Drone-based environmental odour monitoring: SNIFFDRONE

Javier Burgués[1,2], Santiago Marco[1,2], Silvia Doñate[3], María D. Esclapez[3], Laura Pastor[3,*]

[1] Signal and Information Processing for Sensing Systems, Institute for Bioengineering of Catalonia, The Barcelona Institute for Science and Technology, Baldiri Reixac 10-12, 08028, Barcelona. Spain
[2] Department of Electronics and Biomedical Engineering, University of Barcelona, Martí i Franqués 1, 08028, Barcelona. Spain.
[3] Depuración de Aguas del Mediterráneo (DAM), Avenida Benjamín Franklin, 21, 46980 Parque Tecnológico, Paterna, Valencia, Spain

*Corresponding author: laura.pastor@dam-aguas.es

ABSTRACT

Malodours produced by wastewater treatment plants (WWTPs) are an expanding concern as cities surround these facilities. Current odour assessment methodologies use costly and infrequent olfactometry measurements involving human panels, which leads to odour measurements with low temporal and spatial resolution that do not allow for proper odour management of the plant. SNIFFDRONE has developed a drone with an integrated chemical sensor array, radio-linked to a base station where machine learning algorithms predict the odour intensity from sensor readings. The system provides 3D intensity odour maps that allow managers to take appropriate control actions.

Keywords: malodours; electronic nose

1. INTRODUCTION

Odours are the main cause of pollution perception, together with dust and noise. In some neighbourhoods, they produce around 60% of air quality complaints[1]. Wastewater treatment plants (WWTPs) produce gaseous emissions that might be olfactory annoying to the surrounding population. Current odour assessment methodologies use costly and infrequent olfactometry measurements involving human panels and continuous monitoring of few gases using fixed gas detectors installed on the plant. This leads to odour measurements with low temporal and spatial resolutions that do not allow for accurate characterization of the odour emission events.

For the first time, SNIFFDRONE has developed a drone with olfaction capabilities able to provide spatially dense odour measurements and localize the source of odour nuisances in WWTPs, leading to a drastic improvement in plant management compared to current practices. This development addressed two main research challenges, namely: (i) To design an electronic system that predicts odour intensity from sensor readings in complex and time-varying odorous gas mixtures using machine learning algorithms, and (ii) To produce 3D maps of time-averaged odour distribution, despite of the well-known complexity of concentration distribution in turbulent plumes. SNIFFDRONE represents a significant leap forward in several aspects: i) up to now, odour robots have been tested towards single odorant chemical sources in relatively simple scenarios, and (ii) most research in odour robots has been based in terrestrial robots.

Currently we have a fully operative drone with an integrated hybrid electronic nose comprising 21 chemical sensors, plus temperature, humidity, and pressure sensors, in a miniature sensor chamber (**Fig. 1**). Additionally, it contains a custom sampling and pumping system to avoid downwash effects, GPS positioning, and a radio connection to a base station for real-time signal processing and data analysis. The system has been calibrated using machine learning algorithms and validated in real operation conditions through several measurement campaigns in a WWTP in Molina de Segura, Murcia, Spain.

Providing real-time odour information to managers help them to make fast decisions, pre-empting potential inconveniences. In a medium-term future, monitoring of odour emissions from a variety of sources like WWTP, landfills or composting plants, using autonomous flying robots with olfaction capabilities will largely improve plant management and it will lead to high societal impact improving drastically the quality of life of people living in proximity. In the long-term, SNIFFDRONE will encourage implementation possibilities of artificial olfaction systems in broader areas, with a strong impact in environmental monitoring.

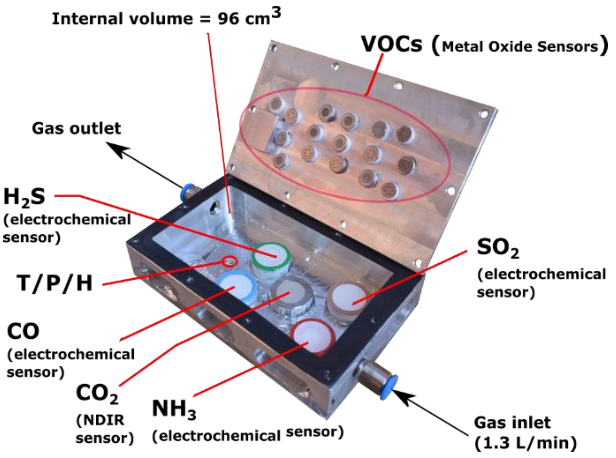

Fig. 1. Miniaturized sensor chamber hosting 21 chemical sensors, plus temperature, humidity, and pressure sensors.

2. STATE OF THE ART

Odours receive growing consideration among atmospheric pollutants. The impact of odours in close neighbourhoods depends on many factors, such odour emission rate, distance, meteorological conditions, topography, and individual sensitivity and tolerance[2]. Natural odours are complex chemical mixtures of thousands of different compounds that can trigger a human perception. The latter is produced in high neural circuits that is not easily captured by technical means. Human perception is a neural construct made based on the raw information provided by about 350 chemical receptor types present in large numbers in the olfactory epithelium[3].

Quantitative and qualitative characterization of odours can only be properly evaluated by sensorial methods involving human panels following standardized protocols (EN13725:2019 & EN16841:2016). However, this results in costly, uncertain, infrequent, and spatially sparse measurements that are insufficient for wastewater plant management. Alternative methods are based on monitoring key compounds, notably H_2S with dedicated analysers or by performing gas chromatography analysis. However, even in these cases the relationship with the perceived odour intensity can be poor.

The technical counterpart of biological olfaction is artificial olfaction, where a chemical sensor array is combined with machine learning algorithms to learn odour classes. Artificial olfaction has obtained promising results in environmental, food quality and medical applications. In fact, e-noses have been applied recently to monitor odour emission in WTTPs at fixed locations with preliminary good results[4]. Although few research groups have obtained initial results using terrestrial robots[5], experiments were limited to academic scenarios with simple operation conditions and high chemical concentrations. Today, the fast progress in drone technology has ignited new interest in flying chemical sensors. However, up to now the state of the art only reports the use of drones to monitor individual gases[6] but the prediction of odour in flying conditions has not been described yet.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

To the best of our knowledge, odour mapping and source localization using drones has not been accomplished or even attempted in realistic scenarios such as emissions in WTTPs. The difficulties are daunting: complex time-varying chemical mixtures, low concentrations of key compounds, and meteorological perturbations. Additionally, plume sensing is distorted by turbulence generated by the drone propellers.

This proposal goes beyond the state of the art in several facets:

1) ***Odour sampling for calibration in operational conditions***: The developed drone carries an electronic nose tighter with a remotely controlled sampling system operating under the lung principle according to EN13725 recommendations (**Fig. 2**). In this manner, the contents of the sampling bag are a mirror of the gas composition reaching the sensor chamber. This method allows the collection of odour bags for dynamic olfactometry (DO) (**Fig. 3**) in order to provide ground truth for the calibration of the predictive models.
2) ***Signal and data processing***: Few companies (e.g. Scentroid, Montreal) currently offer drones fitted with chemical sensors, however with the only intention of monitoring single pollutants, i.e. they do not perform proper odour sensing or any signal or data elaboration beyond data logging. Instead, our drone uses machine learning algorithms to map the sensor array pattern of response to odour intensity. The software at the base station allows the estimation of dense odour maps using interpolation algorithms.
3) ***Field experiments:*** While current research has been based on simplified exploration areas of limited size, absence of obstacles, and uniform wind conditions, this proposal includes field experiments in realistic conditions, i.e. flying over WWTPs for robot development and validation. For the first time, the complexity of this type of operating conditions is addressed. Several measurement campaigns have been carried out, including four full days of plant monitoring in diverse meteorological conditions. The drone has built-in odour prediction models able to cope with four different emission sources. Multivariate

predictive models have been validated in blind conditions on the same WWTP in a separate date.

Tab. 1. Comparison of SNIFFDRONE with state-of-the-art environmental drones

State of the art	SNIFFDRONE
Measurement of single gases	Estimation of odour intensity
Univariate calibration	Machine Learning Predictive models
Calibration in lab	Calibration in field conditions

Fig. 2. Odour-sensitive drone carrying an electronic nose and an odour sampling device.

4. PROJECT RESULTS

The first result of this project is a fully operative drone that can predict the odour intensity of ambient air samples in real-time and collect samples for post-flight laboratory analysis. Since any chemical measurement system must be calibrated under similar conditions to those expected in the operational scenario, we calibrated the e-nose using data acquired by the drone at selected emission sources of a WWTP.

Data collection

Four measurement campaigns were planned for collecting the necessary data to calibrate and validate the e-nose predictions. We focused on the four most odour-intense sources of the WWTP, namely: (a) Settlers, (b) Biological reactors, (c) Deodorisation chimney, and (d) Desander. By taking measurements at several distances from these sources, we were able to cover a large odour intensity range spanning five orders of magnitude (10 – 10^5 ou_E/m^3). A total of 42 measurements were collected in four measurement days distributed in three weeks (Table 2). Each of these samples includes the e-nose real-time measurements signals during one minute and the odour intensity estimated by DO according to EN13725.

Tab. 2. Field measurements plan. The value in each cell indicates the number of samples collected.

Day	Settler	Biolog.	Desander	Chimney	Total
1	3	3	2	2	10
2	2	2	2	2	8
3	3	3	3	3	12
4	3	3	3	3	12
Total	11	11	10	10	42

Fig. 3. Estimation of odour intensity by dynamic olfactometry. Reproduced with permission from Scentroid.

E-nose calibration and validation

The e-nose was calibrated using Partial Least Squares (PLS) regression. Data from three days was used for model calibration, and the remaining day was used for external validation. The process was repeated four times, changing the validation day. Feature selection, pre-processing and model complexity were all optimized using internal validation samples in a cross-validation (CV) scheme. Models based on four sensors, and logarithmic transformations of ***X*** (regressor matrix) and y (response vector) yielded the best results. The predictions of external validation samples (i.e. not seen during calibration) show no bias, and good correlation with DO (ρ=0.86) (**Fig. 4**). All sources are predicted with similar accuracy. The limits of acceptance (LoA), according to Bland-Altman[7], are [0.25x, 3.91x] with a 95% confidence. This is a factor of two worse than the accuracy of DO ([0.5x, 2x]). This mild degradation is more than offset by the cost reduction and the increase in spatial and temporal resolution.

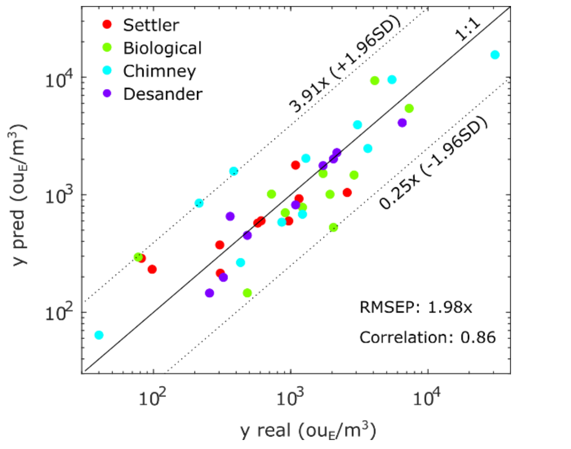

Fig. 4. Drone based odour estimation compared with Dynamic Olfactometry in external validation samples. The marker color indicates the odour source. The ideal prediction line (1:1) and the upper and lower limits of acceptance (LoA) are shown. LoA and RMSEP values are provided as factors (ratios).

Odour mapping

The drone with the calibrated e-nose performed a validation flight over the plant to map the odour intensity (Fig. 5). As expected, the highest odour emissions were concentrated on the left side of the plant, which contains the deodorisation chimney and primary treatment elements that receive the influent water, such as the stage A pre-aeration basins and the primary settlers. The right side of the plant is less odorous because it contains secondary treatment elements that treat cleaner wastewater that has been already pre-treated. The map also shows how the wind disperses the odour from the primary treatment sources to the south of the plant. These emissions will probably extend outside of the plant and can potentially reach nearby populations. Thus, this type of map is highly informative for plant managers, which can take the appropriate odour abatement measures.

5. FUTURE PROJECT VISION

The potentialities demonstrated by SNIFFDRONE preliminary prototype encourages the further development until reaching a pre-commercial stage and widening the applications to other sectors in which odour emissions have a strong impact.

5.1. Technology Scaling

In Phase 1, the preliminary prototype has been tested and validated in a relevant industrial environment, so its current development status is close to TRL 5. More validation tests are required for fine-tuning of the algorithms. ATTRACT Phase 2 will allow the technology scale up to a pre-industrial product achieving TRL 8 (system complete and qualified).

For this purpose, it will be necessary to test and demonstrate the technology in different scenarios and meteorological conditions. Our proposal is to validate the technology in at least four WWTPs, and also apply it in other areas of interest, such as composting plants, landfills, and agriculture application of sludge.

Furthermore, it is necessary to fully characterize the device and prepare it for the market uptake by: (i) definition of the product specifications (including calibration and maintenance protocols); (ii) development of a user-friendly digital platform for data logging and visualization; and (iii) establishment of general procedures and user manuals for a proper operation of the device by a technician with an appropriate training, including the definition of troubleshooting procedures.

On the other hand, for widening the potential applications, particulate matter (PM) sensors may be added to the e-nose to allow a holistic and instantaneous diagnosis of air pollution using a single device.

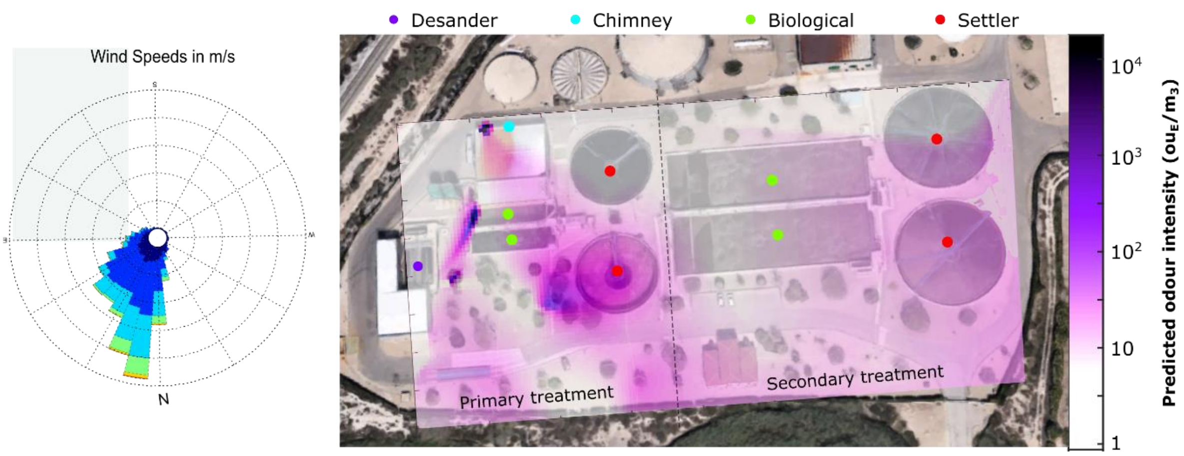

Fig. 5. Odour map produced by the drone during a survey flight. Wind was measured with an in-situ anemometer placed at 10 m a.g.l.

5.2. Project Synergies and Outreach

To achieve these ambitious goals, the Phase 2 project consortium will include new partners that can help in the serial production and standardization of the product. In this line, manufacturers of drones and chemical sensors will join the consortium. Potential end-users of the SNIFFDRONE product and key market uptake stakeholders (e.g. policymakers, civic associations, local and regional authorities, sanitation service providers, farmer associations, waste facilities managers) will be early engaged in the project to accelerate the commercialization and meet legislation requirements. Dissemination of the project results will be assured through training and educational activities including at least: participation in three conferences/events; organization of two training seminars and two innovation workshops, publication of two peer-reviewed scientific papers, and continuous promotion via online newsletters, company websites, and social networks.

5.3. Technology application and demonstration cases

SNIFFDRONE Phase 2 will demonstrate the following benefits, with a direct impact on European Societal Challenges, especially in the main areas of *Health, demographic change and wellbeing* and *Climate action, environment, resource efficiency and raw materials:*

1) ***For science:*** the first flying device able to measure odour concentration will be demonstrated in different industrial environments. This is a step forward in understanding and assessing the challenges associated to machine olfaction in field conditions.

2) ***For industry:*** the technical and economic feasibility of a drone-based odour monitoring system will be compared to existing solutions currently in use by industrial operators, allowing them to save costs and improve plant management from an odour impact point of view.

3) ***For the society:*** a proper monitoring of odour and pollutants in industrial environments will allow an early response to the processes causing the nuisances, leading to a better quality of life of the surrounding populations.

5.4. Technology commercialization

SNIFFDRONE consortium leading partner, DAM, is a large company strongly committed with the commercial exploitation of the SNIFFDRONE product, including its own resources in the cost structure of the Business Plan. DAM manages more than 300 WWTPs, and their main customers are Spanish regional public administrations and environmental authorities that have already manifested their interest in SNIFFDRONE project results.

Moreover, the kind of measurements SNIFFDRONE can provide are particularly interesting for calibrating and validating atmospheric dispersion models for odours and pollutants. Therefore, we are already exploring strategic alliances with companies that commercialize dispersion simulation tools.

Finally, we expect to get additional funding from capital investment rounds on new processes (e.g. World Water Innovation Fund), and also apply for R+D+i grants as part of bigger consortium projects, such as the EU Horizon and LIFE programmes in which DAM has proven experience.

5.5. Envisioned risks

The main risks have been identified and described as follows, taking into account those codes:

Acronyms: Impact (I), Probability (P), High (H), Medium (M), Low (L), and Contingency Plan (CP).

- E-nose calibration lifetime is short due to sensor ageing. I (M); P(H). CP: A systematic recalibration operation protocol will be defined.

- E-nose calibration models do not properly predict odour intensity beyond calibration conditions. I(M); P(M). CP: Additional calibration points will be added to improve model coverage to changing plant conditions.

- Highly specialized technicians for management of the device and interpretation of the results are required. I(M); P(L). *CP: Development of user-friendly tools, work protocols, good practices, and customer training protocols.*

5.6. Liaison with Student Teams and Socio-Economic Study

As in SNIFFDRONE Phase 1, the scientific team is strongly committed with the training of MSc. and PhD level students. PhD. Santiago Marco, full professor at the University of Barcelona, and PhD. Laura Pastor have extensive experience in university level teaching and will continue with the mentoring activities through pre-scheduled online and face-to-face meetings.

SNIFFDRONE researchers will contribute to the ATTRACT Phase 2 socio-economic study participating in interviews, providing technology impact references, identifying the main identified stakeholders, and undertaking ad hoc surveys.

6. ACKNOWLEDGEMENT

We would like to acknowledge, the Departament d'Universitats, Recerca i Societat de la Informacio de la Generalitat de Catalunya (expedient 2017 SGR 1721); the Comissionat per a Universitats i Recerca del DIUE de la Generalitat de Catalunya; and the European Social Fund (ESF). Additional financial support has been provided by the Institut de Bioenginyeria de Catalunya (IBEC). IBEC is a member of the CERCA Programme/Generalitat de Catalunya.

Authors gratefully acknowledge Entidad de Saneamiento y Depuración de Aguas Residuales de la Región de Murcia (ESAMUR) for the interest and collaboration.

This project has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222

7. REFERENCES

[1] D-NOSES consortium. (2019) Odour Pollution: A growing societal concern. D-Noses Policy Brief #1.

[2] Conti, C., Guarino, M. and Bacenetti, J. (2020) Measurements techniques and models to assess odor annoyance: A review. *Environment International*, Elsevier. **134**, 105261. https://doi.org/10.1016/j.envint.2019.105261

[3] Thomas-Danguin, T., Sinding, C., Romagny, S., El Mountassir, F., Atanasova, B., Le Berre, E. et al. (2014) The perception of odor objects in everyday life: a review on the processing of odor mixtures. *Frontiers in Psychology*, **5**, 1–18. https://doi.org/10.3389/fpsyg.2014.00504

[4] Blanco-Rodríguez, A., Camara, V.F., Campo, F., Becherán, L., Durán, A., Vieira, V.D. et al. (2018) Development of an electronic nose to characterize odours emitted from different stages in a wastewater treatment plant. *Water Research*, **134**, 92–100. https://doi.org/10.1016/j.watres.2018.01.067

[5] Monroy, J. and Gonzalez-Jimenez, J. (2018) Towards Odor-Sensitive Mobile Robots. In: Nakamoto T, editor. *Electronic Nose Technologies and Advances in Machine Olfaction*, IGI Global. p. 244–63. https://doi.org/10.4018/978-1-5225-3862-2.ch012

[6] Rohi, G., Ejofodomi, O. and Ofualagba, G. (2020) Autonomous monitoring, analysis, and countering of air pollution using environmental drones. *Heliyon*, Elsevier Ltd. **6**, e03252. https://doi.org/10.1016/j.heliyon.2020.e03252

[7] Bland, J.M. and Altman, D.G. (1999) Measuring agreement in method comparison studies. Stat. Methods Med. Res. p. 135–60. https://doi.org/10.1191/096228099673819272