

Intelligent Sensor Systems for Energy-Efficient Monitoring of Production Processes: Lightweight Drift Compensation for Screen-Printed Ion Sensors



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Motivation

Demand for cost-efficient printed ion sensors for process monitoring¹⁻⁴

- Monitor specific ion concentrations and enable real-time decision making
- Optimize resource usage and enhance productivity
- Target domains: agriculture, water quality management, industrial processes

Frequent challenges

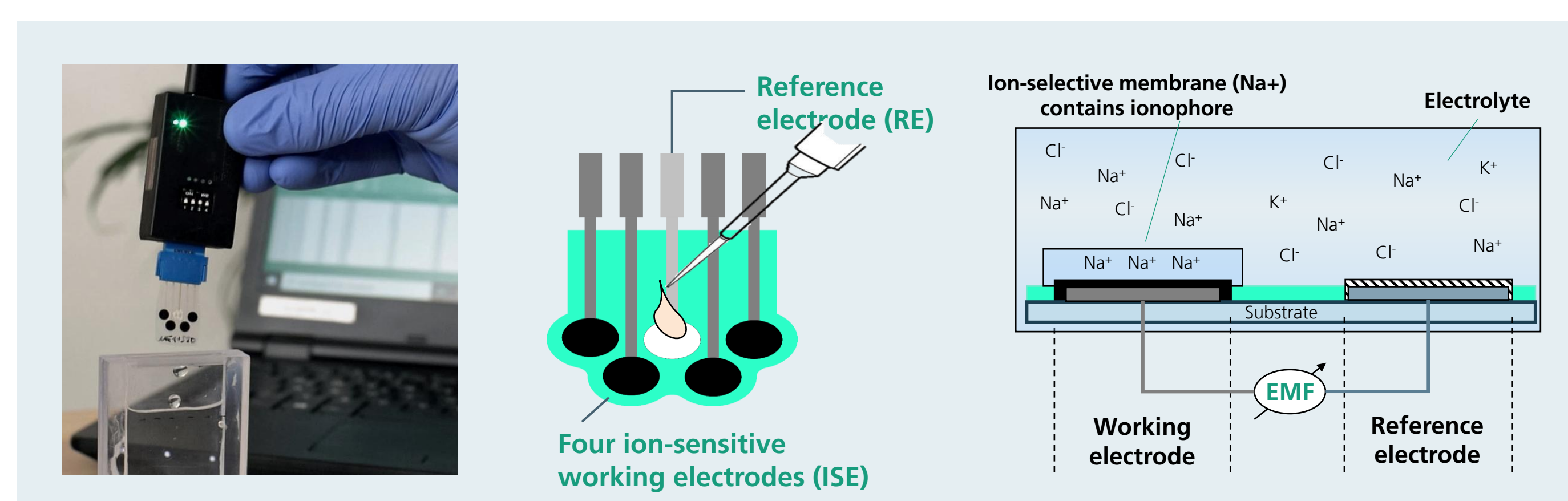
- Calibration varies between sensors
- Sensor drift leads to inaccurate readings over time

Solution approach

- Apply machine learning (ML) algorithms possibly directly on the device
- Use regression and Kalman filter for calibration and drift compensation

Printed Ion Sensors

- Four working electrodes (Ag or C), one Ag/AgCl reference electrode, polymer encapsulation manufactured by screen printing
- Ion-selective working electrode (ISE): ionophore in a polymer matrix deposited on a conductive substrate (e.g., graphite) for selective interaction with target ions (Na⁺, K⁺, Cl⁻)
- Reference electrode (RE): defined polymer matrix with stabilized electrochemical potential



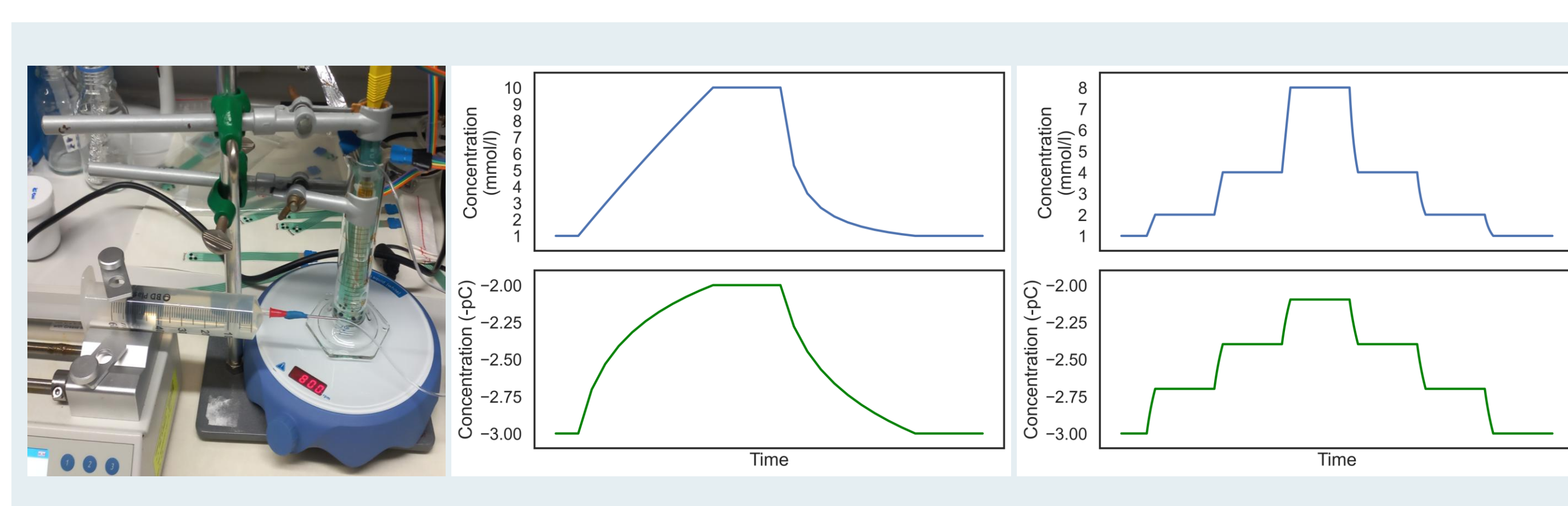
Printed ion sensors fabricated at the IISB: Setup and working principle

- Electromotive force (EMF) measured between ISE and RE with initial characterization vs. an Ag/AgCl glass reference electrode enables calculation of concentration from the Nernst equation:

$$EMF = E^0 + \frac{RT}{Fz_i} \ln a_i \approx E^0 + 2,303 \frac{RT}{Fz_i} (-pC), \text{ with } pC = -\log a_i$$

Drift Experiments

- Scenario: fertilizing a field via drip irrigation in a concentration range of 1–10 mmol/l NaCl
- Sequence: fertilization, dilution, and constant concentration (30 min per step)
- Syringe pump dispenses NaCl solution at defined flow rate and magnetic stirrer for rapid mixing



Sequence of fertilization, dilution, and constant concentration with a 30 min duration of each step

Calibration and Drift Compensation

- Obtain EMF_{measured} between the ion sensitive electrodes and the reference electrode with initial offset normalization to 0 V
- Linear regression to obtain the measured $EMF_{\text{calibrated}}$ and the concentration-related $EMF_{\text{concentration}}$ reflecting the Nernstian behavior:

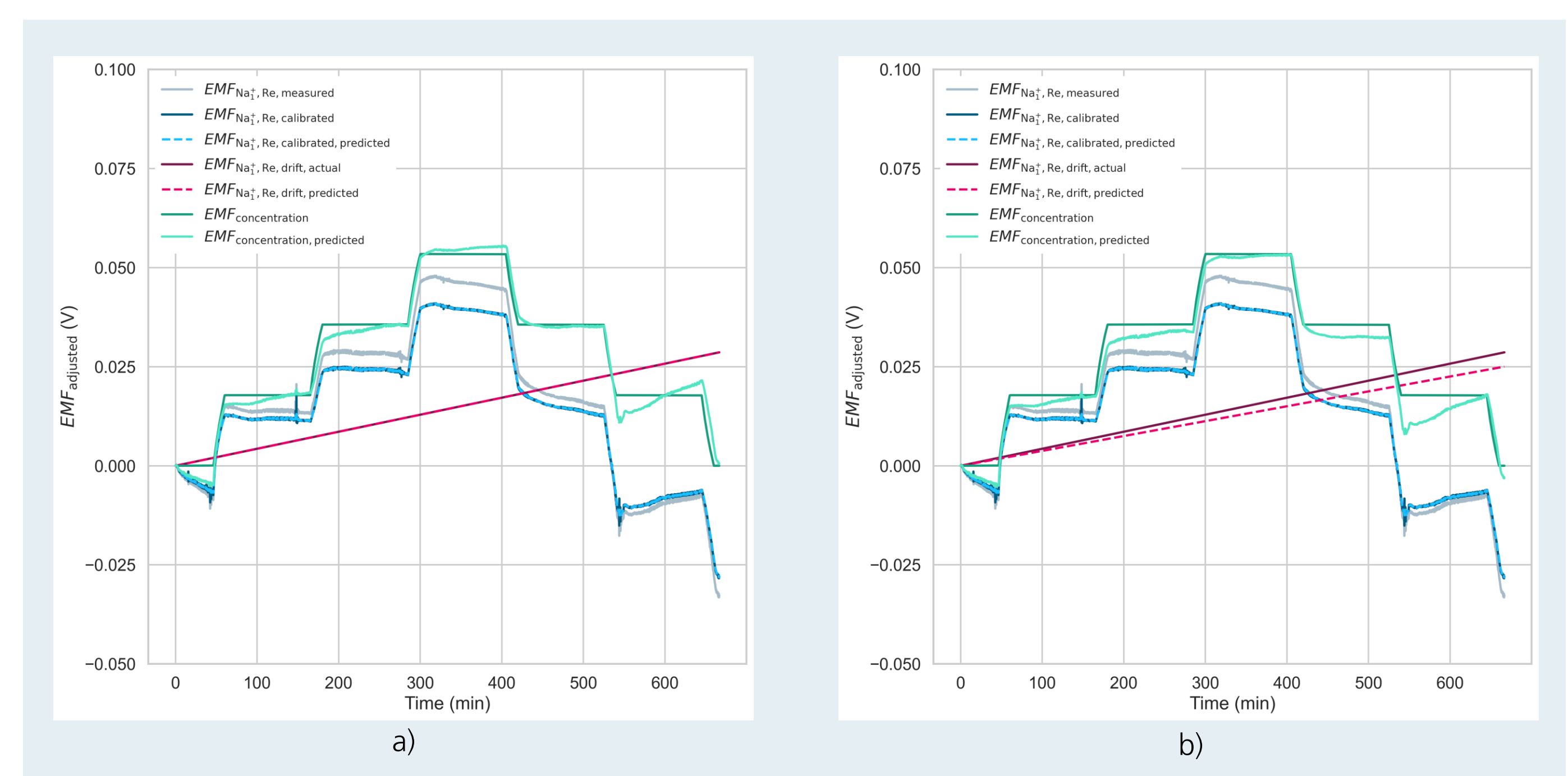
$$EMF_{\text{concentration}} = a \cdot EMF_{\text{measured}} + b \cdot t + \varepsilon = EMF_{\text{calibrated}} + EMF_{\text{drift}} + \varepsilon$$

- Kalman filter to estimate $EMF_{\text{concentration}}$ from the characterized drift of a single sensor or characterized over multiple sensors with $EMF_{\text{calibrated}}$ as the measured property:

$$\begin{bmatrix} EMF_{\text{calibrated},k} \\ EMF_{\text{concentration},k} \\ EMF_{\text{drift},k} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} EMF_{\text{calibrated},k-1} \\ EMF_{\text{concentration},k-1} \\ EMF_{\text{drift},k-1} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & b \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + \mathbf{w}_k$$

Results and Discussion

- Kalman filtering enables real-time drift compensation
 - Exact b yields accurate $EMF_{\text{concentration}}$ and drift reconstruction
 - Average b preserves $EMF_{\text{concentration}}$ with sensor-dependent deviations



Reconstruction of the concentration profile: Predicted $EMF_{\text{calibrated}}$, EMF_{drift} , and $EMF_{\text{concentration}}$ for one representative sensor and experiment. Results assume either sensor-specific (a) or averaged drift coefficients (b).

- The assessed ion-sensor system with measurement electronics and an ML-based calibration and drift compensation module exhibits low computational complexity and energy demand (< 1 kWh over 10 years)
- Future improvements should target more reproducible potentiometric sensors to address inter-sensor variability and concurrent drift mechanisms⁵ (e.g., water immersion), and extension of sensor dynamics characterization

Summary

Lightweight ML techniques (regression and Kalman filter) compensate drift in cost-efficient, screen-printed ion sensors:

- Enable real-time calibration and drift correction on edge hardware
- Improve accuracy with low computational and energy demand
- Support scalable sensing for agriculture, water quality, and industrial monitoring

Acknowledgment

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³ D. Song, C. Mao, C. Jiang, R. Liang, and G. Lisak, "Printed potentiometric sensors," *TrAC Trends Anal. Chem.*, vol. 192, Art. 118420, 2025.
⁴ A. M. Al-Amri, "Printed Sensors for Environmental Monitoring: Advancements, Challenges, and Future Directions," *Chemosensors*, vol. 13, no. 8, p. 285, 2025.
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