Development of a Carbon Dioxide Monitoring Rotorcraft Unmanned Aerial Vehicle

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***Abstract*—This paper describes the development of a carbon dioxide (CO_2) sensing rotorcraft unmanned aerial vehicle (RUAV) and the experiences gained throughout its development as well as during its first deployment in a CO_2 trial. The aim of the flying measurement platform is to enable the creation of detailed gas distribution maps of larger areas in a relatively short timeframe for reasonable costs.**

I. Introduction

The need for mobile gas detection and mapping equipment emerges from various domains: Government regulations require landfills and waste disposals to be monitored, industrial sites have to check their equipment to detect gas leaks in an early stage to prevent potential danger to workforce and material, and carbon capture and sequestration (CCS) projects have to monitor vast areas to ensure the security of CO_2 storage.

Conventional gas detection and mapping is mostly done by taking samples manually by trained personnel or by deploying stationary gas monitoring instruments at predefined positions. To remain within reasonable costs, the result is either a temporally or spatially sparse coverage. Sensor networks can tackle these problems, but only if each sensor node is inexpensive and easy to deploy [1]. To detect gas leaks, sensors need to be within close proximity of the leak due to rapid dilution and dispersion in the atmosphere. For CO_2, where there is already a significant background concentration in the atmosphere (i.e. ~390 ppm), the problem is further exacerbated. Statistical analysis of high precision CO_2 measurements and leak simulations show that for a CO_2 leak at a distance 1 km away from a high precision measurement station, a point source leak would need to be in the order 20 t/d before it could be detected [2].

The task of manually collecting gas samples can also be dangerous depending on the gaseous substance to be measured. Therefore, the deployment of robots for such gas sampling applications is highly desirable.

An economic solution for spatially as well as temporally dense coverage is the deployment of mobile robots: The amount of expensive high accuracy sensors necessary can be reduced to one piece per robot and the spatial coverage is merely limited by the robot's on-board power. A sparse temporal resolution can be overcome by repeatedly sending the same robot into the field or by alternating robots with identical configuration. Remote controlled operation of the robot allows the operator to stay in a safe distance. With autonomous operation of the gas sensing platform the operator can solely concentrate on the results received from the robot while not being present at the emission site at all.

II. Related Work

Previous work regarding mobile robot aided detection and mapping of gaseous substances include terrestrial as well as aerial robots. In [3] the authors present a ground based system called Gasbot developed for landfill monitoring tasks. The platform is based on an ATRV-JR robot and can detect methane (CH_4) leaks indoors as well as outdoors in rough terrain. The system uses the Sewerin Remote Methane Leak Detector (RMLD), a Tunable Diode Laser Absorption Spectroscopy (TDLAS) sensor which reports gas concentrations as integral measurements over the path of the laser beam. The RMLD can measure CH_4 concentrations of as low as 5 ppm·m at distances up to 15 m. Larger distances can be covered with less accuracy [4]. Using the approach presented in [5] a gas distribution grid map can be calculated based on the TDLAS measurements and their respective laser beam paths. To successfully construct a gas distribution map, one has to collect multiple measurements for each grid cell from various angles. Wind gusts negatively influence the results in outdoor setups due to the problem that the gas concentration of a cell cannot be assumed as constant between multiple measurements anymore. Errors in the position estimation of the robot further degrade the quality of the gas distribution map due to the faulty start and end position estimations of the laser beams.

A gas-sensitive quadrocopter for adaptive gas source localization and gas distribution mapping is presented in [6]. The platform is based on the AirRobot AR100-B and is equipped with a Dräger X-am 5600, a gas probe designed for personal monitoring applications which is able to sense up to six gases simultaneously. The unit uses infrared and electrochemical sensors to produce its measurements (for details see [7]). A modification of the sensor has been necessary to stay within the payload limits of the quadrocopter [8]. In addition to the gas sensor, a humidity and temperature sensor has been integrated into the platform as well. To gain a gas concentration with the least amount of dilution caused by the rotors of the quadrocopter, three approaches to transport the gas to the sensor have been tested in a wind tunnel: A passive approach (gas measurements are taken during normal flight), a semi-active approach (the suction effect of the rotors is used to transport the gas through a small pipe to the sensor) and an active approach (a dedicated fan inside a tube which protrudes from the radius of the quadrocopter is used to push the gas towards the sensor). While none of the approaches reached the reference gas concentration, the active approach performed best with 66%, followed by the semiactive approach with 52% of the reference concentration. For their real-world CO_2 distribution experiments around the geochemically active Tuscany Region, the semi-active approach has been chosen by Neumann et al. due to its applicability and good sensitivity. During these experiments, 20 s worth of measurements have been taken for each predefined sensing location. Based on these measurements and the approach described in [9] a distribution map has been created. While the first run showed promising results with the calculated distribution map depicting the source location at its actual location, the following three runs estimated the source location with an offset of around 10 m. The authors give the destruction of the preexperimental gas distribution caused by the first experimental run with the quadrocopter in combination with a too short waiting period between the test runs as reason for that phenomenon.

III. Development Goal and Initial Application

The intention of this feasibility study is to find out if a RUAV can be a useful tool for monitoring and tracking gaseous substances in midair as well as detecting gas leaks over large areas. A good compromise between accuracy, spatial and temporal resolution is necessary to enable the RUAV to be used for these tasks.

As initial application we want to use the developed RUAV to monitor the CO_2 distribution over the GA-CO2CRC Ginninderra Controlled Release Facility. The facility is an area of approximately the size of a soccer field which is used for surface as well as shallow sub-surface CO_2 release tests. Previous research undertaken at the experimental site with statically deployed sensors showed that the CO_2 perturbation to be expected during a sub-surface test is around 10 ppm above the ambient CO_2 concentration about 20 m away from the emission source [1]. The release rate for these experiments has been 100 kg of gaseous CO_2 per day.

IV. Development of the RUAV

A. Implications of the gas sensor choice

The choice of the gas probe has great implications on the possible type and size of the aerial platform: The dimension of the RUAV is bounded by the weight and size of the sensor, and the response time of the probe dictates the maximum speed the aerial vehicle is allowed to fly. Even the technology used by the sensor has great implications onto the flying platform: If one would for example use a TDLAS sensor on the RUAV, it would be necessary that each position one wants to have measured is covered by multiple individual measurements to allow the calculation of the CO_2 concentration at that point. On the other hand, if one would use an NDIR (Non-Dispersive Infra-Red) system, it would be necessary to fly over the whole area of interest because the sensor only measures at its current location. That again means that even the flight path of the RUAV is dependent on the choice of the sensor and therefore also the path planning component of the aerial vehicle depends on this crucial decision. Of course the predominant factors of each sensor are its accuracy and noise values. The magnitude these values are allowed to have is predetermined by the application. Therefore, it is important to know what one expects to measure before selecting the sensor. The last step should be to decide which platform should be used which is dependent on which RUAV actually can cope with the sensor size and weight and of course other constraints regarding additional sensors, actuators and communication modules for the control of the RUAV.

B. Choosing the CO_2 sensor

Even though TDLAS sensors are highly accurate, a decision against them was made early on due to the fact that the sensors need a surface on which the laser beam bounces back to the device to make a measurement. With increasing altitude the reflective properties of a grassy surface will not be enough anymore to gain reliable measurements without reflective beacons on the ground. The distribution of such beacons over a larger area is not feasible.

An inevitable effect of all RUAVs is the mixing of the gaseous substances in the volume around the aerial platform due to the rotors of the RUAV. With an equal distribution of the targeted gas in this volume one will measure the actual concentration of the gas at the current position. For unequal distributions one will measure a concentration lower than the maximum concentration of the gas inside this volume. Another fact to be kept in mind is the time necessary for the sensor to compute a single measurement. The value of each measurement can be seen as the average CO_2 concentration of the volume the RUAV was flying through during this time interval. The velocity of the RUAV is therefore bounded by the immutable measurement time and the targeted spatial resolution.

Based on these points and the CO_2 concentrations measured on the experimental site in earlier trials, the authors were targeting a NDIR sensor with high accuracy and a fast measurement time. The decision was made to use the Vaisala GMP343 CO_2 sensor which features an accuracy of $\pm$(3 ppm + 1% of reading) and a noise of $\pm$3 ppm within the measurement range of 0...1000 ppm. The fastest response time of the sensor is 2 s (without filter attachment and internal filtering).

C. Choosing the aerial platform

The decision which RUAV platform to use was heavily influenced by the fact that a platform change might be necessary later on to accomodate other sensors, with most likely different weight and size, to measure other gases than the currently anticipated CO_2.

Quadrocopter, available with waypoint-based flight off-the-shelf for a reasonable price do unfortunately not scale very well. If more payload is required, the upgrade to an Quadrocopter is a platform with more rotors, e.g. a Hexa- or Octacopter. The behavior of these platforms is different from the one of the Quadrocopter, making changes in the control algorithms necessary. More rotors (and therefore more motors and motor controllers) also mean an increased amount of point-of-failures.

Helicopter-based systems with main and tail rotor on the other side are available in multiple sizes, allowing payloads from just a few grams up to several kilograms. The designs of the RUAVs remain relatively consistent throughout the spectrum (except slighter variations in the swash plate and tail-rotor design), allowing the re-use of the same underlying control algorithms after platform changes and making possible adjustments to the RUAV size later on less troublesome. Unfortunately, off-the-shelf kits with waypoint-based flight are not available in the same price range than quadrocopters are.

Based on the size and the weight of the Vaisala GMP343 CO_2 sensor as well as the extra payload of a processing unit, sensors for position and height estimation, a sensor gimbal as well as additional batteries, we decided to use the electric powered RC helicopter T-Rex 700E from the manufacturer Align as base platform for the RUAV.

D. Testing the Vaisala GMP343 CO_2 Probe in motion

The CO_2 sensor chosen for the experiments has initially been developed for static usage and was not intended to be moved around while taking measurements. Therefore, tests have been necessary to check if the probe delivers meaningful CO_2 values while being in motion. Of special interests in conjunction with the CO_2 values have been the temperature and velocity measurements: Due to the movement of the probe, the resulting air flow cools down the sensor which might have an effect on the measured CO_2 concentration. In addition to that, accelerations might change the pressure of the gas inside the measurement chamber influencing the values as well.

For practicality reasons we decided to do the CO_2 sensor tests with a car. We also used the opportunity to test if all other hardware components intended for the use on the helicopter were working nicely together. For the experiments, the CO_2 probe was mounted on a rod allowing it to be deployed out of the window of a car (see Fig. 1). All other hardware was mounted on a MDF board which has been put into the rear of the car close to the back window to ensure reasonable GPS reception.

To make use of the fastest response rate of the sensor of less than 2 s per measurement, the filter has been detached and all software filtering, averaging and smoothing has been disabled / the raw values of the sensor (CO2RAW) have been used. Temperature, pressure, relative humidity, and oxygen compensation as well as the built-in linearization have been kept enabled. The heating of the probe has been enabled as well.

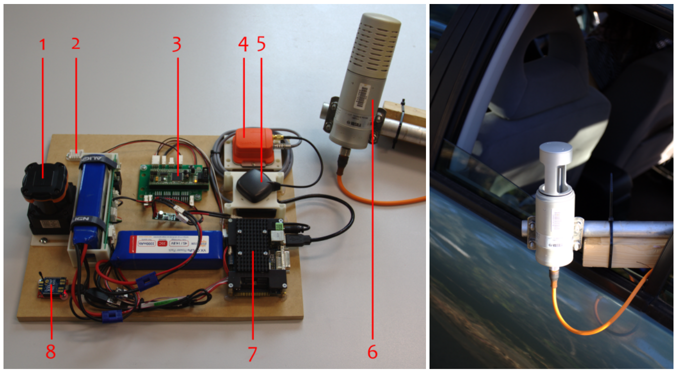

Fig. 1. left: (1) Laser range finder Hokuyo UTM-30LX (2) RHT03 humidity and temperature sensor (3) Controller board featuring the AVR microcontroller ATxmega256A3 (4) Xsens MTi-G (GPS aided attitude and heading reference system) (5) GPS antenna (6) Vaisala GMP343 CO_2 probe (7) Main processing unit Kontron pITX-SP featuring an Atom processor (8) XBee PRO S2B 2.4 Ghz module for communication; right: The Vaisala GMP343 CO_2 probe without filter attachment ranging out of the back window of a car during the experiment.

The track driven for the experiment can be split into three logical parts: In the first part (0 s to 377 s) we have been driven the car through the campus. We chose a weekend for the experiment to only meet a very low amount of traffic in this area. For the second part (377 s to 752 s) we drove through the city to experience some CO_2 perturbations due to other traffic on the road. We then drove back via a road with low traffic (third part, 752 s to the end of the trial).

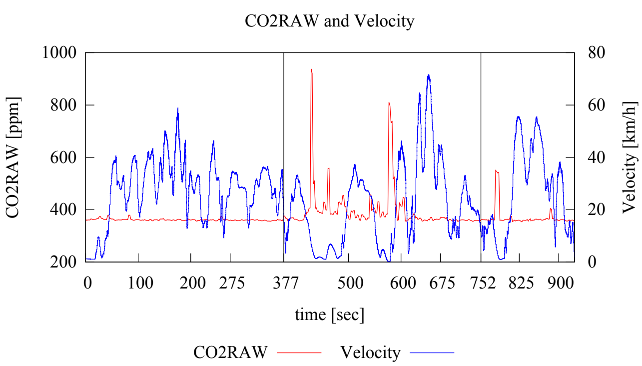

Fig. 2. No direct connection between CO_2 concentration and velocity or acceleration can be found. Significant peaks can be seen when the car was approaching or standing at traffic lights.

The results of the test run can be seen in Fig. 2 and Fig. 3. During the first part of the experiment a relative constant CO_2 concentration with an average of 366 ppm has been measured. Before starting to drive (first 17 s of trial), a slightly lower average CO_2 concentration of 362 ppm has been measured. The city-part of the trial shows as expected higher CO_2 perturbations. Spikes can be seen where the car was approaching or waiting at traffic lights and the sensor was measuring the exhaust gases of the banked up traffic. The third part of the experiment shows a relatively stable CO_2 concentration again

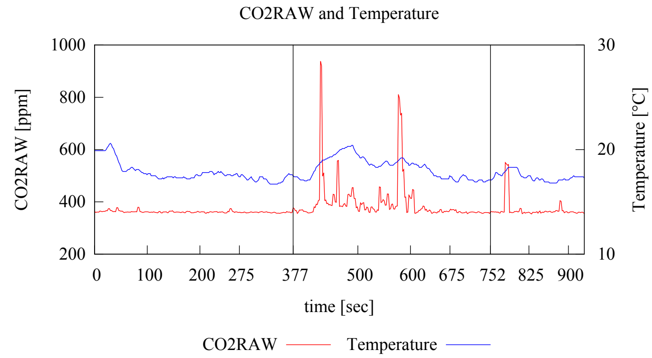

Fig. 3. No direct connection between temperature and CO_2 concentration can be seen. At the start of the experiment the sensor is cooled down by the air flow created by the driving car. While standing on traffic lights, the heating system rises the temperature of the probe again.

which is merely interrupted by the effects of standing at a traffic light and a minor perturbation close to the end of the trial.

A tight coupling between acceleration and measured CO_2 concentration or temperature and measured CO_2 concentration cannot be found in the graphs. In Fig. 3 one can see that the built-in heating system of the sensor has not been able to keep the temperature of the probe at a constant level. At the start of the trial, the temperature drops due to the air flow caused by the driving car and then keeps relatively constant while the car is maintaining speed. In the first half of the second phase of the experiment, the temperature rises with the car driving with lower speed or standing at traffic lights. The resulting lower air flow allows the heating system to raise the temperature of the probe again. Due to the fact, that the heating is primarily used to prevent dew on the surface of the optics, we decided to disable the heating for the further experiments.

E. The experimental platform

All parts previously mounted on the MDF board have been put on the helicopter (see Fig. 4) after the successful initial experiments.

Fig. 4. The measurement platform based on the Align T-Rex 700E.

The weight of the Vaisala GMP343 CO_2 probe on the sensor gimbal in the front of the helicopter made it necessary to extend the battery tray for the main batteries to allow these to be pushed further back, acting as a counter weight. All payload is powered by a dedicated 4 S LiPo battery, ensuring a clean power supply to the sensors and computational units without ripples introduced by the motor or servos.

V. CO_2 Trial

A. Experimental Setup

For the initial CO_2 surface release experiment, a ground level CO_2 release chamber has been used. The CO_2 release rate has been set to an equivalent of 100 kg of CO_2 per day. The weather conditions were good: sunny and calm with only sporadic and minor wind gusts.

Fig. 5. T-Rex 700E flying over the CO_2 source (Photography by Ben Coughlan).

The purpose of the experiment has been to check whether it is possible to use the developed RUAV to sense CO_2 in midair or not. We therefore flew the helicopter remote-controlled repeatedly in about two meters height over the emission source (see Fig. 5).

The Vaisala GMP343 was used with its air filter attached and set to a 2 s measurement time. The manufacturer recommends not to use the air filter in conjunction with the fastest response rate. But in our case with the CO_2 sensor being fully subject to the downwash of the helicopter main blades, a steady airflow through the measurement chamber can be guaranteed even with the filter still attached. The advantage of keeping the air filter attached is that the dust particles dispersed by the helicopter do not get into the measurement chamber and pollute its surface, which could negatively influence the measurements.

B. Interpretation of the Results

Fig. 6 shows the measured CO_2 concentration throughout the flight. The experiment can be logically split into four parts: (I) measuring the ambient CO_2 concentration with the helicopter standing on the landing pad, (II) spin-up phase, (III) flying phase, and (IV) post-flying phase.

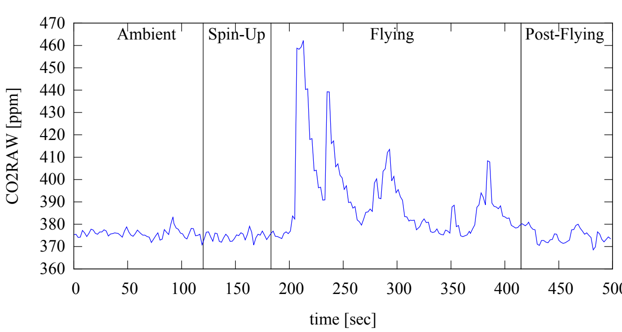

Fig. 6. Recorded CO_2 Measurements.

During the first phase, a relatively constant ambient CO_2 concentration with an average of 376 ppm has been measured by the Vaisala GMP343. The following spin-up phase did only have a minor effect onto the measured ambient CO_2 concentration which dropped to an average of 375 ppm.

A major jump in the CO_2 concentration can be seen in the graph when the helicopter has been flown over the emission source for the first time. Each consecutive flyover resulted in the corresponding CO_2 spike in the graph being less significant than its preceding one. This can be mainly traced back to the ongoing dilution of the air-CO_2-mixture through the main rotor blades of the helicopter. Variations in wind speed and the altitude of the helicopter while flying repeatedly over the emission source will also affect the CO_2 readings.

After landing the RUAV one can see the CO_2 concentration relatively quickly recovers to the levels recorded in the first phase (the average CO_2 concentration in phase IV is 375 ppm).

VI. Conclusion and Further Work

These encouraging results of the first experiment suggest that RUAVs could be a potentially useful tool for detecting CO_2 leaks over large areas.

Further experiments will be conducted with the RUAV flying along predefined grid-lines to allow the creation of a CO_2 distribution map with evenly spread measurements over the application area. A distribution map would enable the user to see if there is any significant CO_2 concentration in the area and to pin-point the areas of interest. For the next experiments we plan to utilize an ultrasonic sensor (Maxbotix MB1320) as well as the Hokuyo UTM-30LX laser range finder to gain the altitude of the RUAV relative to the ground. That would allow us to create the CO_2 distribution map relative to the actual terrain of the area.

Current work is focussing on automating the aerial platform to enable autonomous flight for coverage over larger areas, the tracking of gas plumes as well as the creation of CO_2 distribution maps for different altitudes.

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