Towards the Development of a Gas Sensor System for Monitoring Pollutant Gases in the Low Troposphere Using Small Unmanned Aerial Vehicles

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Abstract— **The world is facing problems due to the effects of increased atmospheric pollution, climate change and global warming. Innovative technologies to identify, quantify and assess fluxes exchange of the pollutant gases between the Earth's surface and atmosphere are required. This paper proposes the development of a gas sensor system for a small UAV to monitor pollutant gases, collect data and geo-locate where the sample was taken. The prototype has two principal systems: a light portable gas sensor and an optional electric–solar powered UAV. The prototype will be suitable to: operate in the lower troposphere (100-500m); collect samples; stamp time and geo-locate each sample. One of the limitations of a small UAV is the limited power available therefore a small and low power consumption payload is designed and built for this research. The specific gases targeted in this research are NO_2, mostly produce by traffic, and NH_3 from farming, with concentrations above 0.05 ppm and 35 ppm respectively which are harmful to human health. The developed prototype will be a useful tool for scientists to analyse the behaviour and tendencies of pollutant gases producing more realistic models of them.**

***Keywords*— Environmental monitoring, Gas sensing, Nanotechnology, Pollutants, UAV.**

I. Introduction

Identifying, quantifying and assessing fluxes exchange of pollutant gases between the Earth's surface and atmosphere is important to have a better understanding of the problems they are causing and future tendencies [1]. Pollutant gases such as CO_2, CH_4, N_2O, N_2O, NH_3 gases are mainly responsible for climate change [2, 3], global warming and plant diseases [4, 5].

Currently, there are different technologies available in the market to measure these gases effectively at the ground level; balloons, satellites and manned airplanes are the options available at the atmospheric level. The use of satellites and manned airplanes can be complex, and expensive to run; balloons do not provide enough capability to sample at multiple locations and have limited motion and dynamics.

Consequently, it is necessary to develop a cost-effective airborne system capable of monitoring pollutant gases and geo-located samples to allow further analysis of the behavior, tendencies and harm of pollutants.

The system proposed in this research has two main components: an optional solar powered UAV and a portable gas sensor system. Solar powered UAVs is a growing technology that provides the best platform to carry the gas sensor system as it can run with renewable energy from the sun to allow uninterrupted flight during sun hours; carbon emissions are not produced; fuel and constant supervision of specialized personnel are not required [6, 7]. In 2008, Noth [6] reported 27h of uninterrupted flight with his solar powered UAV (Sky-sailor). These recent advances in this field open the possibility of an uninterrupted flight platform during sun hours to monitor the atmosphere carrying small payload (<500 *g*).

The idea of installing a gas sensor system in a UAV for environmental purposes is a growing field and several pioneering works have been developed in this area.

Berman E. et al. [8] developed a compact, lightweight atmospheric gas analyzer integrated in a UAV. The unit analyzes CH_4, CO_2 and water vapor. The analyzer was used to measure gas concentrations in flight providing measurements at altitudes as low as 10 meters and in remote locations. This integrated instrument-aircraft system allows numerous and efficient measurements of carbon dioxide, methane, and water vapor concentrations at low-altitudes and in remote or dangerous locations. Their research is part of the US National Oceanic and Atmospheric Administration (NOAA) which aim to deploy a fleet of 40 UAVs to monitor climate change [9] and create a global climatic survey network.

Astuti et al. [10, 11] installed an off the shelf CO_2 and SO_2 gas sensor system on a UAV to monitor volcanic eruptions. The UAV had a 5kg payload weight, 30 min of flight autonomy, 3 km working range, and was powered by an internal combustion engine. The author demonstrated the feasibility of mounting a gas sensor system on a UAV, but the experiment has to be conducted several times in order to verify the correlation between the measurements of interest and the emissions produced by the petrol combustion of the UAV engine. Kuroki Y. et al. [12] developed an expert system simulation program to map contaminant sources and plume calculation using a UAV as an instrument. The expert system navigated an autonomous aircraft which was launched into a virtual world to collect concentration data. This information is then used to back calculate source, strength and location as well as the wind direction.

Gonzalez et al. [13] developed a spore trap to localize potential pathogen sources over crops and plants proving the ability to spatially monitor spores and protocols to interpret their spatial distribution, Frances et al. [15] integrated a biosensor system on a UAV with a 4.5 kg payload to identify aerosolized bacteria harmful for human beings. Even though, previous research facts reveal the feasibility of placing environmental sensors on UAVs, flight autonomy is limited due to heavy gas sensing payload and fuel. As a result, the design and development of the portable gas sensor system needs to suit the payload and energy constraint of a small UAV.

Metal oxide (MOX) nanowires are the best candidates for a portable gas sensor technology. Nanotechnology has enabled the development of this type of gas sensors to be smaller, inexpensive and highly efficient in a broad range of applications [16]. Improved sensitivity is a major attraction for the use of nanosensors. Additionally, nanostructured materials minimize the time required for analytes to diffuse into or out of the sensor volume [16]. This definitely improves the time required for a sensor to raise an alarm preventing a potential disaster and reducing sampling time.

The final aim of this research is to design and develop an optional electric solar powered UAV fitted with a gas sensor system to track NO_2 and NH_3 gases in the lower atmosphere (100-500m). At this stage, a low power, light and small gas nanosensor system was designed, built and tested in the laboratory successfully. The system will represents a useful tool for scientists to monitor pollutant gases over large areas or specific locations such as a volcano; factory; bushfire or any possible source of pollutants. Additionally, the extended range of UAVs can allow sampling to be undertaken over multiple remote locations. The rest of this paper is organized as follows: (i) *system design and construction* describes the selection of the components, calibration and lab testing. (ii) *gas sensor system and UAV architecture* define the interactions of the UAV-Gas sensor system and depict the principal components; (iii) *Conclusions* summarise the results and define the research direction of the project.

II. SYSTEM DESIGN AND CONSTRUCTION

A. Gas sensor and Sensor Board Interface

The development of the gas sensors is a collaborative research between Brescia University (Italy) and QUT (Australia). The produced sensors are a thin film of WO_3:Fe (10% at) 500nm thickness, In_2O_3 and SnO_2 nanowires bundles to target NO_2 and NH_3 at first instance. The sensor response was calculated as $(R_{gas}-R_{air})/R_{air}$, shorted as ΔR/R. The response (T_{resp}) and recovery (T_{rec}) time were calculated as the time the sensor resistance/current takes to reach 90% and 63% of its final value, respectively. Among the sensor produced WO_3 based samples exhibit better response to NO_2 at 250°C with about 6 min T_{resp} and 2 min T_{rec} (Fig 1). SnO_2 and In_2O_3 were tested at different concentrations of NH_3 at 500 °C (Fig 1)

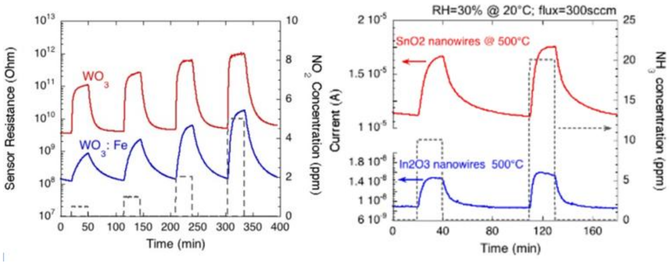

Fig 1. Dynamic response of : WO_3 to NO_2; SnO_2 and In_2O_3 to NH_3.

These sensors were made at the nanoscale because structures at this dimension show improved surface to volume ratio. Therefore, there is potential to detect a single molecule or atom resulting in enhancement in the device sensitivity in comparison with the conventional thin film technology [16]. The fundamental sensing mechanism for the resistive metal oxide based gas sensors relies on the change in their electrical conductivity due to charge transfer between surface complexes, such as O−, O_2−, H+, and OH−, and interacting molecules [17]. Normally this process requires activation energy so that MOX sensors only operate at high temperatures, generally above 200 ˚C [18-20], thus a heating system is required (Rh, Fig 2).

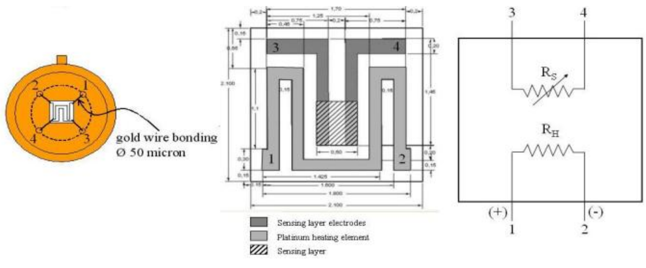

Fig 2 Metal Oxide Nanowire Gas Sensor (*Pictures from E. Comini, g.f., M. Ferroni, G. Sberveglieri, Gas sensing properties of zinc oxide nanostructures prepared by thermal evaporation. Applied Physics A, 2007. 88: p. 45-48)

The change in resistivity of the sensor can vary from 10^3 Ω to 10^9Ω depending on the gas and concentration. The Resistance-to-Time converter (RTC) circuit was implemented to easily read this huge change in resistance in a reliable, efficient and low power consumption manner, beside its low weight. The circuit is based on the oscillating circuit proposed by Depari et al. [21-23]. A oscillating voltage (V_{exc}) is applied to excite the sensor and a (100pF-1nF) capacitor (C_i) integrates the current flowing through the sensor; the capacitor works with an operational amplifier (OPA350) as an inverting integrator (Int). The sensor V_{exc} and the integrator output (V_{op}) have the same period, a falling or rising ramp depend on the sensor current direction. The timing behavior of the circuit is explained in Fig 3.

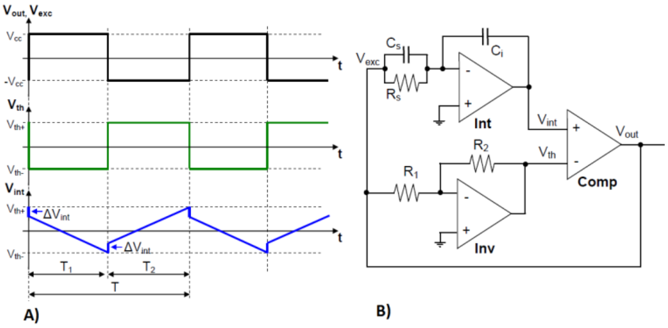

Fig 3. a) Timing diagram; b) Resistance to Period Converter circuit.

The comparator (TLC3702,Fig 3-b) compares the voltage threshold (Vth) and the ramp generating a square wave voltage signal which period is proportional to the sensor resistance (R_{sen}). The relation between the sensor resistance and the square wave period is defined in Equation 1. Finally, a microprocessor (ATMega 128) estimates the sensor resistance by means of reading the output frequency of the comparator.

$$R_{sen} = \frac{T}{4(GC_i)} \qquad (1)$$

Equation 1. Relation between sensor resistance and square signal period. T: square wave period, G: gain between R2/R1, C_i: integrator capacitor.

To calibrate the system the sensor resistance was emulated with a wide range of resistors from 479K Ω to 5G. The 12 patron resistors were measured at a 1% accuracy with a SourceMeter (KEITHLEY 2400), 25°C, 30 % humidity. The system takes three samples and the average is the final value, the highest relative standard deviation is 0.92% showing the reliability of the measurements. After, the estimated values are stored in memory to be transmitted when required. The average raw estimated values versus the nominal resistor's value revealed a maximum of 11.27% relative error especially in the low resistance region. To calibrate and improve the accuracy of the system the average raw data was processed with the Weight Least Mean Square (WLMS) method finding a new $R_{estimated}$ =1.005 *(R_{raw})-39982.4 Ω reducing the system relative error to a maximum of 3.58% (Fig 4).

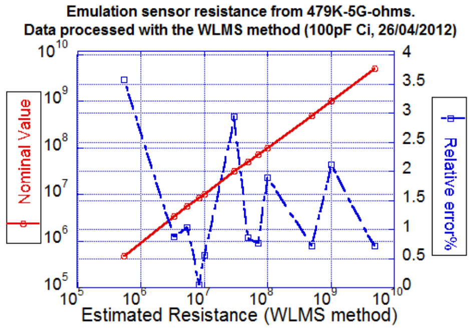

Fig 4. Nominal resistor value vs sensor board interface estimations; estimated resistance vs relative error.

B. Gas sensor system assembly

The gas sensor system has four main parts as depicted in Fig 5 (i) the gas sensor and embedded heater; (ii) the sensor board interface; (iii) the microprocessor, power and transmission board and (iv) the solenoid, pipe line and gas chamber. The battery is not listed as the instrument can use the UAV battery (6V-12V).

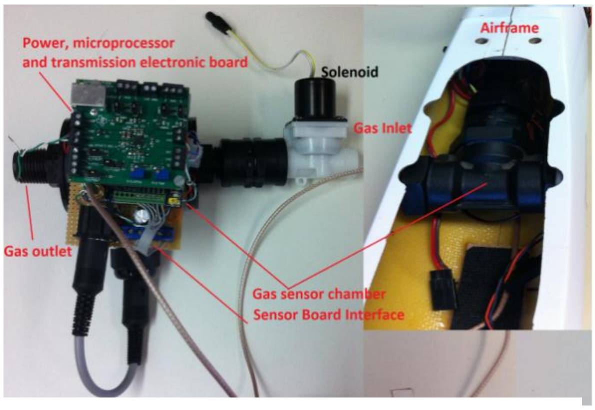

Fig 5. Gas sensor system assembly

The system requires about 800 mWH (3.3V and 6V) to run. The sensor heater is the highest power consumer due to the high temperature required (250°C). The current to the heater is accurately controlled by the microprocessor with a PWM signal and a feedback shunt resistor ensuring the delivery of the right power/temperature to the sensor. The energy system can be optimised with future production of smaller sensors using micro machinery instruments, this process is ongoing. Another way to save more energy is to highly integrate all the electronic components in just one PCB with higher efficient components. The goal is to achieve 0.5W which is the energy required by the Skysailor UAV's [6] payload. This UAV registered 27h continuous flight in 2008.

In terms of weight and volume, the first prototype is less than 400g (Fig 6) and the volume of the electronic boards is a box of 40 mm X 70 mm X 90 mm. The pneumatics system dimension is about 180mm long, 12.7mm in diameter which can fit in most of the small UAVs as a payload.

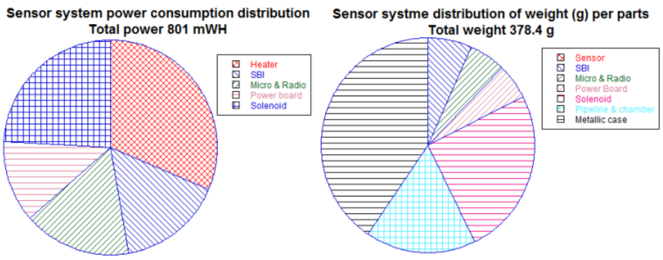

Fig 6 Gas sensor system: power and weight distribution

The system is going to be installed in an airframe 1.3m long, 3.6 m wing span, 14 aspect ratio equipped with an electric motor (Green Falcon UAV). The electronic box and the gas chamber have to be installed inside the airframe while the pneumatic system can be attached on top of the airframe to collect and release the samples. The next step is to test the system in a wind tunnel to evaluate aerodynamic and sampling performances with NO_2 and NH_3 gases at different concentrations and wind speed.

C. Gas Sensor and UAV Architecture

Once the mission is determined for the UAV [14, 24], the airplane takes off heading toward the targeted location. When the autopilot reaches the location it will send an order to the gas sensor electronics to open the solenoid valve for at least 2s which is time enough to let the gas flow through the system ensuring there is not any residue left. After then, it closes the valve to trap the sample and let the sensor temperature stabilize and prepare for measurements. The microprocessor takes three readings and averages them for the final result. Finally, the system opens again the valve ready to take the next sample (Fig 7).

D. UAV Mission

One of the main objectives of the UAV mission is to remain on flight as long as possible monitoring pollutant gases. To achieve this goal three main strategies are proposed: (i) development of a light weight/low power payload (discussed in previous sections); (ii) integration to the wings high performance/low weight solar cells; and (iii) the use of wind energy to optimize UAV path planning [24]. Solar energy is the principal energy option for an UAV as it is unlimited and available on flight. Efficiency and weight are the technological constrains of solar cells for UAV applications. To solve the problem of weight, in this research we are working towards the development of a light encapsulation using off the shelf naked solar cells (15-17% $^{\eta}$) and encapsulating them with a water clear urethane rubber, UV treated that provide enough flexibility to shape the wing, and provide 95% transparency. The results about the output power performance and mechanical properties will be published in further papers. We can also exploit wind as source of energy as this is available on flight, but is more complex to harvest than solar power [24].

III. CONCLUSION

This paper reports on the first gas nanosensor system designed and developed for a small UAV to track NO_2 and NH_3 in low atmospheres. The prototype reveals the feasibility of a low power, light and small gas sensor system built to track pollutant gases in the lower atmospheres. The system is a necessary tool for scientist to better understand and model pollutant gas behaviour and to provide verification of satellite observations. Ongoing activities focus on testing the system in a wind tunnel with gases at different concentration and wind speed are on their way. Further work will allow the UAV to test the capability of estimating atmospheric levels of NO_2 and NH_3 and interpreting the spatial distribution of the samples.

The vision of the project is to develop an uninterrupted flight platform to monitor the skies transmitting real time data to a ground platform or network.

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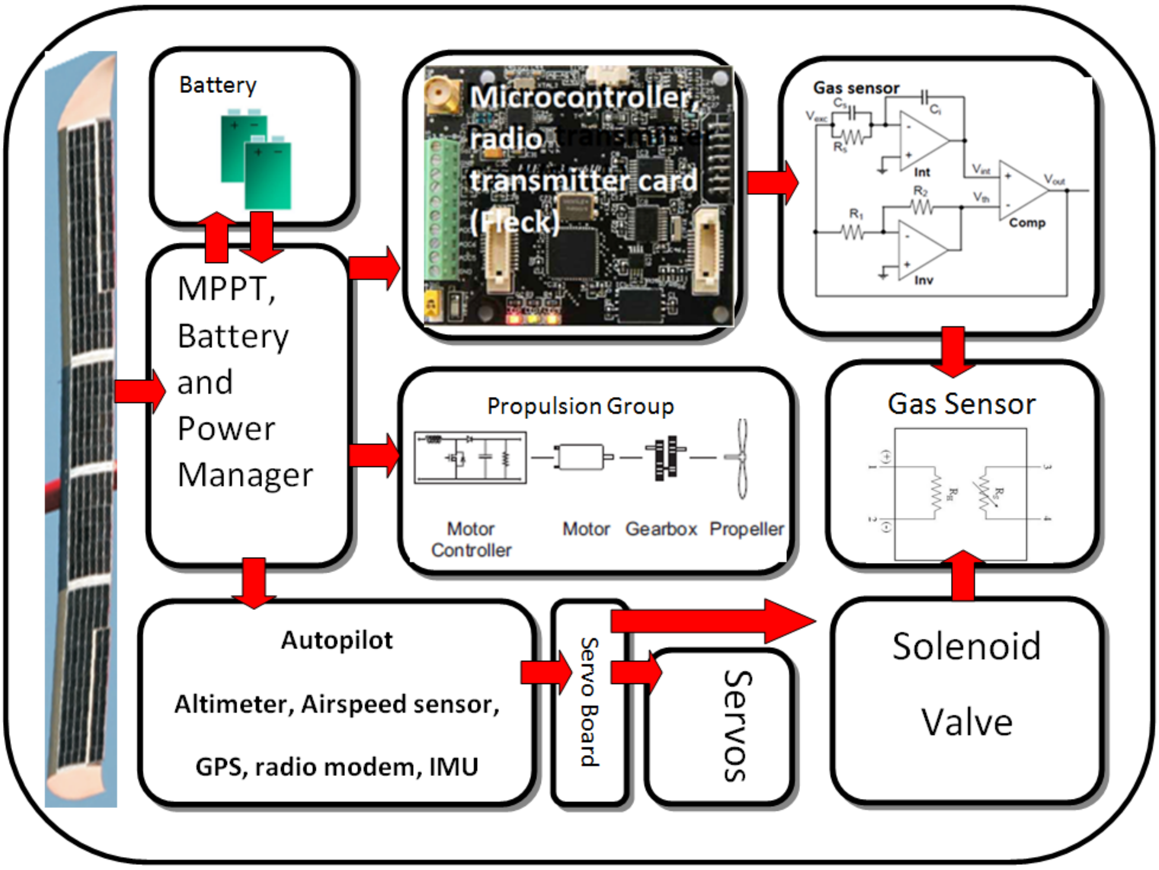

Fig 7. General UAV - Gas sensor system architecture

Table 1. Sensor resistance estimation after calibration; relative standard deviation of three samples per resistor; absolute and relative error

Nominal value	WLMS(Rs=1.005* Rraw-39982.4Ω)	Relative standard deviation	Absolute error	Relative error
4.79E+05	4.96E+05	0.89%	-17120.05	-3.58%
3.36E+06	3.33E+06	0.92%	29450.74	0.88%
5.48E+06	5.42E+06	0.47%	56577.05	1.03%
8.37E+06	8.36E+06	0.48%	4421.29	0.05%
9.97E+06	1.00E+07	0.35%	-54811.36	-0.55%
3.10E+07	3.01E+07	0.19%	910954.82	2.94%
4.99E+07	5.03E+07	0.12%	-424047.02	-0.85%
7.22E+07	7.28E+07	0.24%	-554359.05	-0.77%
9.95E+07	9.76E+07	0.01%	1883808.69	1.89%
5.00E+08	4.96E+08	0.06%	3615652.54	0.72%
1.00E+09	1.02E+09	0.03%	-21119345.04	-2.11%
5.00E+09	4.96E+09	0.03%	35785297.44	0.72%