Micro-Drone for the Characterization and Self-Optimizing Search of Hazardous Gaseous Substance Sources

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Abstract

BAM Federal Institute for Materials Research and Testing, in cooperation with the AirRobot GmbH & Co. KG company, has developed a flying remote-controlled measuring system. The system is capable of operating in a variety of scenarios of gas emissions, e.g. exhaust gas from chimneys, flue gas in a fire, gas emissions in the case of an accident of chemical or hazardous goods or in the case of a terrorist act involving toxic gases. Thus it can measure the gas concentration in the immediate vicinity of the object which causes the emission. A further stage of extension is to enhance the system for plume tracking and identification of sources of hazardous gases.

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1. Introduction

At present time, the release of critical gases is an acute threat and mainly responsible for a multitude of immense dangers and problems – both global (ozone hole, global warming, climate change) and local (smog, pollution, poisoning hazard in the case of an accident or terrorist attack). Gases may be released in many different ways with different backgrounds: as exhaust from traffic or industry, as flue gas from volitional or unintentional fires, as a consequence of a chemical or dangerous goods accident, or as the result of a terrorist attack.

The fundamental requirement for gas emission control as well as effective counteractive measures is the measurement of the relevant gas concentration in the immediate vicinity of the source. A flexible and mobile measurement device is needed to measure gas concentrations in many different scenarios of gas release. The measurement systems used so far barely fulfil these requirements and show further constraints: measuring vehicles equipped with appropriate gas analysis technology can certainly carry out highly selective gas measurements, but they are generally ground based and cannot reach the emission source. Therefore, only telemetry can often be carried out. Smaller handheld measurement devices are flexible and inexpensive, but danger to people prevents their use very close to the emission source.

An even greater technical challenge is the airborne search for hazardous gaseous substance sources which has great significance e.g. in the field of leak detection, landfill monitoring and fight against terrorism. In many areas this is an unsolved problem. Many methods of mobile robot navigation to locate sources of hazardous materials are based on the search behaviour of insects and other animals, which use their olfaction to locate food, to detect danger or even to find mates. They are well known in the literature [1] under the topics “odour-source localization” and “plume-tracking”. Implementations of these methods have been tested and evaluated so far on ground-based robot platforms, AUVs (Autonomous Underwater Vehicles) and simple-structure blimps.

The objective of this work is to implement a micro UAV (Unmanned Aerial Vehicle; also referred to as micro-drone) for the measurement of gas concentrations. Additionally, an airborne route planning and optimization strategy has to be realized for the localization of gas emission sources.

2 Development of a Mobile Measurement System

2.1 Development of the Equipment Technology

Recent developments in the field of mini UAV and mobile gas measurement technique have established new possibilities to search for and characterize hazardous airborne substances. The Federal Institute for Materials Research and Testing (BAM), in cooperation with the AirRobot GmbH & Co. KG company, has developed a mobile and flexible measurement system as part of a R&D project funded by the Federal Ministry of Economics and Technology (BMWi). The concept of the project includes the development of a gas sensor module for the AirRobot drone AR100 (**Fig.1**), which can be used in different scenarios. Validation and optimization of the system is also part of the project.

The compact design and excellent manoeuvrability of the remotely controlled quadrocopter (AR100) make possible precise navigation and enable the device to enter small passages. The maximum payload weight amounts to 200 g with a total flight weight of about 1.3 kg. The diameter of the AR100 is 1 m. The maximum flight time is about 30 min. at a maximum wind load of 8 m s^{-1}. A powerful wireless radio link enables for the ground station to communicate with the AR100 and its payload and in-

cludes both the control and the data transmission units of the payload. The operating distance of the remote control is 1 km. The AR100 can be flown by sight and via onboard video camera and head-up display.

Fig. 1. AirRobot AR100

A commercially available 5 gas detector was used in the AR100, which was originally designed for the personal safety. For this reason the device features low weight and compact design. The modular concept allows the ad hoc exchange of sensors in the gas detector, which enables users to customize it for their specific application. Depending on the scenario, the gas detector can detect many combustible gases and vapours (catalytic Ex sensor) as well as different (toxic) gases e.g. O_2, CO, H_2S, NH_3, CO_2, SO_2, PH_3, HCN, NO_2, Cl_2 (electrochemical sensors). A significant reduction in weight has been achieved by the removal of unnecessary components and the integrated rechargeable battery. Hence, the total weight of the gas detector amounts to less than the payload limitation. A more lightweight lithium-based battery buffers the sensors until their next mission to achieve fast operational readiness. An additional electronic circuit controls the communication between the gas detector and the drone via appropriate device interfaces. A temperature and humidity sensor was also integrated as both factors may affect the measurement data. The case of the gas detector is protected against water and dust according to IP 67 and therefore capable of working outdoors.

Gas transport to the chemical sensors is a critical process due to the rotors of the quadrocopter and the turbulence caused by them. Various solutions are available depending on the application and basic conditions. The gas transport can take place passively (without any auxiliary device), semi-actively (using the air flow generated by the rotors) or actively (using an additional fan). When using the passive principle, the T_{50} / T_{90}[1] times of the sensors are relevant. In order to achieve faster measurements with less residence time of the drone the other two gas transport principles should be applied.

2.2 Development of Search Algorithms

By combining video data, flight control data, GPS coordinates (Global Positioning System) and measurement data from the gas sensors a new method to access the expansion and the dispersion of specific gases should be developed. The objective is to coordinate adequate measures e.g. local evacuation. In addition, a data base for the self-optimizing search of hazardous gaseous substance sources. For this purpose, the sensor system of the flight control unit will be used to determine wind speed and direction. Adaptability to microdrones of existing search algorithms will be analyzed and, if applicable, a porting will be accomplished. The combination of existing and the development of new search algorithms offer further possibilities. The results should be simulated by CFD (Computational Fluid Dynamics) methods and evaluated and validated by field tests.

The IMU (Inertial Measurement Unit) is an important part of the drone. It provides the basis for flight control and can be read out in operation. The IMU consists of three orthogonally arranged accelerometers, which detect linear accelerations along the x-, y- and z-axes, and three orthogonally arranged rotation rate sensors, which measure angular accelerations along the x-, y- and z-axes. Magnetic field sensors (compass) and GPS are used to improve the accuracy of the IMU and to compensate for sensor drift [3]. The IMU of the AR100 also contains a barometric pressure sensor to control the drones' altitude.

Corresponding user software will be developed to control and configure the gas detector and to allow the data evaluation and storage. It covers all important information and therefore enables estimating the risk potential and gas dispersion. Thus proper counteractions can be introduced promptly and a localisation of the emission source can be started.

3 Validation Experiments: Gas Measurement

Experiments in laboratory scale were carried out in a 20 m³ test chamber to measure different CO_2 concentrations for the validation of the system with respect to the measurement of gas concentrations in a medium-sized volume consisting of the same gas compounding. Two commercially available gas detectors which were placed at different positions in the chamber were used as reference systems. One of them was identical to the one used in the drones' payload. A circulating pump and another fan were used to achieve homogeneous intermixing of the entire volume. The chamber was flushed at the beginning of each trial i.e. the contained gas / air mixture was replaced with "clean" air to assure a CO_2-free test chamber.

[1] "The response time of the sensor is commonly specified by the T_{90} or T_{50} time. T_{90} is the time for the sensor's response current to reach 90% of its steady-state value. Similarly, the T_{50} metric is the time required for the sensor to reach 50% of its steady-state value [2]."

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The induction of CO_2 was carried out in series and intermittently for about 30 s to regulate the CO_2 concentration. In the first trial the AR100 was started after CO_2 had been introduced into the chamber. In the second trial the AR100 was started before CO_2 was induced.

By taking into account the accuracy of the used CO_2 sensors of the different measurement devices used and the position-dependent delay[2], all values measured by the device of AR100 coincide with those measured by the reference devices (**Fig. 2**). Therefore, the ability of the entire system to measure gas concentrations in a medium-sized volume has been verified. As a further step the enhancement of the design and optimization of the system are being planned to implement a more pointwise gas concentration measurement.

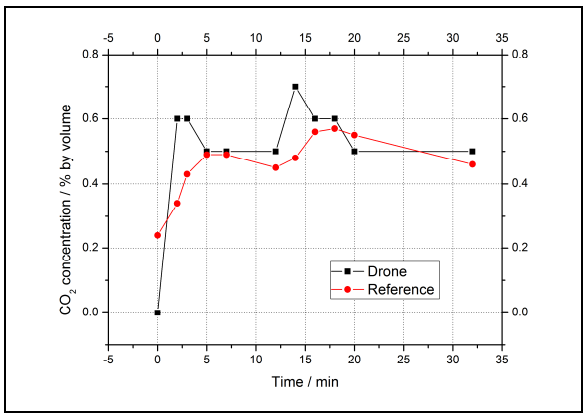

Fig. 2. Comparison of the measured CO_2 concentration at the drone and a reference device vs. time (the drone was in the air before the experiment started)

4 Basics for the Localization of Emission Sources

Based on the presented measuring system, a new method for localizing an emission source using plume tracking [1] or gas distribution mapping [1, 4, 5] should be developed. Kowadlo and Russell give in [1] an excellent summary of the existing algorithms[3] that will be used for comparison. For plume tracking in general and in some cases of gas distribution mapping [4] information about wind speed and direction is essential. In the following section a new approach to determine the wind vector (wind speed and direction) from the existing measurement data of the IMU will be presented.

4.1 Determination of the Wind Vector

The determination of the wind vector is based on the roll and pitch angle of the AR100 as well as the orientation of the system with respect to the magnetic north pole. The drones' IMU provides the necessary data. The resulting angle ψ from roll and pitch angle can finally be used to calculate the drag F_D.

$$F_D = \frac{g \cdot m}{\tan\left(\frac{\pi}{2} - \psi\right)}, \tag{1}$$

where g is the acceleration due to gravity and m is the total weight of the system.

The wind speed can be calculated by using the definition of the drag coefficient c_d.

$$v_W = \sqrt{\frac{2 \cdot F_D}{\rho \cdot A_{proj} \cdot c_d}}, \tag{2}$$

where A_{proj} is the projected surface area and ρ is the density of the fluid (in this case air). Latter can be calculated from the temperature and humidity. When the drone holds a steady position via GPS (or manually), v_W equals the actual wind speed. If the drone is flying forward, the wind speed can be calculated as the difference of v_W and the actual flight speed using GPS. A filter is used for noise reduction of the data. The wind direction can be calculated by transformation of the coordinate systems (from local to global using the given values and the compass). Fig. 3 shows the relationship between the forces.

A_{proj} and c_d can be determined using an imaging technique based on the resulting inclination angle of the drone and wind tunnel experiments.

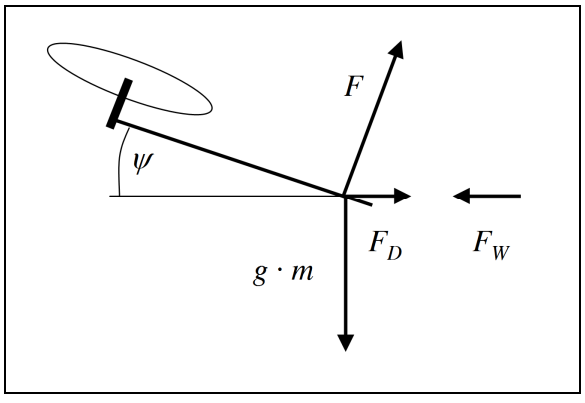

Fig. 3. Triangle of forces

[2] The time needed to achieve a homogeneous concentration in the test chamber.
[3] Except the new approach called infotaxis (see [6] for further information).

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4.2 Experimental Study

The TU Dresden operates a wind tunnel of design type "Götting" (**Fig. 4**) which was most suitable for experiments on the micro-drone. The tunnel has a stream diameter of about 3 m and an almost 4.5 m long test section. This provided sufficient space for the experiments. However, because of the light structure of the drone, it was not possible to mount it on a force balance. Therefore, the wind vector was calculated based on an experimentally determined function.

Different series of measurement were performed in the wind tunnel with and without payload and in different radial orientations of the drone. The wind tunnel provided speeds from 0.0 up to 7.5 m s^{-1} with an increment step of 0.5 m s^{-1}. Data were collected from the drones' IMU for about 30 s and were considered valid if the drone held its position (controlled via camera) and wind speed in the wind tunnel was steady.

A relationship between the inclination of the AR100 and the wind speed based on different series of measurement has been established. A quadratic function was derived by interpolation which can be used to directly calculate the wind speed. Further results showed that different radial orientations of the drone seem to be irrelevant and can be neglected. Payload plays a minor but significant role in the determination of wind speed and was regarded accordingly.

Fig. 5 shows the inclination of the AR100 at different wind speeds. The error bars indicate the standard deviation from the mean values. **Fig. 6** shows the comparison between the inclination angles with and without payload.

5 Conclusion

The combination of a UAV and a mobile and flexible gas measuring device creates new possibilities to estimate the risk potential of different scenarios without endangering people. Furthermore a big step forward in direction of aerial-based plume tracking and mapping has been accomplished by calculating the wind vector from flight control data. Now, it is an important next step to evaluate the existing plume tracking algorithms in simulations and experiments regarding their adaptability and optimize them for this new task as well as develop new algorithms in this area of application.

6 Acknowledgement

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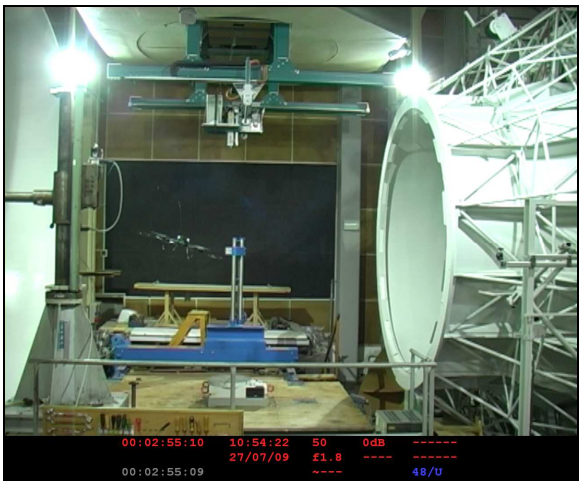

Fig. 4. AR100 in the wind tunnel at 7.5 m s^{-1}

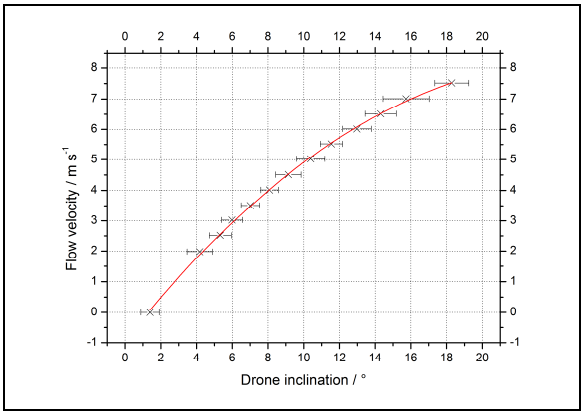

Fig. 5. Inclination of the drone at different wind speeds (with payload)

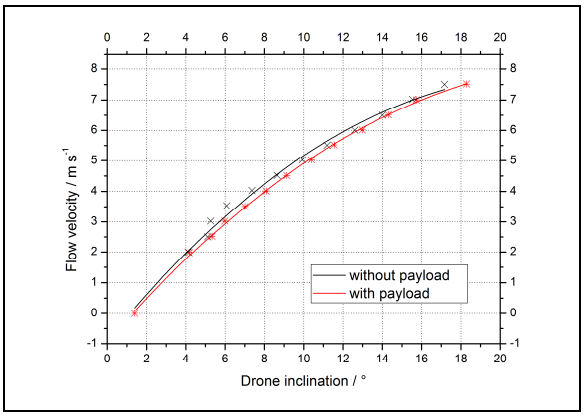

Fig. 6. Comparison between the inclination angles with and without payload

7 Literature

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