Real-Time Measurements of Gaseous and Particulate Emissions from Livestock Buildings and Manure Stores with Novel UAV-Based System

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Abstract In the framework of the European environmental policies towards a green transition, the adoption of strategies to improve the sustainability of the agricultural system is a key element. In a perspective of adaptive farm management where a continuous monitoring process is implemented to meet the goal of environmental and economic sustainability of food productions, new tools need to be developed to provide cost-effective and real time measurements. In this context, a novel system based on Unmanned Aerial Vehicles (UAVs) and on prototypical measurement units (MU) equipped with low-cost sensors was designed and developed. The system is based on a flexible architecture, which can be adapted to a variety of operational fields. The MU is provided with a multisensor board to monitor environmental conditions, gaseous pollutants (CO_2, CH_4, NH_3) and particulate matter. A prototype version of the system was tested in a commercial dairy farm to assess its technical feasibility. In-flight and ground-based measurements were performed and cross-referenced with data collected by commercial dataloggers and colorimetric tubes. The test showed that a system integrating ground and in-flight measurements of air pollutants is feasible and could be implemented at farm level. Despite the accuracy of measurements could be improved, the test proved that average measurements of carbon dioxide over a 10 min time span can be considered as a reliable indicator of the actual CO_2 levels.

Keywords greenhouse gases · sustainable livestock farming · drones · dairy farming

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1 Introduction

Pursuing sustainable and smart agricultural systems is the trending strategy to face the upcoming challenges regarding food chain safety and integrity of ecosystems in a scenario where, by 2050, global population will grow by 22% [1] and global greenhouse gases (GHGs) emissions from the agricultural sector will be increased between 26 and 54% [2]. The European environmental policies are targeting a reduction of 55% of GHGs emissions by 2030 and aim to ensure food security in the face of climate change and biodiversity loss. Smart agriculture, in the context of Industry 4.0, is able to provide farmers a variety of tools to address food production challenges associated with farm productivity, environmental impact, food security, crop losses and sustainability [3] as well as to monitor and analyze a wide series of environmental factors. Among the most used Industry 4.0 technologies for the digitalization of agriculture are Internet of Things (IoT), wireless sensor networks, cloud computing and autonomous robotic systems as drones [3]. Their integration in agricultural and farming activities is intended to provide farmers with up-to-date decision support tools towards an improvement of the enterprise efficiency and sustainability. In particular, drones equipped with chemical sensing payloads are becoming the new frontier of real-time monitoring in a variety of fields [4]. Rotary (RW) or fixed-wing (FW) drones were employed in atmospheric chemistry research, for experimental measurements of atmospheric constituents, as CH_4, CO_2, NO_x and O_3, and of thermodynamic variables (temperature, humidity, atmospheric pressure, wind), or to investigate vertical and horizontal variations in GHGs in the atmospheric boundary layer. Additional relevant applications are related to in-flight emission monitoring in industrial activities. The monitoring of fugitive emissions in industrial sites specifically targets combustion gases (SO_2, NO_x, CO), VOCs, acid gases (HCl, HF, NH_3) or GHGs as in the case of refineries (CH_4) and waste treatment sites (CH_4, CO_2, N_2O). The use of sensing drones in precision agriculture, conversely, is still pioneering. This technology was tested in different plant production systems, to study environmental conditions in greenhouses [5] or to assess fruit maturity in orchards [6]. When coming to the applications in the field of livestock farming, knowledge and experiences are still lacking. One attempt was made to evaluate the use of methane sensing UAVs for emission quantification in a dairy farm [7]. In all cases, the restrictions in payload capacity of small drones needs lightweight and low-power sensing technologies. A current limitation to the implementation of small and low-cost UAV-based gas monitoring systems is the availability of sensors on the market with appropriate limits of detection and accuracy. Among the wide array of gas sensors, the most popular for drone-based measurements are represented by amperometric gas sensors (cheap, quite selective for some gases but slow response and recover time), metal oxide semiconductor sensors (small, less selective, faster response, durable), non-dispersive infrared sensors (less accuracy, more power consumption, more expensive), and photoionization detectors (high cost, low specificity). In this framework, the aim of this research is to develop an integrated system for ground and in-flight gas and particulate matter (PM) measurement in livestock farms, providing real-time data from low-cost sensors that could be integrated in a decision-support system helping farmers, researchers and public authorities to achieve the goals of sustainable production systems.

2 Materials and Methods

2.1 Description of the System

A system integrating ground and in-flight assessment of air pollutants by means of prototype measurement units (MU) was developed. The unit is designed to transmit data in real-time in a cloud environment and to provide their graphical representation on a web-application (Fig. 1a). The MU was developed with limited size (120 × 100 × 67 mm) and weight (0.75 kg) in order to be used both for ground measurements and to be installed as payload to medium-size drones (Fig. 1b).

The system was organized into four levels, concerning: 1) the set of commercial low-cost sensors embedded in the MU; 2) the data transmission system of the MU; 3) the cloud environment for data storage; 4) the digital dashboard for real-time data visualization.

The MU embedded in total 7 sensors selected to monitor air quality and assess environmental conditions (Table 1). Three sensors were devoted to gas sensing, specifically CO_2 (Non-Dispersive InfraRed sensor), CH_4 and NH_3 (electrochemical sensors); one sensor recorded the air concentration of particulate matter ($PM_{2.5}$, PM_{10}; optical sensor); three sensors were inserted to monitor environmental conditions: air temperature (°C), relative humidity (%) and atmospheric pressure (hPa). The MU was provided with a fan ensuring an adequate airflow inside the device.

The system for data collection, processing and transmission was composed by a Raspberry Pi® and an ESP32® board. Air quality and environmental variables measurements were both stored on board and transmitted real-time to a cloud platform

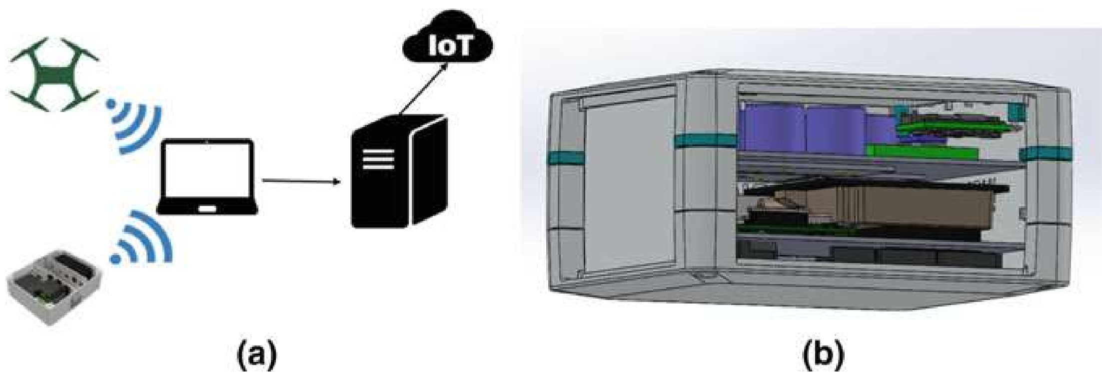

Fig. 1 **1a**, **1b**.1a: graphical representation of the system.1b: 3D design of the prototype MU

Table 1 Sensors embedded in the prototype MU: type, measurement range and accuracy (declared by manufacturer)

Measurement	Sensor type	Measurement range	Accuracy
$PM_{2.5}$,PM_{10}	Optical	0 to 999.9 $\mu g/m^3$	± 10 $\mu g/m^3$
NH_3	Electrochemical	0 to 100 ppm	± 3 ppm
CH_4	Electrochemical	0 to 10,000 ppm	± 100 ppm
CO_2	Non-dispersive infrared	400 to 10,000 ppm	± 30 ppm
Atmospheric pressure	–	300 to 1100 hPa	± 1 hPa
Temperature	–	−40 to 70 °C	± 0.1 °C
RH	–	0 to 100%	± 0.1% RH

where they could be accessed and downloaded in spreadsheet format or graphically visualized as time series plots.

2.2 *Description of the Field Test*

A technical test of the prototype system was carried out in a commercial dairy farm located in Borgo San Lorenzo, Florence, Central Italy. The dairy cattle herd was composed in total by 135 heads, with 65 lactating cows. The farm also hosted donkeys (N = 4), beef cattle (N = 12), and poultry. Lactating cows were housed in a cubicle pen inside the main building, while the other cows and youngstock were allocated in pens with deep straw bedding. Slurry was mechanically separated after being removed from the barn; the solid fraction was stored in an uncovered outdoor area while the liquid fraction was stored in an uncovered concrete tank.

The test was carried out during one day. The prototype measurement unit was deployed in 2 locations: outdoor, at an external side of the cattle barn in proximity to the uncovered slurry tank and to the solid manure storage, and inside the building in the feeding corridor (Fig. 2a). Recordings were performed for 12 min at each location, at a sampling rate of 1 record every 5 s. In total, 276 measurements were collected. In order to cross-reference measurements, simultaneous recordings of CO_2 concentration (ppm), temperature (°C) and relative humidity (%) were collected using a commercial data logger equipped with an infrared sensor (HD31 handheld data logger; HD31.B3 probe for CO_2. DeltaOhm s.r.l.). NH_3 concentration (ppm) was determined using Dräger tubes (outdoor: ammonia 0.25/a, range 0.2–3 ppm; indoor: ammonia 2/a range 2–30 ppm) coupled with Dräger-Tube pump Accuro.

The MU was then deployed as payload to a quadcopter drone (DJI® Matrice 300), with RTK positioning system, as in Fig. 2b. The unit was placed in the upper side of the UAV, to avoid the downwash in the bottom part of the drone and to minimize airflow turbulences generated by the rotors.

Measurements were recorded during a flight over the cattle barn and manure storages at an average height of 30 m a.g.l., with a total duration of 8.5 min. During

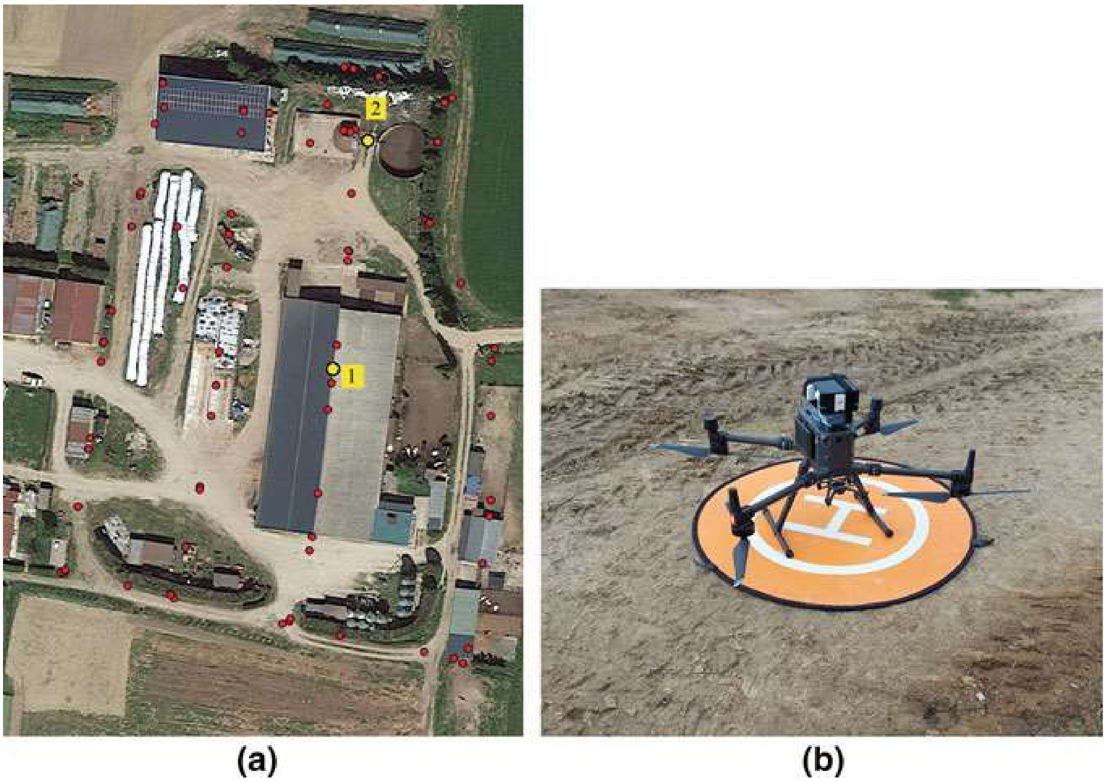

Fig. 2 **2a**, **2b**.2a: Satellite image of the study farm with location of the ground MU (1: indoor, 2: outdoor) and of the UAV sampling points. 2b: quadcopter UAV equipped with the prototype MU

the flight, the drone stopped at predefined coordinates (i.e. waypoints) and recorded air quality and environmental data. Overall, 77 recordings were collected.

Data were downloaded in a spreadsheet format. Descriptive statistics of the collected measurements were computed. Moreover, the correlation with data recorded by the commercial data logger was evaluated with Pearson correlation coefficient.

3 Results and Discussion

The technical test carried out with the prototype MU assessed the feasibility of ground and in-flight measurements. Among the whole set of sensors, 5 provided measurements in the expected range. The NH_3 sensor was not able to yield concentration measurements, since gas concentrations were under the detection limit of the sensor (1 ppm). Indeed, simultaneous measurement carried out with the tubes indicated an ammonia concentration of 0.75 ppm for indoor environment and 0 ppm for outdoor environment. The NH_3 sensor however, tested under laboratory conditions (data not published), showed good response to ammonia variations at low, medium and high concentrations. The CH_4 electrochemical sensor yielded values that were

Table 2 Descriptive statistics of indoor ground measurements (N = 141)

	Min–Max	Ave ± S.D
Temperature (°C)	28.89–30.40	29.66 ± 0.42
Relative humidity (%)	57.04–60.66	58.86 ± 0.79
Atmospheric pressure (hPa)	980.24–980.41	980.35 ± 0.04
PM_{10} (μg/m^3)	7.60–19.70	10.61 ± 2.24
$PM_{2.5}$ (μg/m^3)	2.90–5.80	3.73 ± 0.61
CO_2 (ppm)	553.00–809.00	632.73 ± 56.59
NH_3 (ppm)	below limit of detection	

Table 3 Descriptive statistics of outdoor ground measurements (N = 135)

	Min - Max	Ave ± S.D
Temperature (°C)	32.02–35.83	34.24 ± 1.24
Relative humidity (%)	46.11–55.24	50.32 ± 2.22
Atmospheric pressure (hPa)	979.79–980.05	979.91 ± 0.06
PM_{10} (μg/m^3)	5.2–11.6	7.8 ± 1.13
$PM_{2.5}$ (μg/m^3)	2.3– 3.2	2.71 ± 0.22
CO_2 (ppm)	420–439	427.8 ± 4.31
NH_3 (ppm)	below limit of detection	

not consistent with expected concentrations in a farming environment, thus results of the recordings were not shown.

Results obtained from ground and in-flight measures are reported in Table 2, Table 3 and Table 4.

Ground measures of environmental parameters (temperature, relative humidity) were comparable to those recorded by the commercial data logger (DL). MU measurements for temperature inside the barn ranged from 28.89 to 30.40 °C, with an average of 29.66 ± 0.42 °C (Table 2). Simultaneous DL measures ranged from 24.41 to 25.29 °C, with an average value of 24.74 ± 0.25 °C. Despite the bias in MU recordings, the two sets of measurements resulted highly correlated ($r_p = 0.923$). The

Table 4 Descriptive statistics of in-flight measurements with UAV (N = 77)

	Min - Max	Ave ± S.D
Temperature (°C)	27.53–28.74	28.06 ± 0.26
Relative humidity (%)	57.98–61.30	59.90 ± 0.82
Atmospheric pressure (hPa)	976.83–980.29	977.18 ± 0.75
PM_{10} (μg/m^3)	5.90–9. 80	8.12 ± 0.85
$PM_{2.5}$ (μg/m^3)	3.00–4.40	3.75 ± 0.31
CO_2 (ppm)	389.00–469.00	421.57 ± 14.87
NH_3 (ppm)	below limit of detection	

relationship also was linear, suggesting that, in indoor conditions, appropriate corrections could ensure an adequate accuracy for this parameter. In the outdoor recording session, however, correlation between MU and DL data was poor ($r_p = 0.430$). As in indoor conditions, the average measurements from MU (34.24 ± 1.24 °C) were higher respect to DL (30.74 ± 1.19 °C), the latter displaying a wider range (28.94–33.17 °C). Despite the absence of wind and direct sunlight at the time of the outdoor test, it appears that measures in external conditions may be affected by greater bias. When considering RH, an inverse tendency in measures bias appeared respect to temperature in indoor conditions. On average, MU tended to underestimate humidity (MU: 58.86 ± 0.79%; DL: 70.35 ± 0.94%), however correlation among the two sets of measures was relevant ($r_p = 0.740$). Conversely, in outdoor conditions, correlation was poor ($r_p = 0.350$), but average values resulted similar (MU: 50.32 ± 2.22%; DL: 49.32 ± 3.07%). Average carbon dioxide values inside the barn resulted comparable when measured with MU (632.73 ± 56.59 ppm) and DL (639.98 ± 36.08 ppm). However, range of measures for MU was wider than the range provided by DL (572–727 ppm). Accordingly, correlation between the two sets of measures, was poor ($r_p = 0.593$). Similarly, in outdoor conditions MU (427.8 ± 4.31 ppm) and DL (428.9 ± 7.47 ppm) provided very similar average values, but data were not correlated ($r_p = -0.06$). When examining the range of measurements in outdoor conditions, DL resulted wider (414–445 ppm).

Recordings of particulate matter showed moderate concentrations, with slightly higher values inside the barn. Feed (total mixed ration) was distributed 1 h prior the time of measurements, thus cows were feeding while the test was carried out. As expected, PM_{10} recordings showed higher values than $PM_{2.5}$, since the latter represents the fraction of PM_{10} with smaller aerodynamic diameter. As to environmental variables measured during the flight (UAV-based measurements), recordings and their variability (range, S.D.) of temperature and RH resulted similar to those collected inside the cattle building (Table 4). In addition, as expected, measurements of CO_2 concentrations highlighted lower values than those collected outside the building. Finally, fine particulate ($PM_{2.5}$) measurements displayed consistent yet slightly higher concentrations than those provided by ground measures, while the opposite occurred for PM_{10} measures. Given that surveying height is able to affect the representativeness and reliability of measurements [4], modeling gas and particulate dispersion under different wind speed and direction conditions would represent a necessary preliminary tool to assess the optimal height for UAV-based measurements.

4 Conclusions

The test carried out at the livestock farming facilities showed that a system integrating ground and in-flight measurements of air pollutants and environmental variables is feasible and could be implemented at farm level. However, the accuracy of measurements (temperature, RH, CO_2) should be improved and further tests in laboratory and field conditions are required. Nevertheless, regarding gaseous concentrations, CO_2

values provided by the MU reflected the expected values under indoor and outdoor conditions. Thus, with the current setup of the prototype MU, average measurements of carbon dioxide over a 10 min time span can be considered as a reliable indicator of the actual CO_2 levels. For ammonia and methane sensors, however, further investigation is required.

Measuring gaseous and particulate air concentrations, both at fixed points at ground and at different heights using UAVs, opens new perspectives towards their implementation within air quality dispersion models as tools to simulate the dispersion of pollutants in the bottom atmospheric boundary layer or to estimate gas emission fluxes from sources using reverse modeling.

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