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Enhancing Selectivity Through Fast Heater Cycles with MOx Sensors

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Summary: Recent advances in MEMS-based metal-oxide (MOx) gas sensors offer new opportunities for high-speed sensing. Here we demonstrate that ultrafast heater cycling, achieved via precision hardware and feedback regulation, enables robust classification of odours on sub-second timescales. Phase-aligned feature extraction from heater-modulated sensor responses yields high classification accuracy, even for brief (20 ms) odour pulses. Beyond generic sensing, we propose that pairing this thermal modulation scheme with selectively engineered MOx films may enable compact, low-power gas sensors that combine temporal acuity with molecular selectivity.

Keywords: Fast heater cycling, MOx sensors, Odour classification, Electronic nose, Selective sensing

Introduction and Motivation

Sensing and interpreting volatile compounds in real time is critical for autonomous agents operating in complex and dynamic environments. While animals demonstrate olfactory processing on millisecond timescales [1], robotic olfactory systems based on metal-oxide (MOx) gas sensors often remain constrained by slow sensor dynamics and limited temporal resolution, rendering them suboptimal for tasks such as odour plume tracking or source localisation [2].

Recent advances in MEMS-based MOx sensor fabrication have enabled substantial reductions in thermal mass, offering the hardware foundation for faster operation [3]. However, most prior work has either relied on isothermal operation or employed slow heater modulation cycles (typically $> 1\,\mathrm{s}$), which limits the temporal fidelity of the recorded sensor response [4, 5].

Here we demonstrate a system for *ultrafast heater cycling*, achieving precise and reproducible temperature transitions on the order of tens of milliseconds [6]. We discuss that this not only improves responsiveness but also unlocks temporally structured sensor features suitable for robust and fast odour classification.

System Design for Fast-Cycled Heater Modulation

Our electronic nose system (Fig. 1a) employs MEMS-based MOx sensors, allowing for rapid thermal transitions when paired with appropriately tuned electronic control. Each sensor is coupled to an independent heater control loop, enabling dynamic temperature modulation at a resolution of $1\,\mathrm{kHz}$. Sensor resistance and heater current are sampled using simultaneous-sampling, 24-bit ADCs, while heater voltages are driven via high-linearity 12-bit DACs, minimising quantisation noise and transient artefacts [6].

We implement both *open-loop feedforward* and *adaptive closed-loop* control strategies to manage hotplate temperatures during fast cycling. A linearised model of the hotplate's thermal response is used for initial control, which is then refined by proportional correction in response to environmental perturbations such as airflow fluctuations. This hybrid control architecture maintains precise target temperatures during rapid transitions between 150 ℃ and 400 ℃, with cycle durations as short as $50\,\mathrm{ms}$ (Fig. 1b).

Signal Processing and Classification

We extract discriminative features from rapidly cycled sensor data by segmenting the sensor output into windows aligned with the heater phase. Each window captures the transient resistance trajectory as the sensor transitions between two temperature setpoints. These segments are then baseline-normalised using a prestimulus reference and log-scaled to mitigate sensor-to-sensor variability and drift effects (Fig. 1c).

The resulting features represent short, high-dimensional trajectories in sensor space that are well-suited to data-driven classification. Classifiers trained only on long pulses $(1\,\mathrm{s})$ retained high performance when tested on much shorter pulses (e.g. $20\,\mathrm{ms}$), and accuracy remained robust even down to 20% of the trained odour concentration [6]. This suggests that heater-synchronised transients encode odour identity more effectively than steady-state signals.

Further, preliminary results suggest that the resulting data features may be subsampled without substantial loss in classification performance. On the mentioned odour discrimination tasks, we observed that downsampling the phase-aligned features by a factor of five—effectively reducing the temporal resolution from $1\,\mathrm{kHz}$ to $200\,\mathrm{Hz}$—

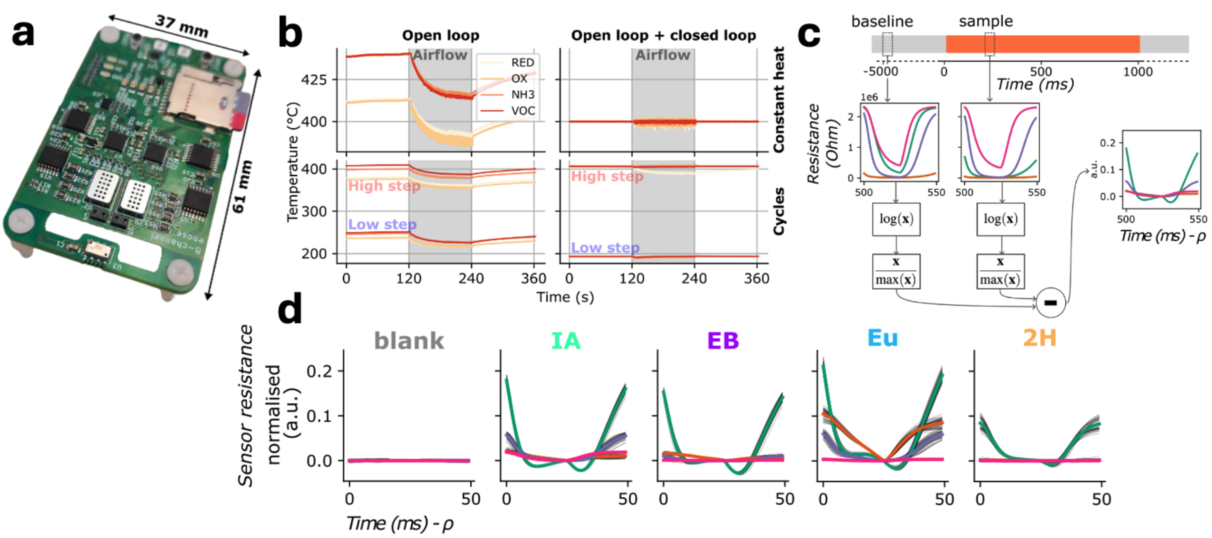

*Fig. 1: **a** Electronic nose circuitry. **b** Open-loop vs. open-loop + closed-loop control of sensor heaters, for constant heat and cycles. **c** Normalisation procedure for the heater modulation data feature. **d** Fifty-millisecond normalised data feature for different gases. Odorants abbreviations: IA, isoamyl acetate; EB, ethyl butyrate; EU, cineol; 2H, 2-heptanone; blank, odorless control. Figure panels and captions adapted from Dennler et al. [6] CC-BY.*

leads to an accuracy drop of less than one percentage point. This indicates that the most informative components of the transient response are preserved at lower sampling rates, opening possibilities for further reductions in data bandwidth, energy consumption, and computational load in embedded or low-power applications.

Extensions to Selective MOx Sensor Design

The fast cycling approach is broadly compatible with structurally and chemically tailored MOx sensing films. Selectivity enhancements achieved via nanoparticle size, film thickness, porosity, or dopant type [7, 8] could be harnessed by pairing them with rapid temperature modulation. This may enable time-resolved gas fingerprints unique to both analyte and material.

In particular, the combination of engineered film properties with heater-driven transient responses could form the basis of compact selective sensors operating at high temporal resolution—suitable for mobile or embedded deployments in robotics, environmental sensing, or health diagnostics.

Conclusion and Outlook

Fast heater cycling dramatically enhances the temporal resolution of MOx-based electronic noses, enabling robust classification of odours on sub-second timescales. Our system achieves millisecond-scale odour recognition through a combination of high-bandwidth sensor interfacing, rapid thermal control, and phase-locked feature extraction. These results demonstrate that even commercially available MOx sensors, when modulated at high speed, can rival the temporal performance previously thought exclusive to biological systems.

Looking ahead, this sensing paradigm invites new directions in sensor material design, where selective MOx films engineered for transient response can be matched with fast modulation schemes. Such integration could pave the way for compact, field-deployable systems capable of disentangling complex odour scenes with high specificity and temporal fidelity.

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