Design and Implementation of an UAV-based Platform for Air Pollution Monitoring and Source Identification ⋆

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Abstract: Air pollution has reached critical levels causing major impacts on health and economy across the globe. Environmental monitoring and control agencies, as well as industries, require a reliable, economical and easy-to-deploy tool, to assess pollution levels and on that basis, take the necessary actions. Current measurement methods using pressurized balloons, satellite imagery, or earth stations result in considerable investment, as well as providing low space-time resolution. In Monterrey, Mexico, the Integrated Environmental Monitoring System (SIMA) consisting of 10 terrestrial monitoring stations, provide online information of pollution levels through its website, however the spatial resolution is low. This research work proposes the design and development of a system for measuring atmospheric pollutants and tracking contamination sources with the use of an Unmanned Aerial Vehicle (UAV) and real-time processing by using a metaheuristic algorithm. This algorithm is based on the simulated annealing methodology to generate the UAV movement directions, in the pollution source search, by considering that it is a stochastic system. The aerial platform will allow to identify in a timely, autonomous and safe manner the sources of air pollution and the monitoring of the air quality with the advantage of providing a high space-time resolution. Early results of this project are shown such as: the design of the monitoring and tracking platform, successfully indoor/outdoor monitoring and autonomous UAV navigation experiments.

Keywords: Air pollution, Unmanned aerial vehicle, Metaheuristic, Sensors, Target tracking

1. INTRODUCTION

According the World Health Organization WHO (2016), air pollution is one of the major factors affecting health of people, leading to one in nine deaths worldwide; 92 % of the population live in areas with levels of contamination that exceed the limits set by the WHO. Short-term and long-term health risks attributed to exposure to air pollution are very critical. The issues related with air pollution are: low birth weight of children (Stieb et al., 2016), lung cancer, death from cardiovascular disease (Carugno et al., 2016), breathing problems predominantly in children (Sepúlveda, 2014); being NO_2, PM (Particulate Matter) and black carbon (BC) the highest impact pollutants (van der Zee et al., 2016).

Big cities have a high degree of pollution due to factors including: population, large sources of pollutants, geographic and meteorological conditions. In Mexico, the cities with the highest pollution are Mexico City, Guadalajara and Monterrey. Particularly, Monterrey is surrounded by mountainous elevations that constitute natural physical barriers for the circulation of the wind inhibiting the eviction of contaminants (González Santiago, 2009). In addition, with mining activities, high levels of PM contamination are maintained for most of the year at levels above recommended by WHO and the regulations in Mexico. As reported by Blanco-Jiménez S. (2015), data collected by the SIMA, of levels of environmental pollution in the Metropolitan Area of Monterrey, show that atmospheric concentrations of PM_{10} (Particulate Material of 10 μm) and $PM_{2.5}$ exceeds the values established in the Official Mexican Standard NOM-025-SSA1-2014 for air quality.

Particulate matter is one of the pollutants of greatest concern in the Metropolitan Area of Monterrey, however, no study addresses spatial and temporal variation with accurate information on sources of pollution. The SIMA

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stations are located strategically to achieve the highest efficiency in monitoring. Apart from this terrestrial monitoring platform, there is no other proposal for the measurement of atmospheric pollution in Monterrey.

Air pollution will soon be considered a priority factor in Monterrey, given the current high levels of pollution and with a growing trend. An emission control tool is imperative, which should be easily deployable and at a reasonable cost. The strategy based on install or move sophisticated pollution analysis equipment in multiple sites is not an economical option, as it requires large investments.

This work proposes the integration of an economical and easily deployable platform composed by an UAV instrumented with multiple pollution sensors, single board computer and communication devices. The platform proposed will allow the user not only to map air pollution in a certain space but also to detect concentrations in emissions from sources of pollution. The pollutant with the greatest impact in the human and environment health is particulate material, so in early stage of the project this pollutant will be analyzed first.

2. UAV FOR AIR QUALITY MONITORING

Common methods used for monitoring pollutants in the atmosphere are performed by balloons with sensors, towers (or ground stations) with sensors, manned air vehicles and satellites. In order to quantify the effects on human health and the environment, detailed information on the distribution characteristics of aerosols and the concentration of pollutant gases is required. However, the spatial and temporal resolution of data collected by ground stations, balloons, manned aircraft and satellites are relatively low and not suitable for local and regional applications. Disadvantages of common platforms have promoted the use of UAVs, which promise effective, multiobjective, flexible solutions, with low cost and high-resolution monitoring of time and space and the advantage of being deployable in hazardous environments.

Multiple applications of environmental monitoring have been developed with the use of UAVs, as is exposed by Villa et al. (2016a). So far, works of air quality monitoring using UAVs are limited to pollutant monitoring, sending data online to a ground terminal and information post-processing (Gallego et al., 2015; Alvarado et al., 2015; Cassano et al., 2016; Long, 2016). Simulations have also been carried out to trace pollution sources (Šmídl and Hofman, 2013; Egorova et al., 2015; Gatsonis et al., 2015). In addition, most of these monitoring platforms use autonomous overhead vehicles and highly sophisticated data processing systems, which entails a high implementation cost, as the vehicles used in the studies of Berman et al. (2012) and Bates et al. (2013).

Recent efforts to implement monitoring systems using UAVs show successful results. Peña et al. (2016), using mixed virtual reality, simulated a coordinated monitoring system of air pollution using a set of UAVs. The navigation of the virtual UAVs were controlled with PID and coordinated monitoring point assignments were calculated through evolutionary algorithms. Villa et al. (2016b) used a hexacopter to measure particulate matter and gases: CO, CO_2, NO and NO_2; captured data by the UAV were sent to a ground station in real time. The contribution of this work are the analysis of the optimal positioning, to perform the measurements, of the UAV with respect to a gas column emitted by a stationary or dynamic source and the adequate location of the sensors. Kersnovski et al. (2017) present a design of an UAV for the monitoring of CO_2, able to find the source of the gas autonomously within a room. The captured data were sent to a ground station in real time, where they were processed to obtain a 3D mapping of the gas concentrations; they also use a camera mounted on the UAV for the recognition of the sources. For navigation control, a Vicon camera system was used to send the UAV position information to the computer at the station, where the new position is calculated, via a PID control, and the coordinates are sent to the vehicle.

3. SYSTEM IMPLEMENTATION

The measurement of atmospheric pollutants must be done tens of meters above ground level. The platform proposed in this research apart from saving the data in a memory attached to the UAV, sends data to a terrestrial base, using the IEEE 802.11 wireless communication protocol, for maintaining a copy of the data in the terrestrial base and to display real-time trends in a Human-Machine Interface (HMI).

In early stage of the project the focus is to measure and track PMs pollutants. Future objectives of the project devise the inclusion of other sensors, such as: CO, CO_2 CH_4 and ammonia. Special considerations in the project are given to the design of the UAV and the coupling of the sensors. The captured data of the atmospheric conditions can be altered by the same presence of the UAV (by the currents of air generated by it). Also, it is important to consider how much the sensor performance, such as its latency, affects the speed at which the UAV should change the sampling position.

3.1 UAV and Sensors

A quadricopter and PM sensor have been integrated so far in the proposed platform.

Quadricopter: The use of quadricopters is common among researchers because they can perform tasks where high precision positioning in 3D spaces is required. It is also the only type of UAV that has the ability to take off and land vertically. The advantages of the quadricopter are: maneuverability, compact design, and easy control, since it is a sub-actuated system (four inputs and six control outputs).

Relevant elements of the quadricopter are: *frame*, which is the basic structure used to mount all the equipment of the aerial vehicle; the direct current motors whose capacity to transform electrical power into speed is characterized in *Kv* (Kilo volts); the flight controller, which keeps the position of the UAV stable; the motors speed controller;

and the battery on which depends the flight time and load capacity of quadricopter. The quadricopter used has the following characteristics:

- *Frame* 480 (48 *cm* wingspan)
- Motors of 1000 *Kv*
- APM Flight Controller
- Speed controller Qbrain of 25 Amperes for each motor
- 5000 *mAh* battery
- GPS and integrated telemetry
- Take-off load capacity of 2.5 *kg* (including UAV weight)
- Autonomy of 20 minutes

Fig. 1 shows the quadricopter used for monitoring and tracking air pollution.

Fig. 1. Quadricopter for air pollution tracking

The control of UAV is performed by high level processing, sending coordinates to guide the UAV navigation, through Mavlink commands.

Particulate Material Sensor: OPC-N2 (Optical Particle Counter, Alphasense Ltd series) sensor allows measurements of particulate materials of 1 μm, 2.5 μm and 10 μm, with SPI protocol communications access. The OPC-N2 classifies each particle size, at rates up to 10,000 particles per second, recording the particle size to one of 16 "bins" covering the size range from 0.38 to 17 μm. Adequate sampling times are from 1 to 10 seconds duration. Data captured by OPC-N2 sensor is recorded in particle size histograms and can be used to calculate the mass of airborne particles per unit volume of air, normally expressed as $\mu g/m^3$. Particle concentrations and derived PM values are unaffected by moderate flow variations, because such variations are monitored and corrected dynamically by the OPC.

For our purposes and considering the PM sensor specifications, sampling time of 4 seconds was established. To synchronize the OPC measurements with the monitoring and tracking system, PM data average will be used with a period defined when design of the platform is completed, according to performance experiments. To minimize the effects of the wind and the turbulence created by the propeller of the quadricopter, the OPC was placed under the UAV.

3.2 Monitoring and tracking system

Fig. 2 shows the monitoring and pollutants tracking system proposed. The quadricopter carries sensors that capture data of atmospheric pollutants and others that support UAV navigation. These data are processed in real-time through a metaheuristic algorithm and as output the system provides the navigation coordinates, which are sent to the flight controller of the quadricopter, to guide it on the search for the source of pollution. A ground control base is also available, which receives real-time data from the UAV and displays trend graphs of air pollutants.

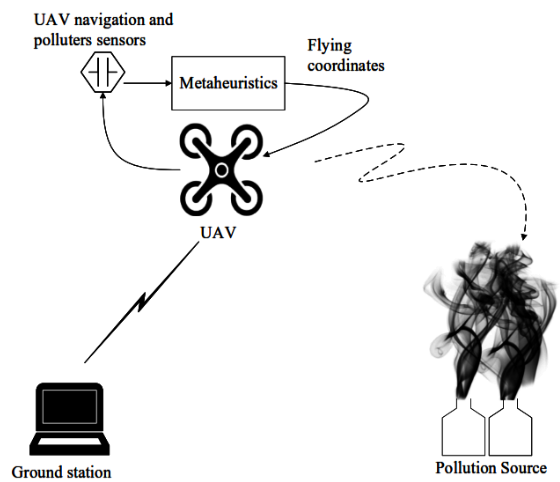

Fig. 2. Environment of monitoring and tracking pollution system

Fig. 3 shows the architecture of the proposed autonomous system. The positioning coordinates for the flight controller are transmitted through the Mavlink protocol to the flying controller of the UAV. From the ground station, through IEEE 802.11 protocol communication, parameters of the system on board the UAV, as sampling period and pollutant selection for tracking, can be set. Also, monitoring routines can be sent through RF communication. A manual remote control is also available to override the automatic control in the UAV in emergency situations. A HMI based on a web application will allow to share sampled data and tracking results on the internet. In addition, a restricted access to the control tool of the platform can be given to any device with internet connection, such as: PCs, smartphones or tablets.

Monitoring: Automatic routines were programmed to capture polluters data and send them to the ground station in real-time. Studies presented by Roldán et al. (2015) and Villa et al. (2016b) will be considered to integrate the sensors to the UAV for correct pollution measurements. In our work, raw data captured by the UAV are processed before being transmitted; outliers elimination and time stamp are performed over the raw

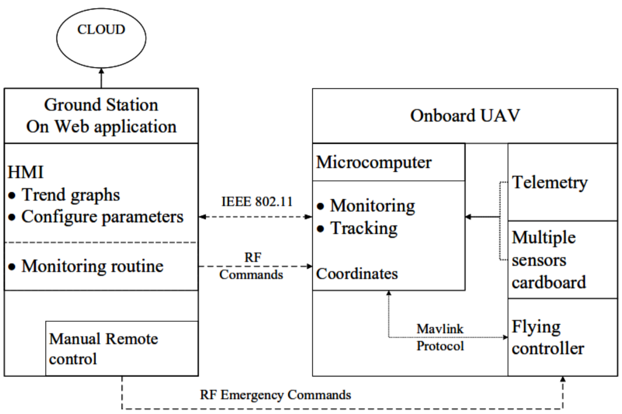

Fig. 3. Aerial platform system architecture

data which include: PM, humidity, temperature and UAV localization information. So far, only PM measurements have been tested. Project objectives include the aggregation of others sensors in a later stage: CO, CO_2, CH_4 and ammonia. Also, in the future, additional UAVs could be included to stablish a coordinated multiple UAVs platform which improve the performance of the monitoring system.

Tracking: This method must consider the stochastic component of the pollutants distribution. A tracking method based on the pollutant dispersion model, considering wind effects, has been studied and demonstrated through synthetic experiments by Šmídl and Hofman (2013). The pollutant dispersion was modeled using combinations of Gaussian functions with dynamic centers due to the effect of the wind vectors. Online adjustment of the dispersion models, resulted in high computational costs, even considering simple models, which is not suitable for our proposed low cost system.

Pollutant distribution can be considered as concentration levels of pollutants in space, whose sources constitute maximums in the dispersion function that is changing over time. Under an optimization approach, multiple intelligent algorithms can be adapted to find the maximum of the dispersion function, which represents the pollutant source, e.g. ANN, genetic algorithms and fuzzy methods.

Here we proposed a metaheuristic algorithm for tracking the pollutant, which is based on gradient ascent considering the simulated annealing methodology (Aarts et al., 2014), which is able to deal with the stochastic component of the system.

The proposed system is oriented to work over multiples sources of pollution, although only one pollutant at a time can be targeted by the system. The metaheuristic algorithm uses raw data of the pollution sensors and the UAV localization as well as historical data. As output, new position for the UAV is generated, in order that points with the highest level of contaminants concentrations are reached by the UAV.

Main steps for the tracking system are:

(1) Select pollutant to track.
(2) Get raw data of pollutants and UAV localization from sensors and GPS.
(3) Pre-processing information: mean filter from the raw data, time stamp with the UAV localization, outlier identification and elimination.
(4) Get next movement for the UAV from the metaheuristic algorithm, by using the pre-processed information and historical values from the Database (DB).
(5) Move UAV to new position and store results in data base.
(6) Go to step 1 until a stable higher threshold pollution concentration is found.

Fig. 4 shows the proposed methodology, that is explained below.

When reading the contaminant sample C_k and recovering the sample C_{k-1} from the DB, taken at times t_k and t_{k-1} respectively, the gradient is calculated as follow:

$$\Delta C = C_k - C_{k-1} \tag{1}$$

If ΔC is greater than zero, the direction of motion of the UAV is towards the contamination concentration. If it is less than zero, the UAV moves in the wrong direction, however, since the system is stochastic, there is a probability that the current direction will remain as the correct one. This probability is assigned as:

$$P(T) = e^{\Delta C/T} \tag{2}$$

where T is the current system temperature (initially assigned as T_0) which decreases at each iteration as:

$$T = T - \Delta T \tag{3}$$

where ΔT, defined experimentally, will allow the selection of alternative directions for the UAV navigation to compensate the stochastic behavior of the environment. T is always greater than zero, so if multiple increments of ΔC are detected, T is set to one. Also if multiple decrements of ΔC are detected when the movement directions of the UAV are not changing, T is set to T_0.

Under a uniform probability distribution $U(0, 1)$, a p probability is selected: if p exceeds the evaluation of P given by equation 2, the UAV returns to its previous position and selects a different direction of motion, which must be defined under a statistical model (*e.g.* Bayesian) built from historical data. From this new position the process is repeated.

As the UAV moves in the correct direction of the concentrations of the pollutant, the system temperature T is decremented by establishing less tolerance to movements in the alternative direction than the determined by the gradient ascending.

If the latest n contaminant measurements mean, μ_{nC}, exceed a defined threshold C_{th} (according to previous studies of the pollutant) it is defined that a source of contamination has been found and the process is over. Parameters T_0, ΔT, n, C_{th} will be fitted according to experimental results.

Eq. 4 shows the definition of the control signal for UAV positioning under the proposal methodology.

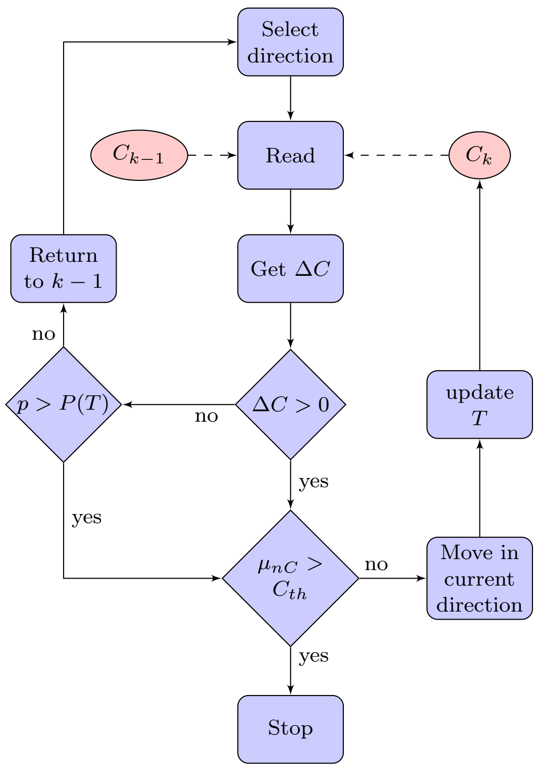

Fig. 4. Pollutant tracking algorithm

$$\overrightarrow{d}_k = \begin{cases} \overrightarrow{d}_{k-1} + r\angle(\theta_{k-1} \pm \gamma e^{-1/T}) & \text{if } \Delta C > 0 \cup p \\ \overrightarrow{d}_{k-1} - r\angle(\theta_{k-1} \pm \beta) + \overrightarrow{\Phi}_k & \text{if } \Delta C \leq 0 \cap q \end{cases} \quad (4)$$

where, $\overrightarrow{d}_k$ is the signal position for the UAV at time t_k, expressed as polar vector, $\overrightarrow{d}_{k-1} = d_{k-1}\angle\theta_{k-1}$ is the polar vector of the last position at time t_{k-1}, r is the resolution of movement for the UAV (magnitude), $\gamma e^{-1/T}$ allows small deviation (decreasing in function of T) from the last direction θ_{k-1}, being γ a positive random number, β is a small random positive angle, which produce a deviation to avoid repetitive points already visited and $\overrightarrow{\Phi}$ allows the UAV to learn directions with the highest probability of pollution concentration for select new directions of movements. Then, $\overrightarrow{d}_k$ gives the UAV position at each time t_k, according the pollutant gradient ΔC and the probabilities p and $q = 1 - p$ aforementioned.

4. RESULTS

This project is at intermediate development stage. Automatic indoor and outdoor monitoring testing have been developed so far, showing good performance. Fig. 5 shows the measures obtained by PM (black, blue, and red line for PM_{10}, $PM_{2.5}$ and PM_1 respectively) sensor integrated in the UAV, flying in a room with a controlled source of contamination. Fig. 6 shows outdoor experiments for pollutants monitoring, where the UAV follows a previously defined trajectory. Results of monitoring routines were successful since the monitoring points set by the user were reached with high resolution by the UAV.

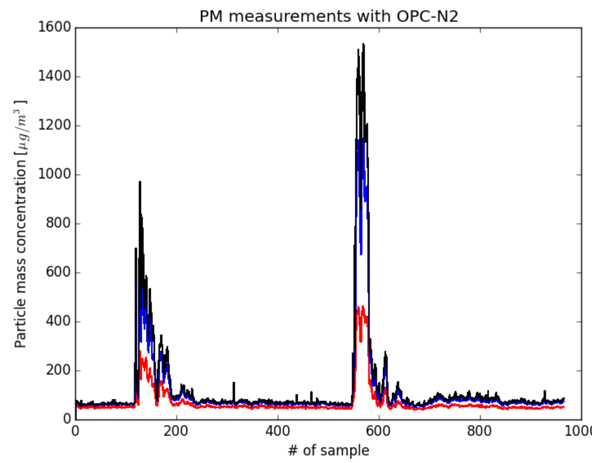

Fig. 5. PM indoor measurements

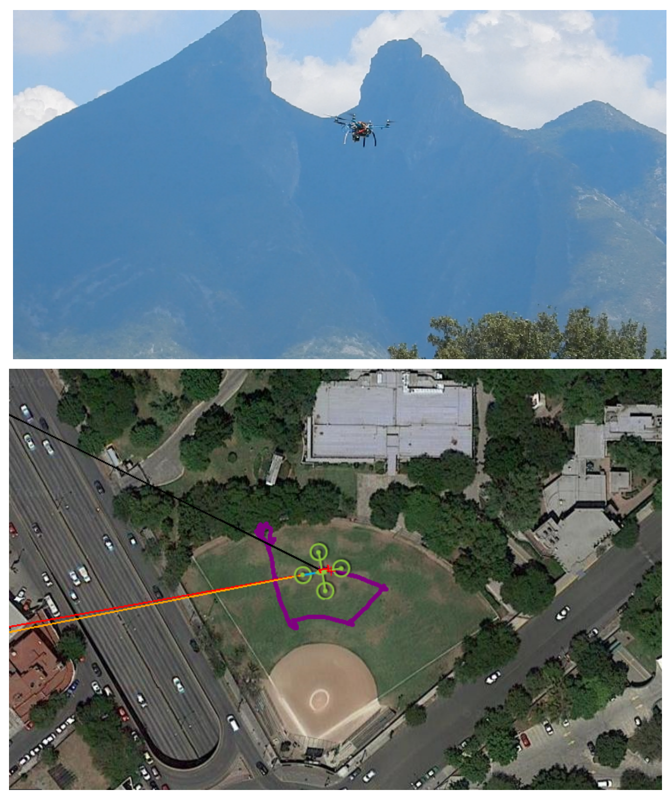

Fig. 6. UAV autonomous navigation to pollutant monitoring

Additional outdoor experiments for tracking pollutants will be developed as a part of the project in the following months.

5. CONCLUSION

The monitoring and tracking a specific contaminant, for the source identification, is addressed with a smart device that will complement the measurements of the existing platforms, such as the terrestrial stations. This aerial platform can also be used in other industrial applications, such as the detection of gas leakages in high risk environments. Additionally, the proposed design of HMI, based on a web application, will allow public access to the captured data, as well as high portability of the control tool of the platform. The work is still in a development phase, so the proposed tracking algorithm and others to be defined, will be experimented once the prototype is finished.

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