DOI 10.5162/EUROSENSORS2025/W7.2.1

The Need for Fast Olfactory Sensing in Turbulent Environments

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Summary: Odour signals in natural environments are shaped by turbulence, resulting in intermittent, rapidly fluctuating plumes. These fluctuations carry essential environmental information, but are only accessible to sensors with sufficiently fast response times. Most conventional sensors are too slow, acting as low-pass filters that obscure many of the plume's informative features. Here we present a physics-informed perspective on why fast sensing is necessary in turbulent environments, and offer a combined approach of fast sensing, plume imaging, and signal processing to translate between controlled experiments and real-world deployment.

Keywords: turbulent odour plumes, high-speed gas sensing, MOx sensors, olfactory robotics

Introduction

Chemical sensing in turbulent environments is increasingly relevant for applications in agriculture, ecology, and autonomous robotics. While many of these are satisfied by static implementations of relatively slow sensors, other would benefit from more dynamic solutions.

Information in Turbulent Odour Plumes

In natural environments, airborne odour signals are transported by turbulent advection rather than smooth diffusion. Turbulence introduces structure across multiple scales, resulting in odour plumes that are intermittent and filamentous, composed of sharp concentration bursts ("bouts") interspersed with clean-air gaps ("blanks"). These features arise from the turbulent energy cascade, in which large eddies break into smaller ones, stretching and folding odour filaments across a wide range of temporal and spatial scales.

Consequentially, turbulent odour signals are neither bandlimited nor continuous. Power spectral analyses often reveal a log-log-linear decaying power-law distribution [1], indicating that significant information resides in high-frequency components. Simultaneously, odour encounters are sparse in time: bouts and inter-bout intervals follow heavy-tailed statistics [2]. This dual character—broadband and sparse—presents a unique challenge for sensing systems.

While turbulent odour plumes may appear chaotic, their statistical structure encodes meaningful spatial information. Features such as amplitude, intermittency, and encounter frequency of bouts correlate with plume dimensions and distance to source [3]. Temporal correlations between odour encounters—either at a single point or across multiple sensors—can reveal source separation or localisation cues [4].

Notably, many of these features are accessible only through fast sensing [5]. Odour concentration fluctuations can exceed $100\,\mathrm{Hz}$ [6], with exposure times down to a few milliseconds [2]. Insects, for example, exhibit olfactory receptor neuron latencies below $2\,\mathrm{ms}$ and resolve odour dynamics well beyond $100\,\mathrm{Hz}$ [7], enabling them to track fast-varying signals and perform complex tasks such as source localisation [8]. Sensors with insufficient temporal resolution fail to resolve these features. Acting as low-pass filters, they smooth rapid fluctuations into slow signals and often erase information on plume structure and source configuration.

Sensor Constraints and Implications

Photoionisation detectors (PIDs) and planar laser-induced fluorescence (PLIF) can resolve odour dynamics at millisecond timescales; however their size, power requirements, and operational complexity make them impractical for most field applications. Among compact and low-cost alternatives, metal-oxide (MOx) gas sensors are the most widely used due to their robustness, sensitivity, and ease of integration. Yet, their response and recovery times often span several seconds to minutes. While these suffice a vast range of applications, they severely constrain the operation of more dynamic solutions, in particular olfactory robotics.

Our recent work [9] demonstrates that MOx sensors, when paired with fast thermal control and high-rate acquisition, can resolve odour dynamics on millisecond timescales—unlocking a new regime of high-speed chemical sensing with compact, low-power hardware. While these results were obtained under highly controlled laboratory conditions, they offer a compelling proof of principle for extending MOx-based sensing to turbulent, real-world environments.

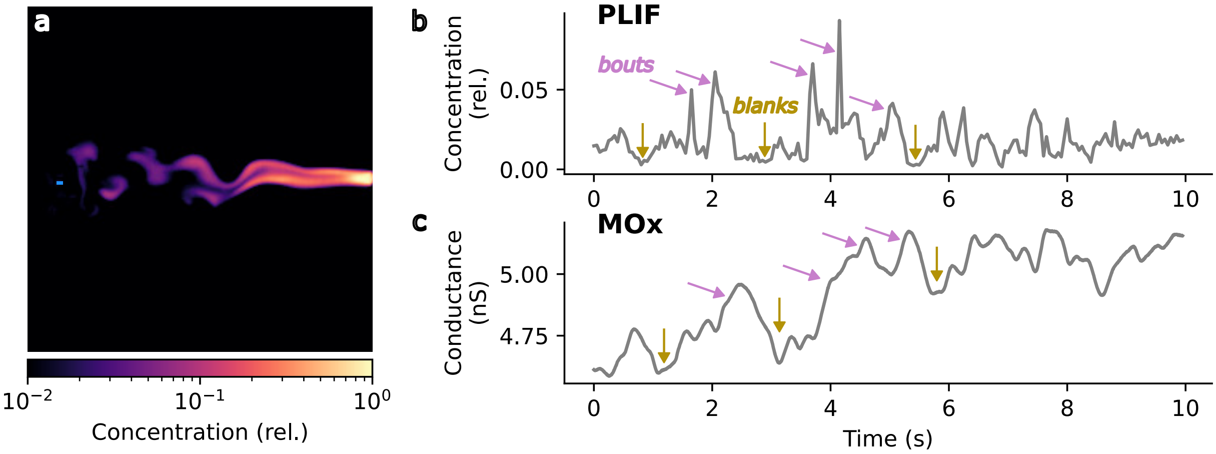

*Fig. 1: **a** Turbulent odour imaging using Planar laser induced fluorescence (PLIF). Blue rectangle denotes sensor location. **b** PLIF time series data extracted from sensor location, illustrating "bouts" and "blanks". **c** Raw MOx sensor data, co-localised and synchronised with point-source PLIF data (unpublished).*

MOx Sensors in Turbulent Environments

Achieving this transition requires not only continued optimisation of hardware, but also advanced post-processing algorithms capable of deconvolving the sensor's response [10]. For this, it is critical to use reliable and non-invasive ground-truth measurements [11].

We collected a comprehensive dataset combining high-resolution imaging with fast gas sensing. In a custom-built wind tunnel, we used a PLIF setup to visualise the turbulent transport of acetone vapour [12]. The vapour was excited using a multi-head, pulsed UV laser, and recorded with a high-speed camera, enabling spatially and temporally resolved plume imaging (see Fig. 1a&b). Simultaneously, we acquired co-localised sensor data using a high-speed e-nose [9] (see Fig. 1c). Different plume structures and flow regimes were tested, for probing the relationship between environmental signal features and sensor performance.

The direct comparison between sensor output and PLIF measurements provides an unique opportunity to evaluate the fidelity with which MOx sensors captures turbulent gas dynamics, enabling qualitative assessment and quantitative modelling of temporal filtering characteristics. Notably, even in the raw data, sub-second plume features are preserved and readily identifiable in the MOx response (see Fig. 1c). Thus, this work forms a valuable testbed for developing and validating model-based and data-driven signal reconstruction algorithms, aiming to recover true concentration signals from the sensors.

Conclusion and Outlook

We argue for a system-level approach where sensor dynamics match environmental bandwidths. Combining fast sensors with signal reconstruction methods offers a practical path toward robust chemical sensing in turbulent, real-world conditions.

Acknowledgements

N.D. acknowledges funding from the Swiss National Science Foundation (Grant SNF #10001714) and the ETHZ Postdoctoral Fellowship (Grant #25-1 FEL-031).

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