Combined GNSS/Visual Inter-Robot Tracking Method for Open-Path Gas Tomography

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***Abstract*—Methane emissions are a significant environmental and safety concern, yet many gas tomography systems intended to measure them require manual alignment, reliable high-bandwidth links, or fiducials. We present a lightweight, fully autonomous framework enabling line-of-sight inter-robot Tunable Diode Laser Absorption Spectroscopy (TDLAS) measurements without such constraints. A sensor robot equipped with a gimbal-mounted TDLAS unit tracks a reflector robot bearing an illuminated, color-controllable target. Coarse localization is achieved via RTK-GNSS, with vision-based fine tracking and passive time synchronization handled onboard. The system, based on off-the-shelf Pixhawk controllers and ArduPilot firmware, was validated in a 15 m × 7 m outdoor trial. Despite GNSS inaccuracies and deliberate occlusion by a methane-filled bag, the system retained lock, recovered from visual loss in under one second, and captured a 2800 ppm·m plume signature. These results demonstrate robust, scalable methane sensing for mobile gas tomography or standalone leak detection. Core components are released open-source to support future deployment.**

I. Introduction

Methane emissions from infrastructures such as pipelines, industrial plants, and landfills are a threat to safety, so rapid detection and precise localization is essential [1]. Recently, the role of methane as a strong green house gas adds to the need for sensor systems for detection and quantification [2], [3]. To enable such systems, a concept for gas tomography of methane emissions from wastewater treatment plants has been developed in a joint effort with the German Environment Agency (UBA) [3]. The envisioned flexible, mobile system, able to quickly acquire 2D concentration data in the field, will require the use of semi-autonomous robots surveying the area of interest. The basic measuring path will be established by one robot carrying a gimbal-mounted Tunable Diode Laser Absorption Spectroscopy (TDLAS) sensor for integral methane concentration measurements ('sensor robot') and a second carrying the reflector needed for the laser beam to return to the sensor ('reflector robot'). For this, a robust, field-deployable tracking and synchronization concept is needed. This paper presents such a concept, to be used later as part of the overall system, and demonstrates its feasibility.

Previous approaches to gas tomography have shown the basic feasibility of the required inter-robot measurement paths, although first with manual targeting [4]. Recent work [5] used automatic positioning of the reflector robot in a leader-follower setup, with visual fiducials for localization error correction. For our use case, however, we expect some constraints which have not been addressed so far. First, we expect low-bandwidth or unreliable communication in the field which rules out leader-follower approaches. Second, since our aim is quantification and not localization, we aim for systematic data acquisition from multiple angles with parallel robot movement. This requires synchronization robust to low-bandwidth/unreliable connections. Addressing these constraints, we present a system more suitable for such a use case. We start with coarse localization of the reflector robot by using a real-time kinematic global navigation satellite system (RTK-GNSS). When the reflector robot is in-view from the sensor robot, a tracking approach with a colored target is applied, similar to [6]. As an extension, we use an *illuminated* target more suitable for changing lighting conditions in the field and develop a tracking algorithm independent of a shared reference frame. To achieve synchronization, we use an autonomous, passive approach based on the shared GNSS timebase available to both robots.

Our main contributions are: 1) A concept for lightweight tracking and synchronization which enables line-of-sight, inter-robot measurement paths, applicable to gas tomography and source localization, 2) Implementation in a two-robot system and test of feasibility under realistic conditions, 3) Demonstration of robust operation in an outdoor environment and autonomous recovery from temporary occlusion and target loss. As a secondary contribution, we release key components of this system open-source.

II. Experimental Setup

A. Hardware Setup

The sensor robot used for the evaluation is shown in Fig. 1. It consists of a four-wheeled frame previously presented in [7], [8]. The system uses a Pixhawk-type autopilot controller running ArduPilot, a companion PC running Ubuntu Server, and a gimbal containing a camera and TDLAS methane sensor. For details the reader is referred to [7], [8]. Additionally, the setup uses a Lightware SF20 rangefinder for measuring distance to the reflector.

The reflector robot, see Fig.1, uses an identical base frame. Instead of the gimbal, it carries a reflector target. The target is made of a white-translucent, polystyrene half-sphere, illuminated from the back by 104 WS2812 LEDs, allowing for color control. The sphere has a diameter of 16 cm, due to manufacturing limitations. To increase reflector area, a piece of cardboard 40 cm by 40 cm is added.

Both robots and the Mission Planner ground station are connected to the same network.

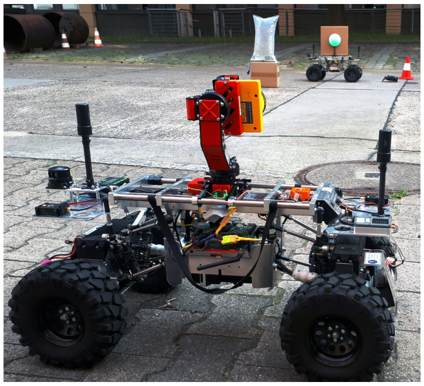

Fig. 1. Setup of the test run. The sensor robot (front) carries the gimbal including camera (black/red) and TDLAS methane sensor (yellow). The reflector robot is in the back. Left of it, a methane-filled bag can be seen.

B. Software Setup

The software setup consists of a python control script running on the sensor robot PC and a Lua script placed on both Pixhawk controllers. The Lua script is in charge of synchronization, while the python script is in charge of tracking and data acquisition. A data-acquisition-only version is run on the reflector robot. Additionally, MAVLink telemetry data is emitted by the Pixhawk controllers.

Both robots's use mavlink-router to forward telemetry data to the ground station. Additionally, the reflector robot's position messages are duplicated to the sensor robot's autopilot. This allows for GNSS tracking using ArduPilot's built-in targeting capabilities. The update frequency for the position data is the standard $2\,\mathrm{Hz}$. For details, see the mavlink-router configuration files [9].

The python script is part of the envisioned broader system which is out of the scope of this paper. Relevant here is that it acquires all sensor and telemetry data, and invokes a tracking class. The tracking class uses OpenCV to perform thresholding in the hue-saturation-value color space followed by contour detection. For details, its code is available at [9]. After the reflector position is determined in this way, a software P controller corrects the yaw/pitch angle of the gimbal. If the reflector disappears, the system resorts to dead reckoning using gimbal stabilization. If no visual lock is reacquired for $1\,\mathrm{s}$, the system switches back to GNSS tracking until the reflector reappears.

For synchronization, the Lua script is executed when the autopilot encounters a SCRIPT_TIME command in his mission command list. The script will then use the parameter of that command to calculate a common start time which is the next multiple of that parameter based on a modulo operation on the GNSS time. For details, see the source code of the script [9].

C. Trial Field

The trial field represents a single angle, $15\,\mathrm{m}$ x $7\,\mathrm{m}$ measurement of a larger gas tomography campaign. A bag filled with $2.5\,\%$ methane ($\pm 2\,\%$) simulates a methane cloud, see Fig. 1. The robots are driven manually to parallel starting points in front of the trial field. The reflector illumination is then switched on, making the sensor robot change from the already-running GNSS tracking to visual tracking automatically. The robots' missions are then started, with a deliberate delay to simulate lag in the previous mission items in a more complex campaign. Both robots then move to their synchronization waypoint at the start of the trial field at low speed. Next, they execute the Lua script. They then continue in parallel along the survey area to their final waypoint at its end. After the mission ends, the reflector is switched off, ending visual tracking. No manual targeting of the gimbal is performed at any point.

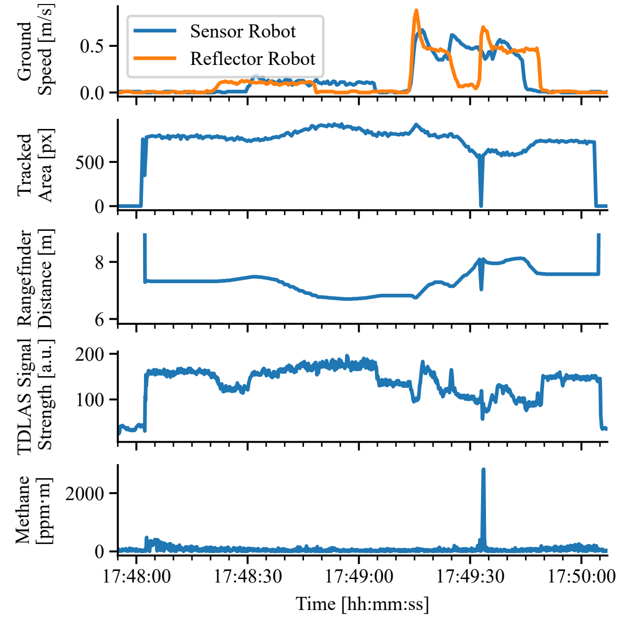

Fig. 2. Results of the test run performed using the tracking and synchronization approach. The robots first drive to their synchronization waypoint slowly and then perform the synchronized, visually-tracked mission which passes the methane-filled bag. At the start and end, the reflector illumination is off.

III. Results and Discussion

A. Results

The results of the test run are shown in Fig. 2. Its individual aspects robot speed, reflector area as perceived by the tracking algorithm, distance to the target as identified by the rangefinder, TDLAS reflected light strength (1f component, see [10]), and integral methane concentration, are discussed in the following paragraphs.

Robot speed: After starting with a deliberate delay (see Sect. II) the robots move at approx. $0.1\,\mathrm{m/s}$ and reach the synchronization point at 17:48:48 and 17:49:04, respectively. After synchronization is performed, they start simultaneously at 17:49:13. The reflector robot then ramps up its speed faster than the sensor robot, with a considerable overshoot. The sensor robot keeps its speed reasonably constant, with some fluctuations. The reflector robot can be seen to slow down considerably between 17:49:25 and 17:49:32, but then recovers. Consequently, the reflector robot reaches the final waypoint after the sensor robot, at 17:49:48 instead of 17:49:44. Both robots then remain stationary.

Tracked area: After the target is activated and visual lock established, the tracked area stays between $573\,\mathrm{px}$ to $925\,\mathrm{px}$ during the whole experiment. When the bag passes between the robots at 17:49:33, obscuring the view, a drop to zero is seen. Detailed examination of the data showed that visual tracking was lost for <1 s at this point. The system recovered autonomously using dead reckoning without resorting to GNSS tracking. After the robots have stopped moving, the tracked area stays constant at $730\,\mathrm{px}$. It then drops to zero when the illumination is switched off.

Rangefinder distance: When visual tracking starts, the rangefinder distance drops to $7.3\,\mathrm{m}$. During the mission, the distance then varies smoothly between $6.7\,\mathrm{m}$ and $8.1\,\mathrm{m}$. When the bag passes between the robots at 17:49:33 a brief reduction in distance by $1.1\,\mathrm{m}$ occurs. When the illumination is finally deactivated, the distance jumps to $14\,\mathrm{m}$ (not on graph).

TDLAS signal strength: Before activation of illumination, the signal strength is $37\,\mathrm{a.u.}$ which rises to $160\,\mathrm{a.u.}$ when visual lock is acquired. The signal then stays roughly at this level, with occasional drops when the robots start moving or change their speed. These fluctuations seem more pronounced when the robots are moving faster during the second part of the mission. When the bag passes between the robots at 17:49:33, a brief decrease by $35\,\mathrm{a.u.}$ down to $57\,\mathrm{a.u.}$ is seen. Except for this drop, during the synchronized test drive part, the signal strength stays between $73\,\mathrm{a.u.}$ to $183\,\mathrm{a.u.}$. After the robots have stopped, the signal plateaus at $147\,\mathrm{a.u.}$. When the reflector illumination is switched off, it finally drops to $36\,\mathrm{a.u.}$.

Integral methane concentration: The most significant feature is a pronounced peak at 17:49:33 with a level of $2800\,\mathrm{ppm{\cdot}m}$. As stated previously, this is where the bag passes between the two robots. Using full width at half maximum (FWHM), this signal is present for $0.39\,\mathrm{s}$, or roughly four samples. There is no other significant feature in the data.

In total, the mission took $1\,\mathrm{min}\ 27\,\mathrm{s}$, including the slow approach and sync time. The core part surveying only the target area of $15\,\mathrm{m}$ by $7\,\mathrm{m}$ took $34\,\mathrm{s}$.

B. Discussion

Even with the robots arriving at their synchronization waypoints at different times, simultaneous start of movement was achieved. The speed control of the robots was seen to not be optimal. As the experiment is situated between two tall buildings ('urban canyon'), this could be caused by the resulting GNSS inaccuracies. Another cause might be inadequate tuning of the robots' speed/location controllers. Such issues will need to be addressed before the system can be used for full-scale measurements in the future. However, in the context of evaluating tracking performance, as in this paper, this is beneficial, as it inadvertently stress-tests the tracking system.

The smooth changes in distance seen by the rangefinder are a first indication that the target was successfully tracked during the whole experiment, with a brief sudden reduction in distance when being reflected off the bag. TDLAS signal strength and tracked area data also indicate that the tracking lock stayed intact even with the inconsistent speed/distance of the robots and during occlusion of the target caused by the bag. A more in-depth analysis reveals that visual tracking loss was immediately ($<1\,\mathrm{s}$) recovered by dead reckoning after passing the bag while never fully loosing track of the reflector. This illustrates that the dead reckoning approach is robust. The feasibility of the combined GNSS/visual approach is demonstrated by the the immediate visual lock when the reflector is switched on (see Fig. 2, 17:48:02), as at this point the system is in GNSS tracking mode, see Sect. II. Additional tests not shown here have furthermore resulted in the system autonomously reestablishing lock using GNSS tracking even after the reflector was fully out of view for several seconds. Overall, the tracking approach evaluation can be seen as successful.

Tracking distance was limited by the experimental area available, not the system. Tests in the laboratory, which allows for max. $10\,\mathrm{m}$, were successful, demonstrating feasibility over longer distances. If needed, a larger illuminated reflector area or higher-resolution camera could extend the range.

The methane signal has clearly shown an obvious peak when passing the bag. This underlines that the presented approach is able to detect even brief and/or small methane clouds, as the bag is only $30\,\mathrm{cm}$ wide and in view for only approx. $0.4\,\mathrm{s}$.

The potential for speedy measurements of this approach is also demonstrated by the results. Even with the excessive approach and wait time used in the test run, the proposed system could be expected to survey an area with a diameter of $15\,\mathrm{m}$ from ten angles in about fifteen minutes. Using the demonstrated speed, a theoretical spatial sampling resolution of approx. $5\,\mathrm{cm}$ would be achieved. Higher speeds might be possible depending on tracking stability at increased velocities, though at the expense of spatial resolution due to the fixed TDLAS sensor sample rate.

More broadly, the results demonstrate that our proposed system is able to achieve synchronized start, robust tracking performance with fallback capabilities, and quick integral concentration measurements of even a small volume of methane. When addressing the flaws previously discussed, this approach can be expected to form the solid base of a full-scale gas tomography sensor system employing inter-robot measurements.

IV. Conclusion and Outlook

This paper demonstrated a combined GNSS/visual inter-robot tracking system for gas tomography, capable of lightweight synchronization and autonomous recovery. Future work will address the imperfections discussed and use this approach as the base for full-scale methane gas tomography.

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