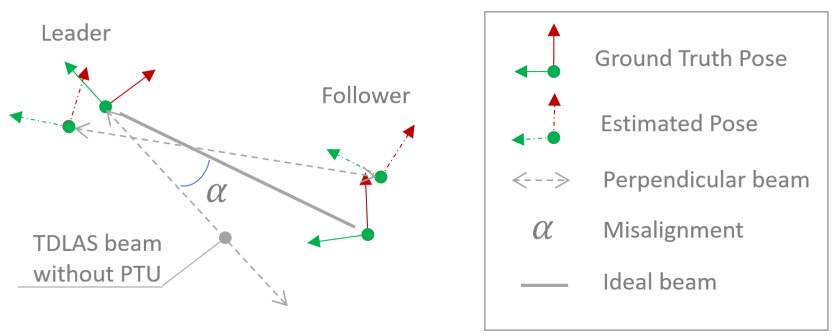

Fig. 4: 2D illustration of the alignment errors between leader and follower due to the inaccuracies in their pose estimation.

inspect the target area by following a predefined path, while the follower will reactively navigate to a pose separated by a fixed distance D and perpendicular to the leader's pose (see Figure 3), with the intention to serve as the reflector.

Although this setup is simple and intuitive, the unavoidable localization errors of both robots (in particular the orientation) make this setup impractical, as illustrated in Figure 4. Current localization methods for mobile robots in outdoor environments rely on cameras [17], GPS [12], 3D lidar [4], or a mixture of them. Regardless of the selected approach, uncertainty in the localization must be taken into consideration when aligning the two robots, especially when the distance between them is large (several meters), as small errors in the orientation estimate make the laser beam miss its target. To overcome this issue, we equip

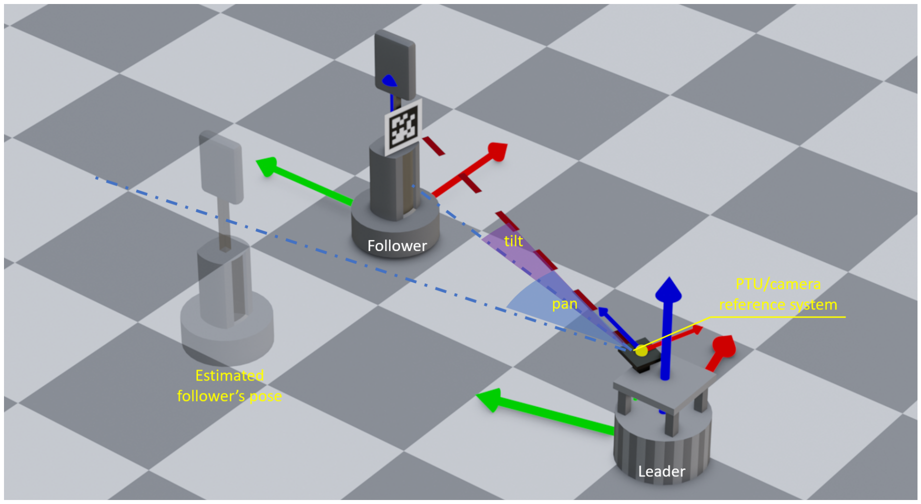

Fig. 5: 3D reconstruction of the relative pose estimation between the leader (PTU/camera) and the follower (fiducial marker). The PTU corrections allow for a proper alignment of the TDLAS emitter and reflector.

the leader robot with a pan-tilt unit (PTU) carrying the TDLAS methane detector and an RGB camera. On the follower, we add a fiducial marker (*e.g.* ArUco, AprilTag, etc. [10]) that is visually detectable from the leader, allowing precise estimation of the relative pose between the leader and the follower. Using a simple control loop, we correct the localization errors, ensuring the TDLAS points to the follower robot's reflector. Figure 5 shows a 3D illustration, depicting the *pan* and *tilt* angles necessary to align the detector and the reflector.

Naturally, this approach is limited by the range the fiducial markers can be detected, limiting the applicability of this solution to very large environments. In fact, the TDLAS detector employed in this work is, according to the manufacturer, able to sense methane if the reflector is up to 100 m from the emitter, while in our experiments, the fiducial markers were not properly detected farther than 10 m. More robust approaches for the relative-pose estimation of both robots must be considered to match the TDLAS detection range, an aspect that is left for future work.

3 Gas Distribution Mapping from Integral Measurements

As in most previous works on gas distribution mapping (GDM) [8,13] we simplify the problem by estimating a discrete two-dimensional map, dividing the space into a rectangular lattice of cells $\mathbf{c} = \{c_i\}_{i=1}^{N}$. Each scalar variable c_i stands for the gas concentration inside the i'th cell with coordinates (x_i, y_i). While the target area is being inspected, the collected integral measurements $\mathbf{y} = \{y_j\}_{j=1}^{P}$ are processed to estimate the 2D concentration grid map $\mathbf{c}$, which can later be

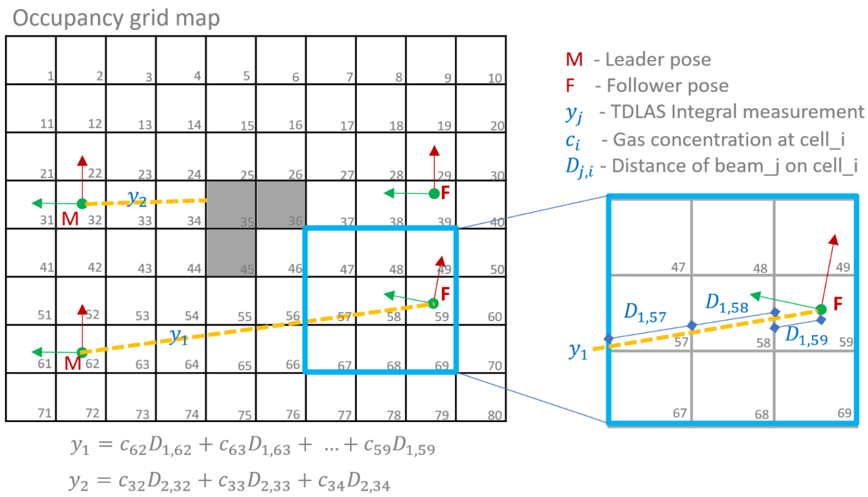

Fig. 6: Illustration of the ray-casting process for two integral measurements y_1 and y_2. Each measurement is expressed as the weighted sum of the gas concentrations over the traversed cells (c_i), employing as weight the distance traveled by the optical beam within each cell ($D_{j,i}$).

used to locate the gas sources present. As the TDLAS detector reports integral measurements with no information about the length of the beam, we localize the optical beam using the estimated poses of both robots and the occupancy grid map of the environment $\mathbf{m}$ (*e.g.* to detect cases where an obstacle is between the leader and the follower).

The set of cells affected by the optical beam of an integral measurement y_j is obtained by ray-casting on the occupancy grid map. The starting point of each ray corresponds to the sensor 2D pose (which accounts for the robot pose and the PTU corrections), while the final point corresponds either to an obstacle in the environment or to the pose of the reflector. An illustration of the ray-casting procedure is presented in Figure 6. To account for the intersection segment between the optical beam and each cell in the map, we define the distance matrix $\mathbf{D}$, where D_{ji} stands for the traveled distance of the optical beam y_j in cell c_i.

Following this notation, an integral measurement can then be expressed as the weighted sum of concentrations over the set of cells:

$$y_j = \sum_{i=1}^{N} D_{ji} c_i + \epsilon \tag{1}$$

which can be generalized for the set of all P measurements as:

$$\mathbf{y}^T = \mathbf{D}\mathbf{c}^T + \epsilon \tag{2}$$

where ϵ stands for the measurement noise.

Fig. 7: Experimental setup. (left) The occupancy grid map with dimensions annotations. (right) Picture of the parking lot from the University of Málaga, and the two robots involved in the experiments, Griaff-X on the left, and Rhodon on the right.

Framed as a convex optimization problem, we use the least-squares approach presented in [2] to estimate the vector of gas concentrations $\mathbf{c}$ that maximizes the likelihood of the measurements. The input to the algorithm is the set of localized integral measurements collected by the TDLAS detector $\mathbf{y}$, together with the intersection distance matrix $\mathbf{D}$, and the output is the vector of estimated gas concentrations $\hat{\mathbf{c}}$. Specifically:

$$\min_{\hat{\mathbf{c}}} \|\mathbf{D}\hat{\mathbf{c}} - \mathbf{y}\|_2^2 + \lambda \|\mathbf{c}\|_2^2 \text{ subject to } \hat{\mathbf{c}} \succeq 0 \quad (3)$$

3.1 Path Planning for Gas Distribution Mapping

As discussed in [1], the task of gas distribution modeling using gas tomography (tomographic reconstruction of local gas distributions from sets of integral gas measurements) requires sampling the area of interest with an overlapping sensing coverage of different viewpoints [3]. Different methods have been proposed to minimize the number of sampling locations and traveling distance for the case of a single robot with a TDLAS detector facing the ground [1]. However, as we are virtually able to take integral measurements in the horizontal plane, much simpler inspection paths can be designed to ensure multiple viewpoints. Particularly, without the aim to get into the subject of trajectory optimality, in this work we propose a trajectory composed of two perpendicular, straight paths for the leader and the follower robots (*i.e.* describing the contour of a rectangle). This simple inspection path ensures that each location is analyzed by two approximately perpendicular viewpoints (since the PTU corrects the misalignment between both mobile platforms, perpendicularity cannot be assumed).

4 Experimental Setup

To analyze the feasibility of the proposed approach, we conducted a set of experiments in a $10.5x14.75m$ parking lot from the University of Málaga (see Figure 7). The external walls were used to help the robots localize in the experimental area, but were never used as reflectors of the TDLAS detector. The role of the leader robot was assigned to *Rhodon*, a Pioneer P3DX mobile platform equipping an Interbotix wxxmls pan-tilt unit, an Owlotech (640x480 px) webcam, and a Falcon TDLAS methane detector (see Figure 8). The role of the follower robot was played out by Giraff-X, equipping a simple Aruco marker (0.16 x 0.16 m) serving as the reflector. For the self-localization and autonomous navigation, both robots are equipped with a 2D Hokuyo UTM-30LX laser rangefinder, and the navigation stack provided by ROS2. The gas source was a closed flask, filled with methane and set approximately at a height of 0.9 m from the ground, corresponding to the TDLAS detector height on Rhodon.

Both robots were commanded to autonomously inspect an area of approximately 70 m^2, trying to keep a distance between them of approximately 10 m (this distance corresponds to the Aruco detection range with the available hardware). Using Figure 7 as a reference, Rhodon was commanded to follow the top and left sides of the environment, while Giraff-X took the bottom and right sides, respectively. The occupancy grid map was generated with a resolution of 0.05 m/cell, while for the gas distribution map, a resolution of 0.2 m/cell was selected. During the inspection, the robots moved at a continuous speed of 0.3 m/s, not being necessary to stop the robots to get measurements, something that considerably reduces the inspection time.

5 Results and Discussion

Figure 9 depicts the laser beams collected during the measurement campaign, colored according to their integral measurement (ppm$x$m) as recorded by the Falcon methane detector. As can be observed, the beams start and end before reaching the environment limits, corroborating the correct alignment between the emitter and the reflector, as well as clearly pointing to the area where the gas source is located, that is, the crossing point of the two beams with higher integral concentration. Since the gas source is a bottle filled with methane, we can ignore in this work the problem related to gas dispersion in uncontrolled environments, being feasible to pinpoint the source location and to determine the range of cells that should contain methane.

From this data, we estimate the GDM as seen in Figure 10, showing the result from the least-square optimization phase and depicting the estimated gas concentration (ppm) for each cell on the map. It is worth noticing that the highest concentration falls close to the ground-truth location, but also that other cells (far from the contained source) show relatively high values. Those correspond to cells affected by the same integral measurement hitting the source, being an undesired side effect of the minimization process, likely corresponding to a local minimum solution.

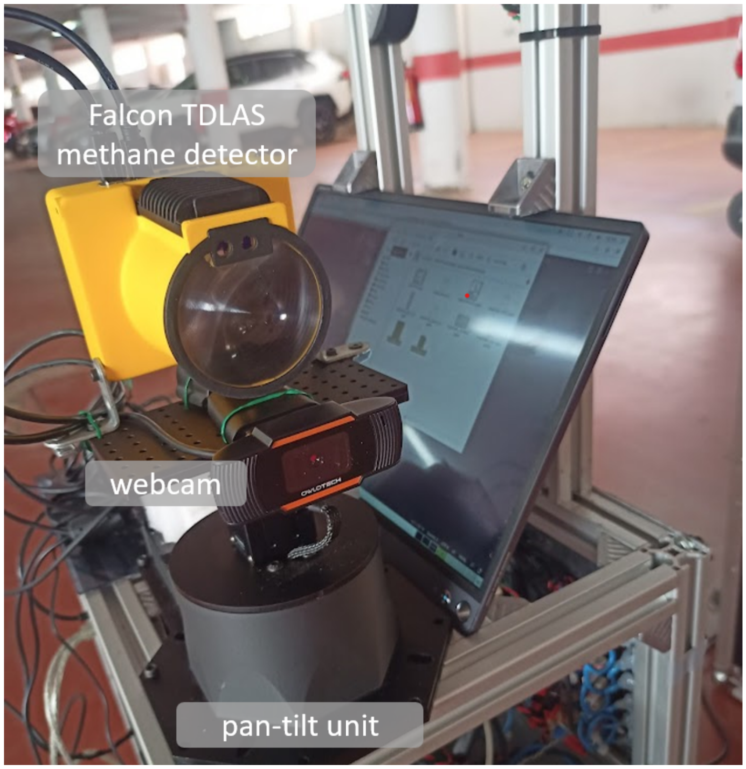

Fig. 8: Detailed view of the pan-tilt unit equipped by Rhodon (the leader robot), the webcam used to detect the Aruco marker in the Giraff-X platform (the follower robot), and the Falcon TDLAS methane detector.

6 Conclusions and Future Work

In this work, we have analyzed the practical case of employing two mobile platforms in a leader-follower formation, to assist in the detection and mapping of methane leaks with a remote gas detector (TDLAS). We have studied the technical difficulties associated with this approach, being the correct alignment of both robots the principal issue when extending the range of measurements. As a first step, we presented an alignment approach based on a pan-tilt unit and Aruco markers to precisely estimate, to some extent, the relative pose between the leader and the follower robots. Results demonstrate that this configuration is feasible for ranges up to 10 m (limited by the Aruco detection), allowing for fast inspection times with no need to stop the robots to take measurements.

Despite the successful results of this study, this approach can not be easily extrapolated to the detection range of the TDLAS, which is in the range of 100 m. Therefore, more precise methods are necessary to estimate the relative pose between the emitter and the reflector at measurement times.

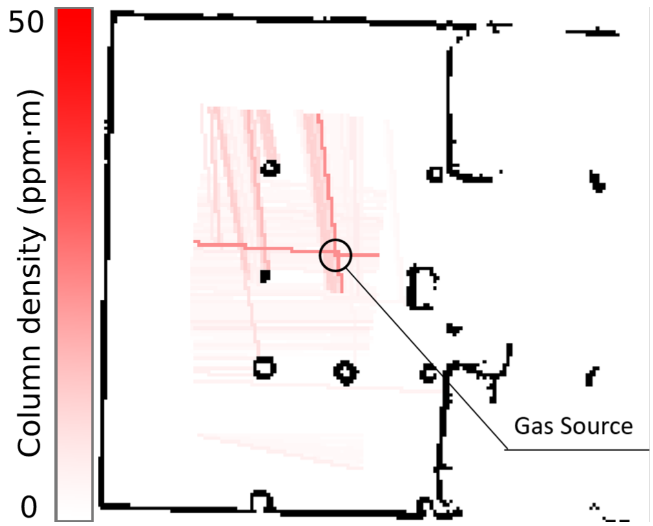

Fig. 9: Map of the TDLAS methane integral measurements. Each optical beam recorded is plotted over the occupancy grid map, with a color relative to the integral measurement ($ppm \cdot m$).

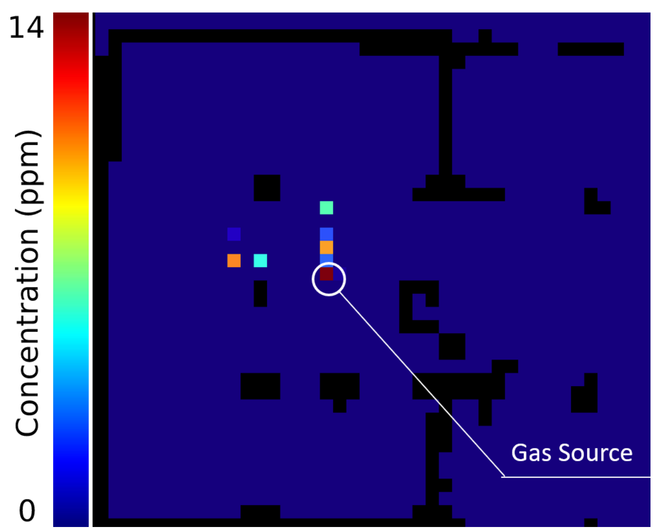

Fig. 10: Gas concentration map, depicting the estimated gas concentration of each cell.

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References

1. Muhammad Asif Arain, Victor Hernandez Bennetts, Erik Schaffernicht, and Achim J Lilienthal. Sniffing out fugitive methane emissions: autonomous remote gas inspection with a mobile robot. *The International Journal of Robotics Research*, 40(4-5):782–814, 2021. doi:10.1177/0278364920954907.
2. Victor Hernandez Bennetts, Erik Schaffernicht, Todor Stoyanov, Achim J. Lilienthal, and Marco Trincavelli. Robot assisted gas tomography — localizing methane leaks in outdoor environments. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 6362–6367, 2014. doi:10.1109/ICRA.2014.6907798.
3. Robert L Byer and Lawrence A Shepp. Two-dimensional remote air-pollution monitoring via tomography. *Optics Letters*, 4(3):75–77, 1979. doi:10.1364/OL.4.000075.
4. Xieyuanli Chen, Ignacio Vizzo, Thomas Läbe, Jens Behley, and Cyrill Stachniss. Range image-based lidar localization for autonomous vehicles. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 5802–5808, 2021. doi:10.1109/ICRA48506.2021.9561335.
5. Abigail Corbett and Brendan Smith. A study of a miniature tdlas system onboard two unmanned aircraft to independently quantify methane emissions from oil and gas production assets and other industrial emitters. *Atmosphere*, 13(5), 2022. doi:10.3390/atmos13050804.
6. Shaobin Feng, Fadi Farha, Qingjuan Li, Yueliang Wan, Yang Xu, Tao Zhang, and Huansheng Ning. Review on smart gas sensing technology. *Sensors (Switzerland)*, 19(17):1–22, 2019. doi:10.3390/s19173760.
7. Magnus Gålfalk, Sören Nilsson Påledal, and David Bastviken. Sensitive drone mapping of methane emissions without the need for supplementary ground-based measurements. *ACS Earth and Space Chemistry*, 5(10):2668–2676, 2021. doi:10.1021/acsearthspacechem.1c00106.
8. Andres Gongora, Javier Monroy, and Javier Gonzalez-Jimenez. Joint estimation of gas & wind maps for fast-response applications. *Applied Mathematical Modelling*, 2020. doi:10.1016/j.apm.2020.06.026.
9. Jun Jiang, Mingxin Zhao, Guo-Ming Ma, Hong-Tu Song, Cheng-Rong Li, Xiao Han, and Chaohai Zhang. Tdlas-based detection of dissolved methane in power transformer oil and field application. *IEEE Sensors Journal*, 18(6):2318–2325, 2018. doi:10.1109/JSEN.2017.2788871.
10. Michail Kalaitzakis, Brennan Cain, Sabrina Carroll, Anand Ambrosi, Camden Whitehead, and Nikolaos Vitzilaios. Fiducial markers for pose estimation: Overview, applications and experimental comparison of the ARtag, AprilTag, ArUco and STag markers. *Journal of Intelligent & Robotic Systems*, 101:1–26, 2021. doi:10.1007/s10846-020-01307-9.
11. Fei Li, Hao Cai, Jiheng Xu, Kai Zhang, Qilin Feng, and Haidong Wang. Gas distribution mapping for indoor environments based on laser absorption spectroscopy: Development of an improved tomographic algorithm. *Building and Environment*, 172:106724, 2020. doi:10.1016/j.buildenv.2020.106724.
12. R. Madhavan, K. Fregene, and L.E. Parker. Distributed heterogeneous outdoor multi-robot localization. In *IEEE International Conference on Robotics and Automation (ICRA)*, volume 1, pages 374–381 vol.1, 2002. doi:10.1109/ROBOT.2002.1013389.
13. Javier Monroy, José-Luis Blanco, and Javier Gonzalez-Jimenez. Time-variant gas distribution mapping with obstacle information. *Autonomous Robots*, 40(1):1–16, 2016. doi:10.1007/s10514-015-9437-0.

14. Jacob Mønster, Peter Kjeldsen, and Charlotte Scheutz. Methodologies for measuring fugitive methane emissions from landfills – a review. *Waste Management*, 87:835–859, 2019. doi:10.1016/j.wasman.2018.12.047.
15. Patrick P. Neumann, Harald Kohlhoff, Dino Hüllmann, Achim J. Lilienthal, and Martin Kluge. Bringing mobile robot olfaction to the next dimension — uav-based remote sensing of gas clouds and source localization. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 3910–3916, 2017. doi:10.1109/ICRA.2017.7989450.
16. Nickolas J Themelis and Priscilla A Ulloa. Methane generation in landfills. *Renewable energy*, 32(7):1243–1257, 2007. doi:10.1016/j.renene.2006.04.020.
17. Christian Weiss, Hashem Tamimi, Andreas Masselli, and Andreas Zell. A hybrid approach for vision-based outdoor robot localization using global and local image features. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 1047–1052, 2007. doi:10.1109/IROS.2007.4398959.