Sicherheit in Technik und Chemie

Bundesanstalt für Materialforschung und -prüfung

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TUTORIAL 4

Chemical and Environmental Sensing with Aerial Robots

Concepts, Constraints, and Applications

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Tutorial Roadmap

What to Expect in the Next 60 Minutes:

Block A
Motivation & Basics
Why is ARO difficult?

Block B
Gas Sensing Principles
In-situ vs. open-path — what can we measure?

Block C
Platform & Constraints
What limits real systems?

Block D
Experiments & Pitfalls
Why naive approaches fail

Block E
Plume-aware Localization
How to find the source

Block F
Wrap-up & Discussion
Key rules + Q&A

Block A

Motivation, ARO/MRO Basics, Tasks, Constraints

“We know what we want to measure.
But physics decides what we can observe.”

Motivation – **Air Pollution**

~7,000,000
premature deaths/year caused by air pollution (WHO)

80×
more potent than CO_2 CH_4 over 20 years

→ Industrial, urban, and disaster scenarios are full of hidden or inaccessible sources

→ Our environment has **"blind spots"** — and we are only beginning to see them

Fixed Monitoring Networks
Necessary — but Not Sufficient

- **Stationary monitoring networks:** sparse and expensive
  - » **Berlin (BLUME):** 17 stations / ~4 M people
  - » **Globally:**
    - ○ **> 60%** of countries lack PM2.5 monitoring
    - ○ Avg. distance to nearest station: **~220 km**
- **Hotspots between stations remain undetected**
- **Static infrastructure cannot follow dynamic sources or emergency scenarios** (e.g., fires, leaks, accidents, traffic)

Picture: SenMVKU

[Martin et al., 2019]

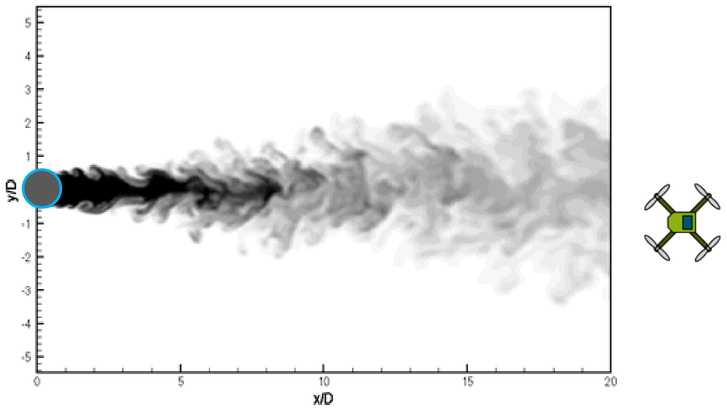
Mobile Robot Olfaction (MRO)

A Promising Technique to Sense the Air

"Smelling Robot"

Mobile Robot Olfaction
Tasks & Challenges

- **Core Tasks**
  - » Odor discrimination and concentration estimation
  - » Trail guidance
  - » **Gas distribution** modeling/**mapping**
  - » **Gas source localization (Block E)**
- **Key Challenges**
  - » Sensor limitations (drift, selectivity, sensitivity)
  - » Complex gas diffusion patterns
  - » Constantly changing wind flows



"Higher concentration does not reliably mean closer to the source."

Why Aerial Robot Olfaction (ARO) is **Fundamentally Difficult**

- **Platform constraints**
  - » Payload limits restrict sensor choice
  - » Flight time limits mission length
- **Physical effect**
  - » Rotors actively disturb and dilute the local gas distribution
- **Open design question:**
  - » Where do you place the sensor? **(Block D)**

Block B

Gas sensing principles: MOX/in-situ und TDLAS/open-path

Gas Sensor Technology
A Quick Overview

From canaries (1911–1986) to modern sensors:

Relevant for ARO:

- **In-Situ (MOX)** → local, lightweight, cheap
- **Open-path (TDLAS)** → remote, selective, expensive

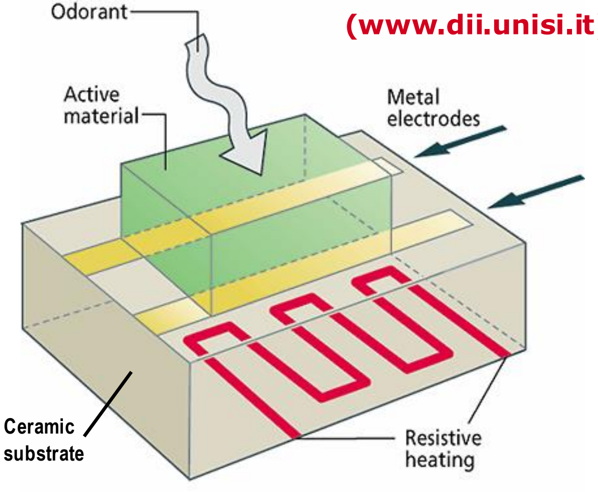
- **Other technologies** (EC, catalytic, IR, QCM…)
  - » Specific limitations in response time, selectivity, or robustness for UAV field use

- **Analytical equipment (GC, MS)**
  - » Gold standard — miniaturized UAV systems emerging, but not yet practical for routine deployment

[Dräger 2008]

MOX Sensors
How They Work

- **Gas molecules adsorb on the sensor surface**
  - » changes electrical resistance of the metal oxide
- **Operating temperature: 300–550°C** (heater built into the sensor)
- **Different gases → different resistance patterns**
  - » selectivity via surface doping or
  - » temperature modulation



(www.dii.unisi.it)

MOX Sensors
Pros and Cons

Advantages
- Lightweight & compact
- Inexpensive
- Commercially available
- Relatively quick response
- Highly sensitive

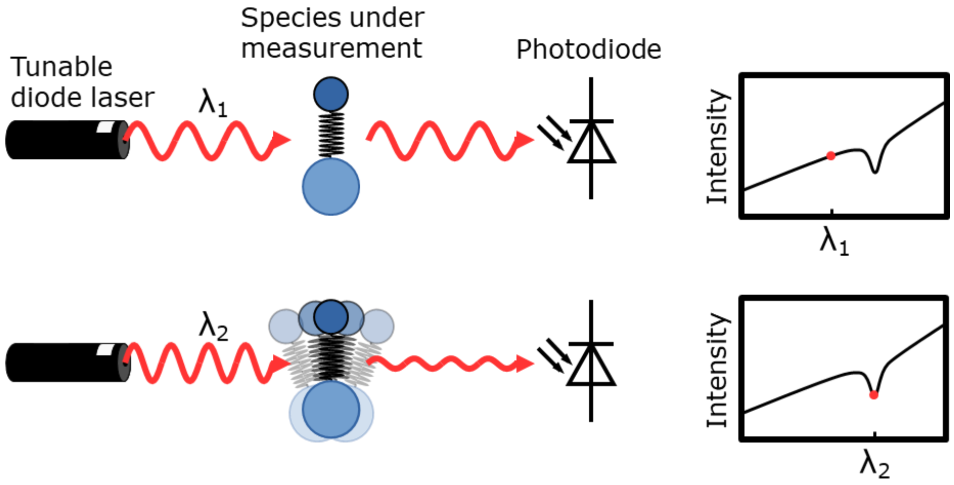
Figaro 2620 – Alcohol / solvent vapor sensor

Disadvantages
- » Poor selectivity
- » Cross-sensitive to temperature and humidity
- » Point measurement only (sensor surface ≈ 1 cm²)
- » High power consumption (due to operating temperature)
- ❖ Slow sensor recovery (~15–70 s)
- ❖ Long-term drift
- ❖ Requires warm-up before use

❖ = particularly critical for ARO

Open-Path Gas Sensing
The Principle

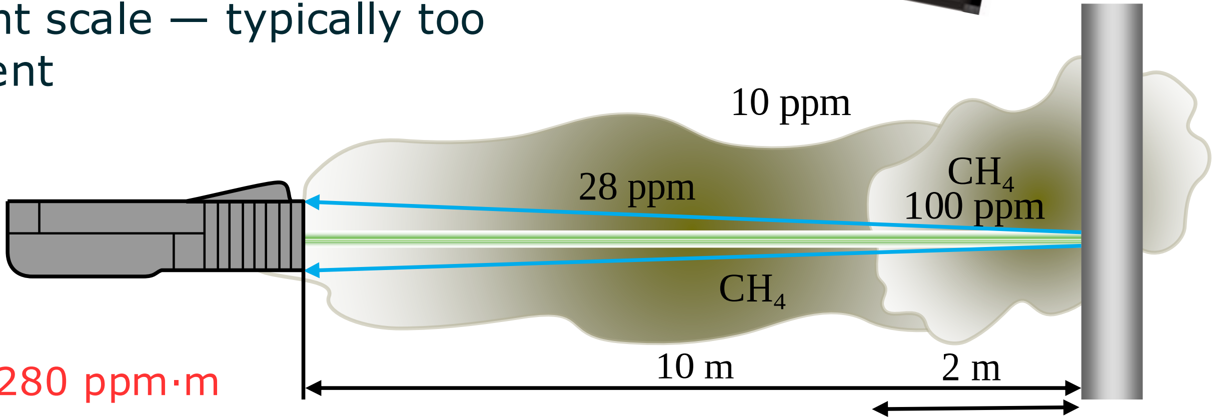
- Light travels through air
- Target gas absorbs light at specific wavelengths
- Absorption → concentration **(Lambert-Beer law)**



Open-Path Gas Sensing
Tunable Diode Laser Absorption Spectroscopy

Relevant systems for ARO
- » TDLAS (Tunable Diode Laser Absorption Spectroscopy)
  - measures along a laser beam
  - integral measurement: concentration × path length [ppm·m]
  - same result regardless of gas distribution along the beam

Other systems (DIAL, DOAS)
- » Same principle, different scale — typically too large for UAV deployment



Measurement: 280 ppm·m

TDLAS Sensors
Pros and Cons

Advantages

- Direct physical measurement — real spectroscopy
- High selectivity, no cross-sensitivity
- Fast response (0.1 s)
- Highly sensitive
- Reference cell enables intrinsic calibration
- No rotor interference — sensor does not need to enter the plume

Disadvantages

- Integral measurement — no spatial resolution along beam
- No range information
- ❖ Very expensive (~15 k€)
- ❖ Heavier than MOX
- ❖ Performance limited by reflections and scattering

❖ = **particularly critical for ARO**

In-Situ vs. Open-Path
What to Choose for ARO?

	MOX / In-Situ	TDLAS / Open-Path
Weight	✓ **Very light**	✗ **Heavy**
Cost	✓ **Cheap**	✗ **Expensive (~15k€)**
Selectivity	✗ **Poor**	✓ **High**
Affected by rotor downwash	✗ **Critical**	✓ **Not affected**
Calibration	✗ **Difficult**	✓ **Self-calibrating**
Response time	~ Seconds	✓ **0.1 s**
Drift	✗ **significant**	✓ **minimal**
Sensing mode	Point	Integral (ppm·m)
Best for	Small drones, swarms, indoor	Larger UAVs, outdoor leak detection

Which Setup Would You Choose?

In-Situ or Open-Path? Single Drone or Swarm?

Scenario A
Pipeline Inspection
- Large open area, several km to cover
- Target gas: methane
- Outdoor, variable wind

Scenario B
IAQ Monitoring
- Factory hall, multiple possible sources
- Unknown VOCs
- Confined space, low ceiling

Scenario C
Emergency Response
- Hazardous goods accident
- Unknown gas, high concentrations possible
- Rapid deployment needed

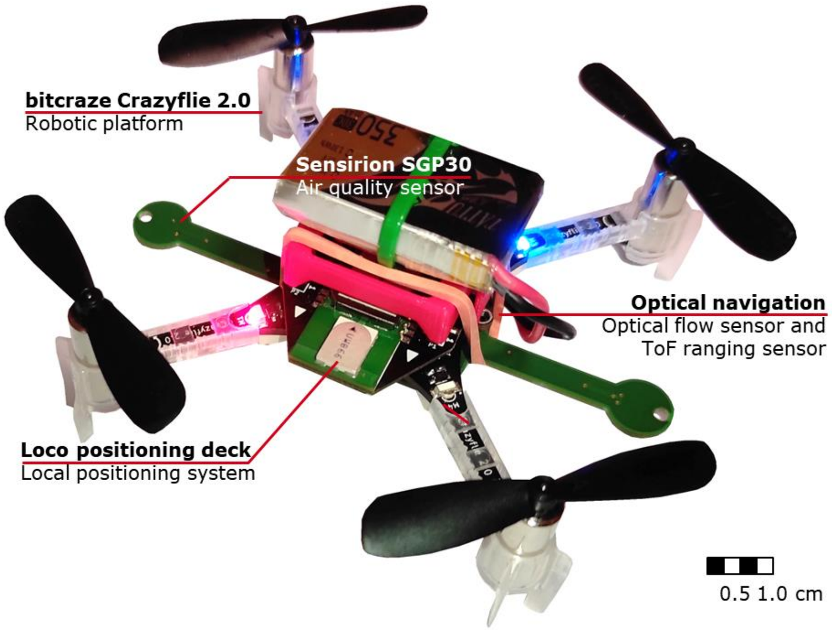
Block C

Platform Integration & Constraints
Example: Nano-Drones

"You've chosen your sensor.
Now put it on a drone — and
see what happens."

The Platform
Bitcraze Crazyflie 2.0

- **Key Specs**
  - » Takeoff weight: max. 42 g **(35.6 g)**
  - » Available payload: 15 g
  - » Diameter: < 0.1 m
  - » Flight time: ≤ 6 min
  - » Indoor positioning via UWB anchor system
  - » Designed for swarm operation
- **ARO Implications**
  - ❖ 15 g payload
    - → ultra-lightweight sensors only
  - ❖ 6 min flight time
    - → mission planning critical



The Sensor Payload
MOX-based IAQ Sensors

- **Why IAQ sensors for the Crazyflie?**
  - » Size: < 2.5 × 2.5 mm^2
  - » Weight: < 1 g
  - » Response time: a few seconds
  - » Measures VOCs — relevant for many industrial and indoor scenarios

Example: Sensirion SGP30

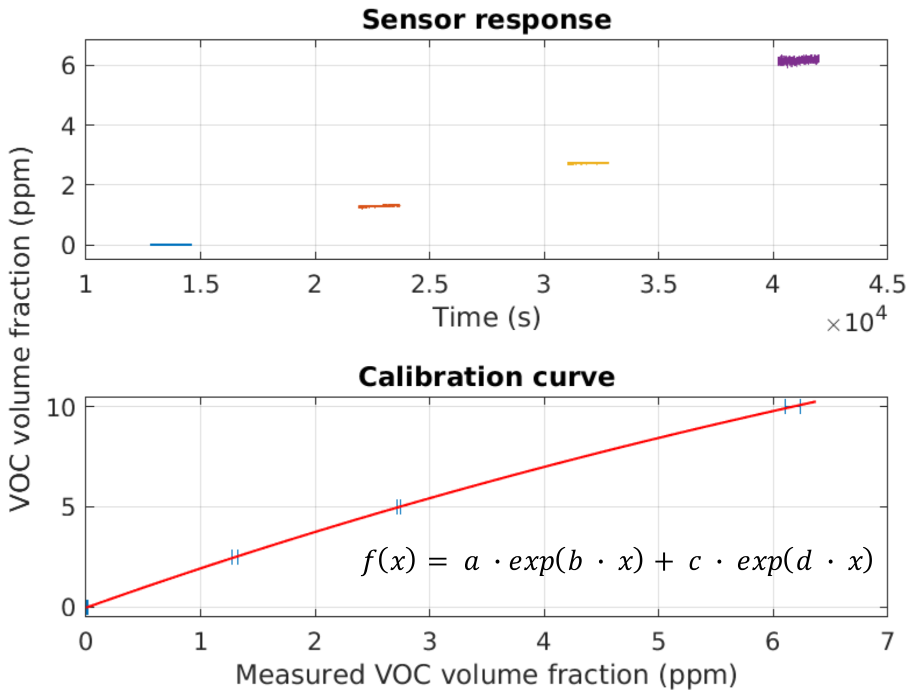
- » MOX-based, integrated T/H compensation
- » Outputs: TVOC [ppb], CO_2-equivalent [ppm]
- ❖ **Trade-off:** low selectivity, sensitive to environmental conditions

MOX-based IAQ sensor modules incl. breakout boards(from left to right): AMS CCS811, SGX MiCS-5524,Sensirion SGP30

Sensor Calibration
How It Works And Why It Matters

- **Goal**
  - » Common baseline for all sensors in the swarm
- **Calibration chamber (30 L)**
  - » Gas mixing system — defined ethanol concentrations
  - » All sensors exposed under identical conditions

❖ **Limitation:**
  - » Lab ≠ field (T, RH, mixed VOCs)
  - » Long-term drift → periodic re-calibration required



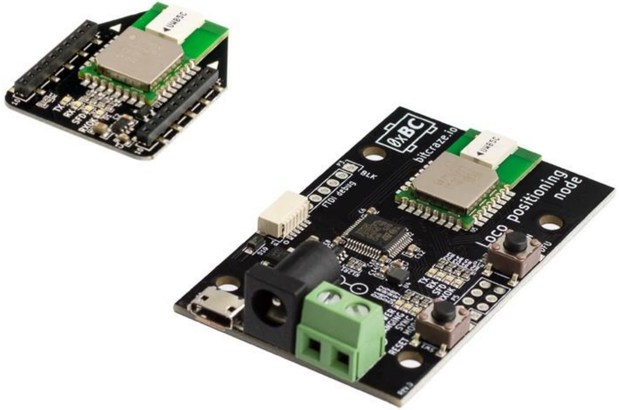
[Neumann et al., ISOEN 2019]

Localization

No Map Without Position

- **Why it matters for ARO**
  - » Gas measurement without position = useless data
  - » Every measurement needs a precise spatial reference
- **Loco Positioning System (LPS):**
  - » UWB-based — like GPS, but indoors
  - » Accuracy: up to ~0.1 m
  - » 8 anchor nodes define the search space
  - » Tag on drone calculates 3D position from time difference of arrival (TDoA)

❖ **Performance depends on anchor placement and environment geometry**



Loco Positioning Deck / tag (left) and Loco Positioning Node / anchor node (right), source: Bitcraze

Block D

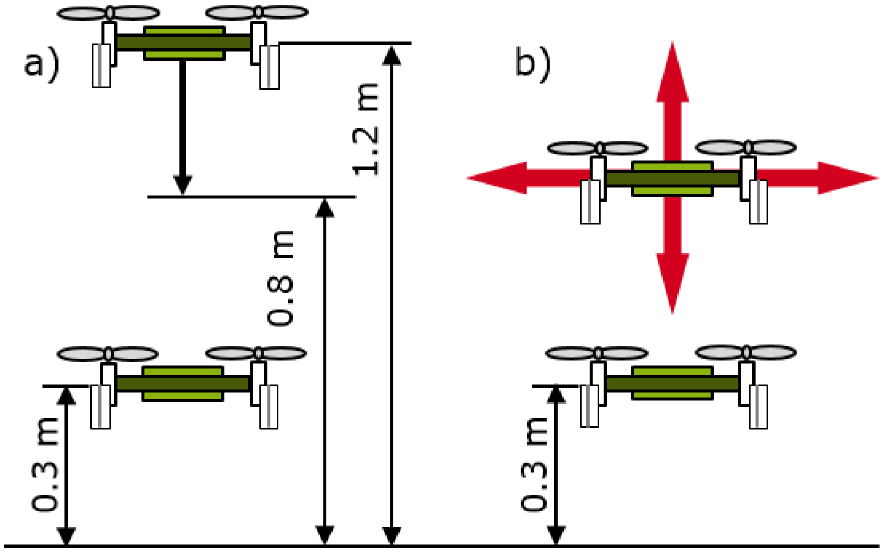
Experiments & Pitfalls

*"We know the constraints.
Now let's see what happens
when we actually fly."*

Rotor Downwash Impact

How Close is Too Close?

- **Research question:**
  - » How does the rotor downwash of one nano-UAV affect the flight stability of another flying below?
- **Experimental setup:**
  - » Two Crazyflies — one hovering, one descending
  - » Vertical and horizontal distance systematically varied
  - » Flight stability measured as combined std. deviation of position (σ_{xyz})



[Neumann et al., Mat. Today 2020]

Rotor Downwash Impact
Results

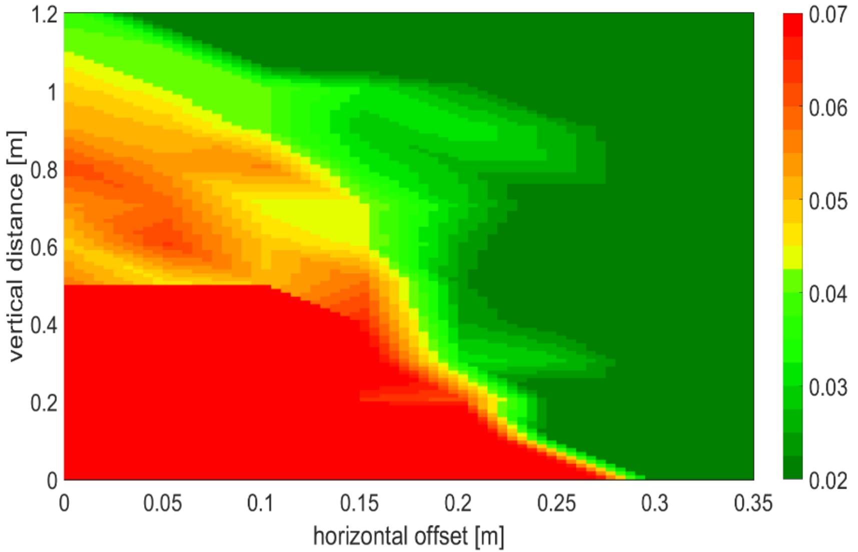
Three zones identified:

- **Safe:** $\sigma_{xyz} < 0.045$ m — no significant impact
- **Critical:** $\sigma_{xyz} < 0.07$ m — noticeable disturbance
- **Unsafe:** $\sigma_{xyz} \geq 0.07$ m — crash risk

Key result:

⚠ Minimum vertical distance: 0.5 m

→ **Direct implication:** swarm trajectories must respect this safety region at all times

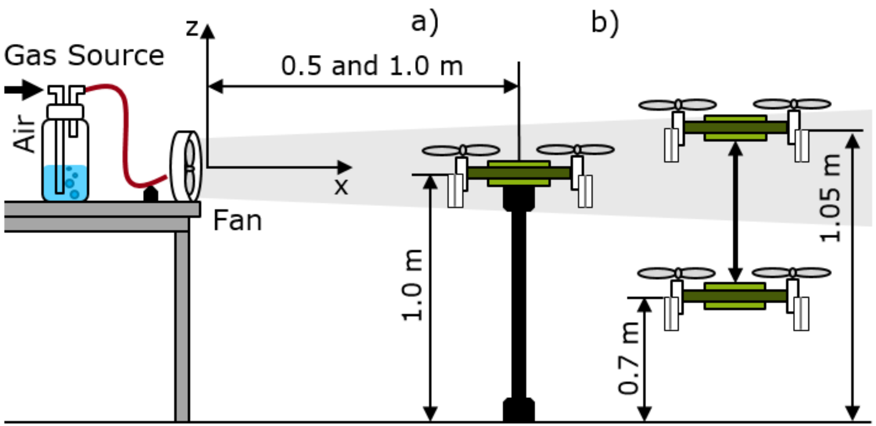


2D Map of the combined standard deviation σ_{xyz} of the hovering copter CF1 in [m].

[Neumann et al., Mat. Today 2020]

Odor Detection
Free-Flying vs Static Drone

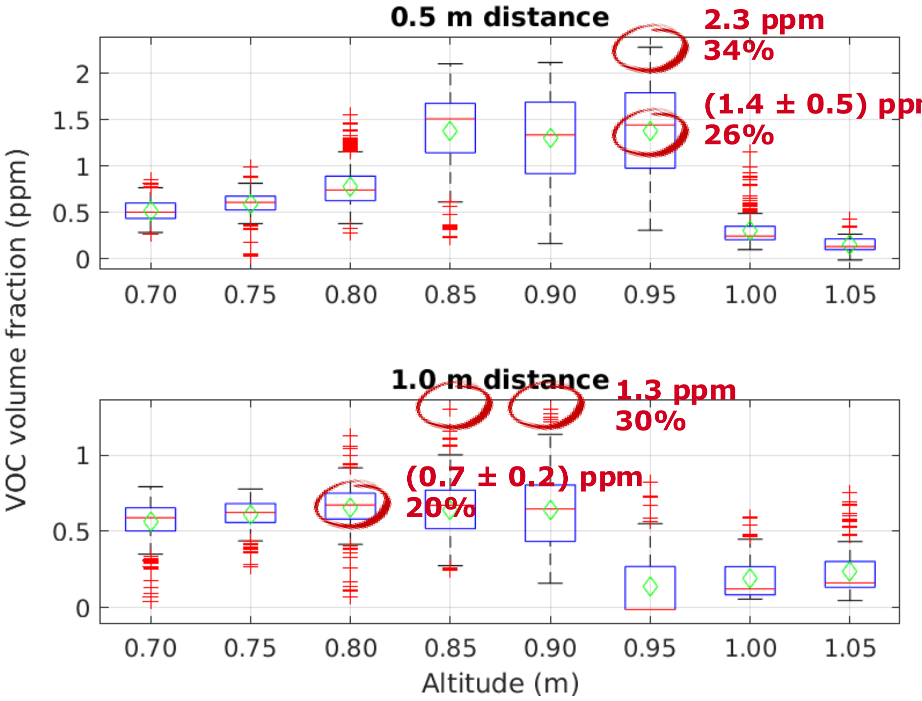
- **Research question**
  - » How much does rotor downwash reduce gas detection performance?
- **Experimental setup**
  - » Arena: 3 × 2.7 × 2 m³
  - » Gas source: ethanol @ 2 l/min
  - » Comparison: stationary vs. flying nano-UAV
  - » Flying altitude varied in 5 cm steps (0.7 m to 1.05 m)



[Neumann et al., ISOEN 2019]

Odor Detection
The Rotor Effect

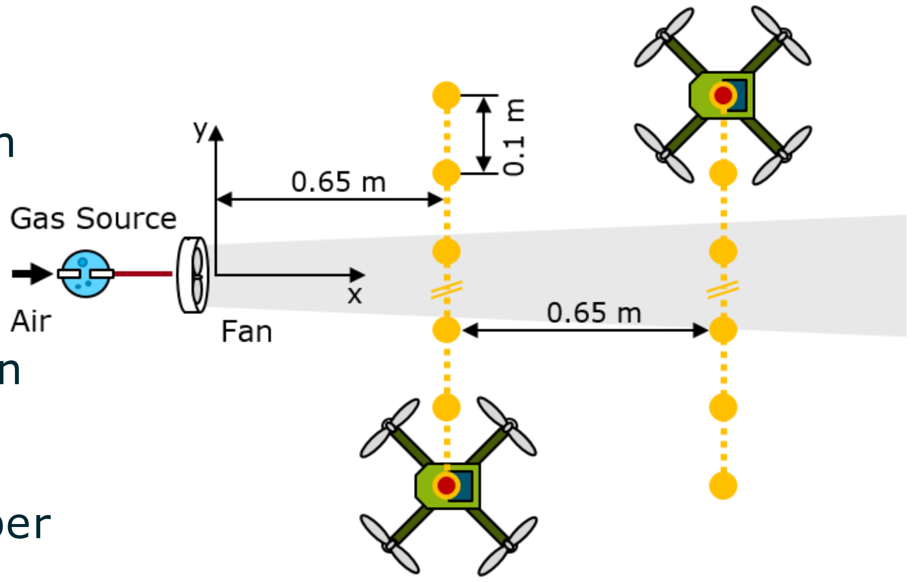
- **Reference (stationary, rotors off)**
  - » **0.5 m distance**
    mean 5.4 ± 0.5 ppm; peak 6.8 ppm
  - » **1.0 m distance**
    mean (3.4 ± 0.5) ppm; peak 4.3 ppm
- **Flying (best result):**
  - → Only 26–34% of reference signal
- **Key finding:**
  - ❖ Rotor downwash reduces detectable concentration by up to 80%
  - ❖ Best position: 0.1–0.15 m below plume centerline



[Neumann et al., ISOEN 2019]

Gas Distribution Mapping
Setup

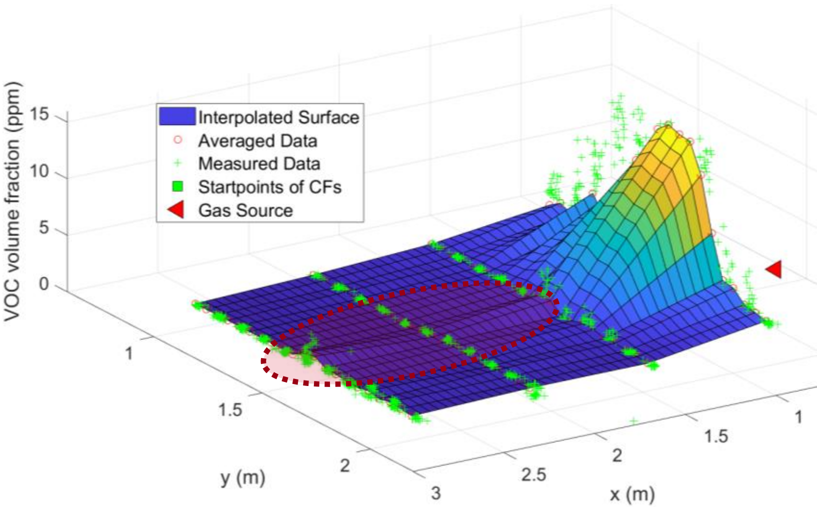
- **Research question**
  - » Can a nano-UAV swarm map a gas distribution despite rotor downwash effects?
- **Experimental setup**
  - » Arena: 3 × 2.7 × 2 m³
  - » Gas source: ethanol @ 2 and 5 l/min
  - » Swarm: 4 nano-UAVs
  - » Predefined sweeping trajectories
  - » Stop-and-measure: 10 s sampling per position
  - » Flight height: 0.85 m (below plume centerline)



[Neumann et al., ISOEN 2019]

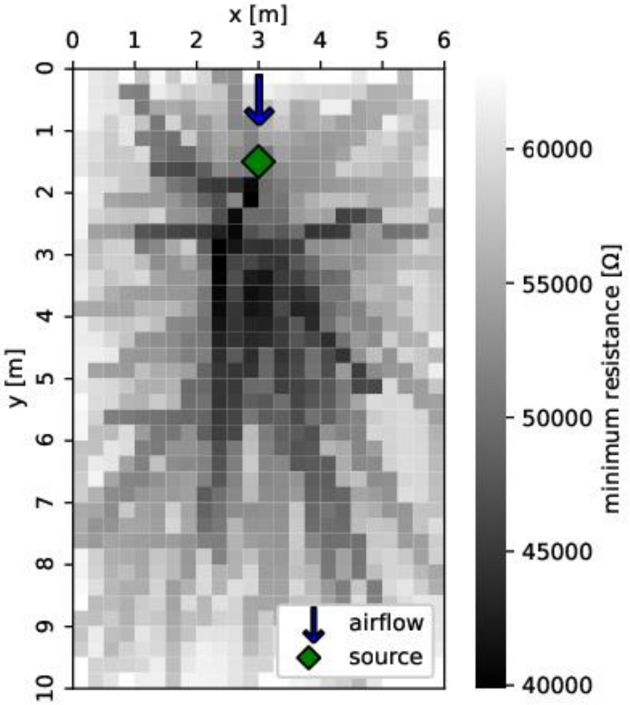
Gas Distribution Mapping
Results

- **Problem discovered**
  - » Drones flying in line downwind of each other cannot detect significant concentration changes
    - → rotor downwash of leading drone redirects plume away from following drone
- **Solution**
  - » Exploration trajectories must account for this
- **Example:**
  - » Offset start positions in y-direction (by 0.5 m)
  - » max. 2 drones in plume centerline at any time



[Neumann et al., ISOEN 2019]

Why Gas Maps Might be Misleading 💬



What you see:

A gas distribution map

What shapes it:

- Rotor-induced redistribution and dilution
- Plume intermittency (turbulent filaments)
- Flight trajectory (sampling pattern → streaks)
- Sensor dynamics (slow recovery → smearing)
- Calibration errors and drift

Map = plume & measurement process
Source ≠ argmax of the map

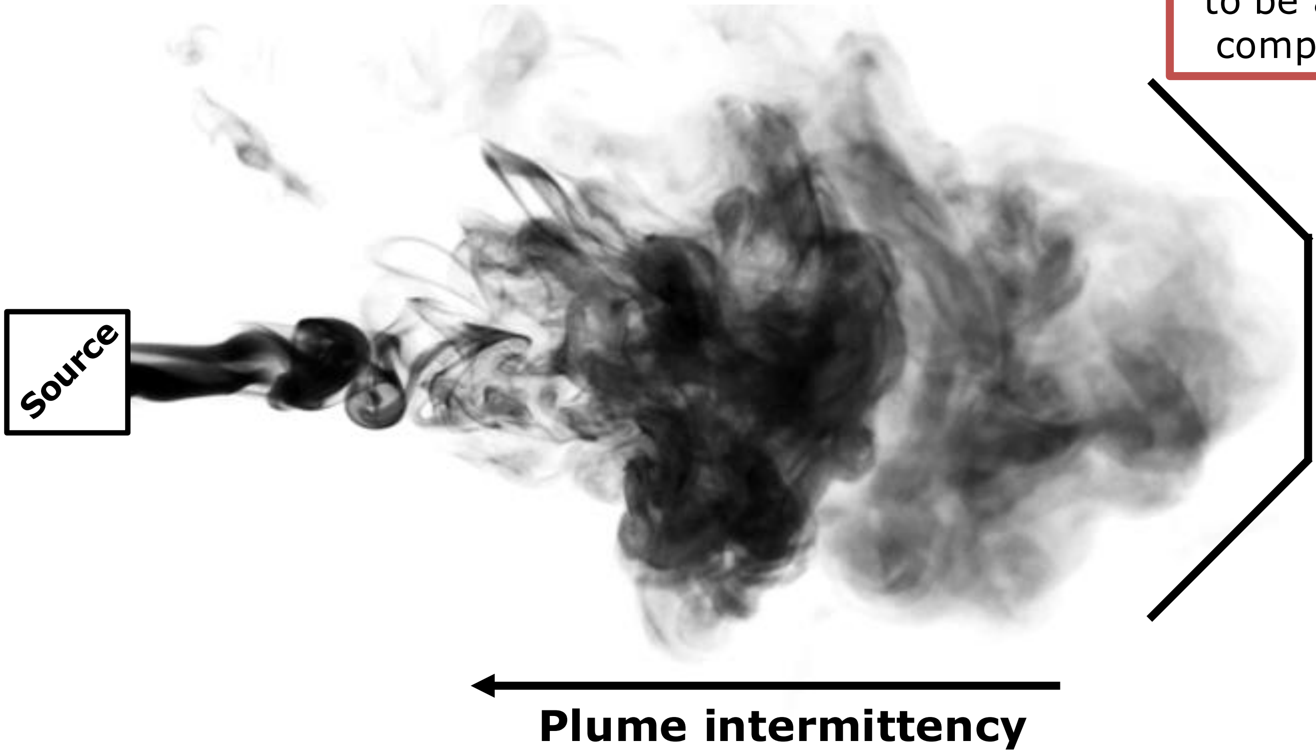
Block E

From Signal to Gas Source Location

"Concentration is a weak indicator. But the structure of the plume is not."

How to Find the Source?
Concentration is a Weak Indicator

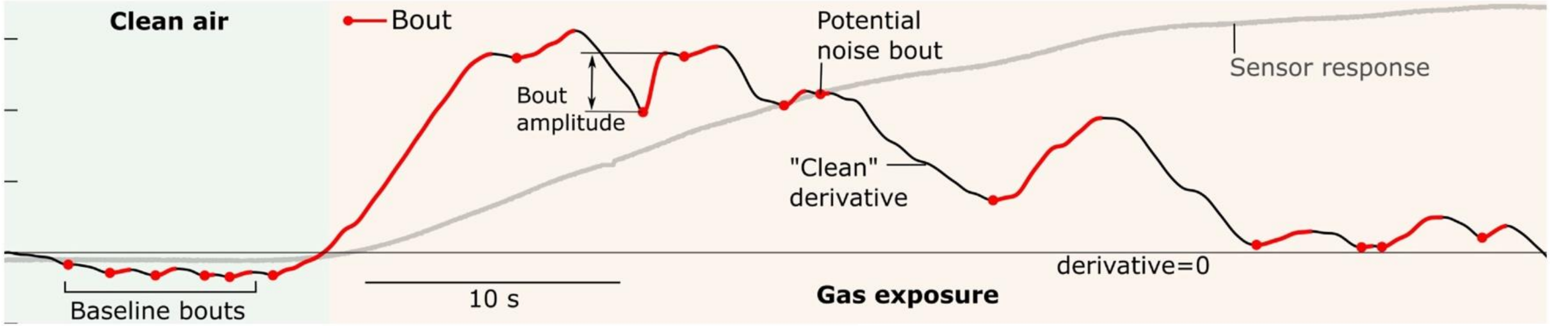
Concentration is expected to be a weak indicator in complex environments!



What is a Bout?

- **Visually:** A bout marks a fresh rise when the sensor encounters a new plume patch
- **Technically:** Rising event in the smoothed first derivative; start/end are located via the second derivative
- **Key advantage:** Bout frequency captures plume intermittency while reducing the influence of MOX recovery and baseline drift

→ Earlier work by **Schmuker et al. (2016)** and **Burgués et al. (2019)**



[Burgués & Marco, Sens. Actuators B 2020]

From Concentration to Plume Structure

Instead of asking:
"How strong is the signal?"

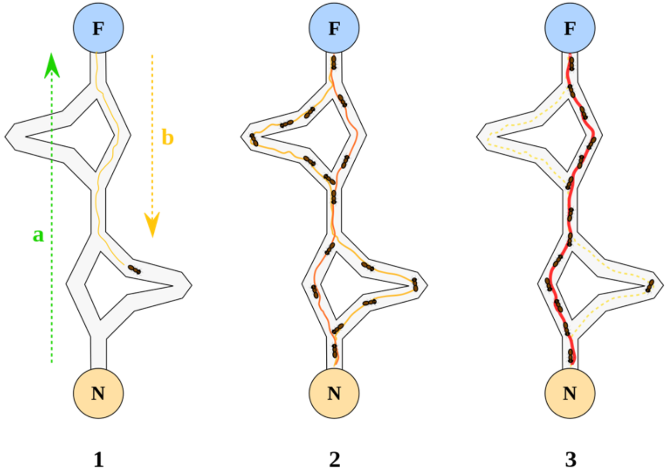
- **Concentration:**
  - » Noisy and intermittent
  - » Slow sensor recovery
  - » Weak spatial indicator

Ask instead:
"How often does a new filament arrive?"

- **Bout frequency:**
  - » Robust measure of plume intermittency
  - » Independent of sensor recovery time
  - » Stronger indicator of source proximity

What Enables Swarm Behavior?

- Each agent must be
  - **Redundant** — losing one drone doesn't break the mission
  - **Distributed** — local decisions, no central controller
  - **Simple** — each drone does little, the swarm does a lot
- Communication medium should be
  - Self-integrating
  - Self-regulating
- **Inspiration:** pheromone communication in insects



Link

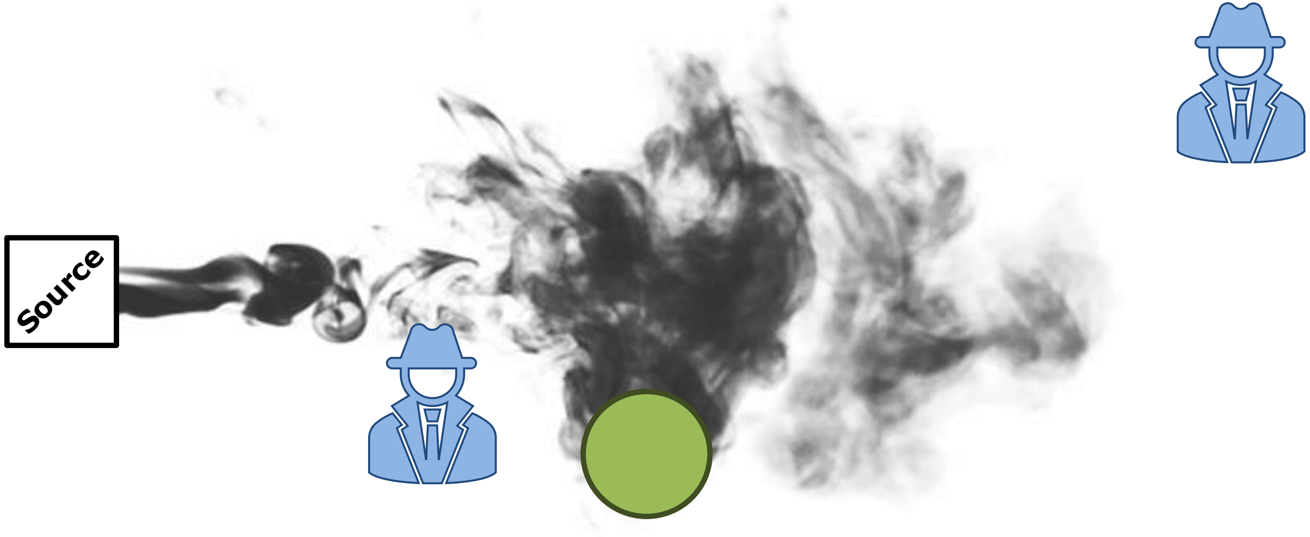
Pheromone System
Repulsion for Collision Avoidance

[Häusler, IEEE Sensors 2023]

Pheromone System
Random Exploration and Plume Encounter

[Häusler, IEEE Sensors 2023]

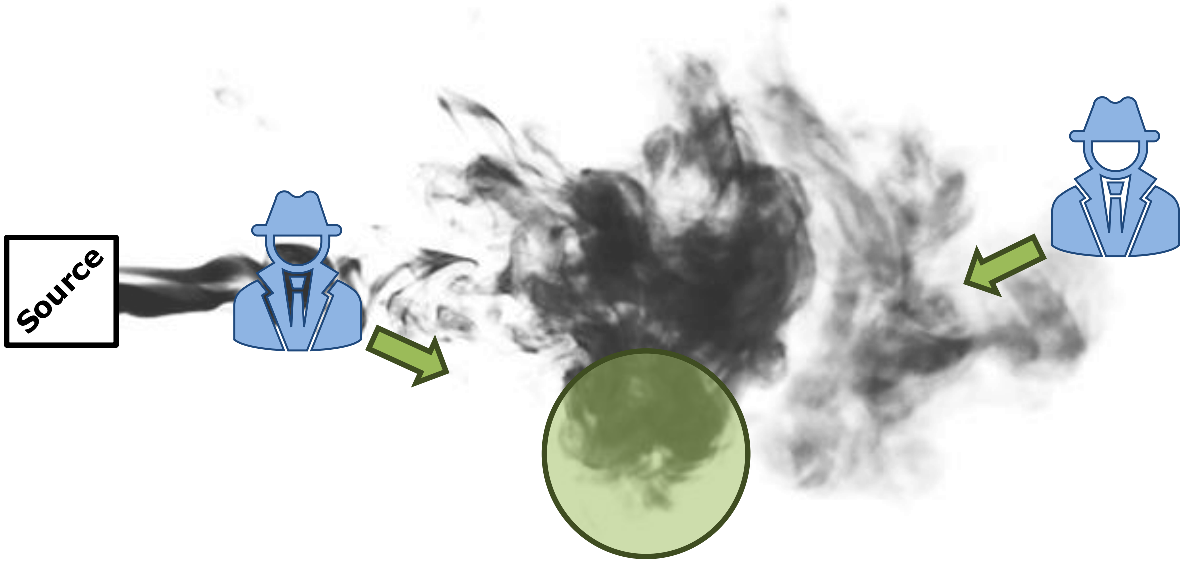
Pheromone System
Pheromone Release



[Häusler, IEEE Sensors 2023]

Pheromone System

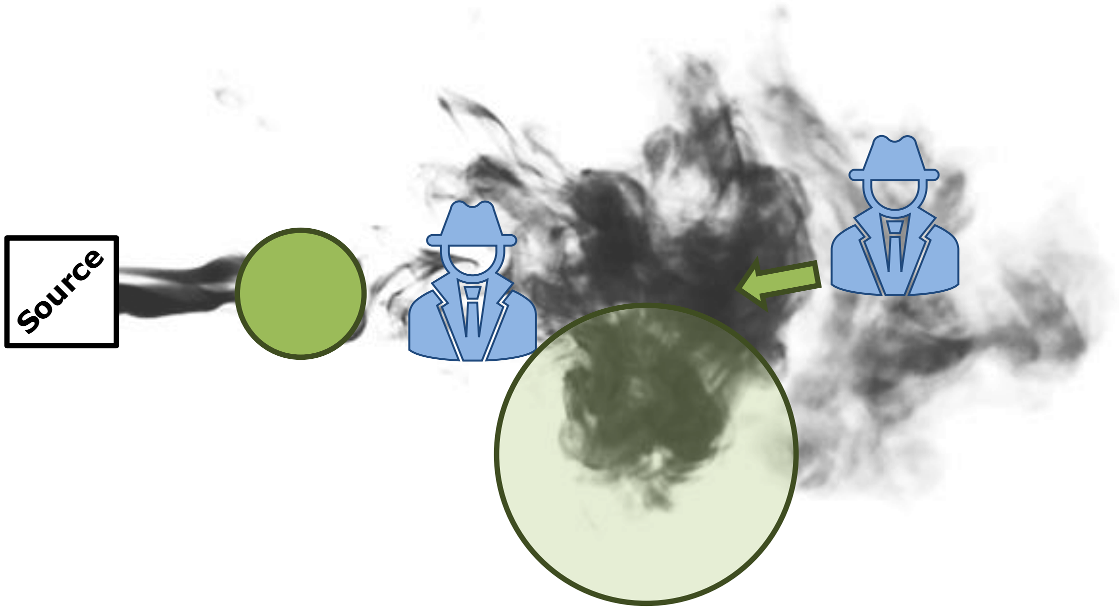
Attraction and Diffusion to/of Pheromone



[Häusler, IEEE Sensors 2023]

Pheromone System

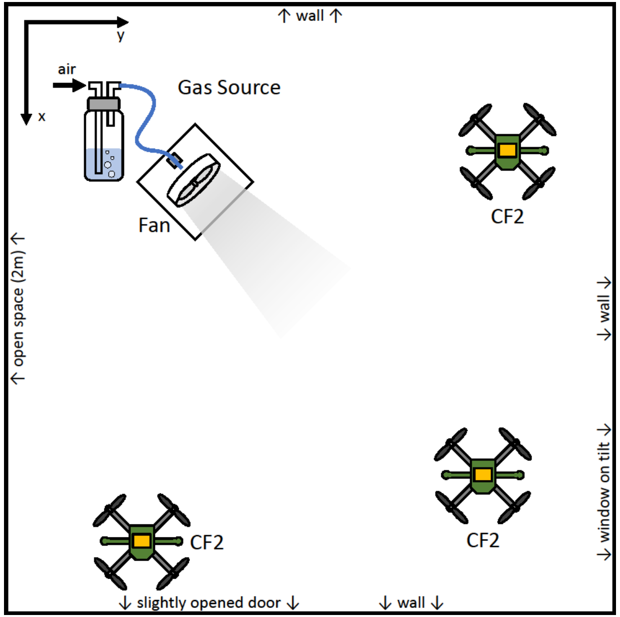
Attraction and Diffusion to/of Pheromone



[Häusler, IEEE Sensors 2023]

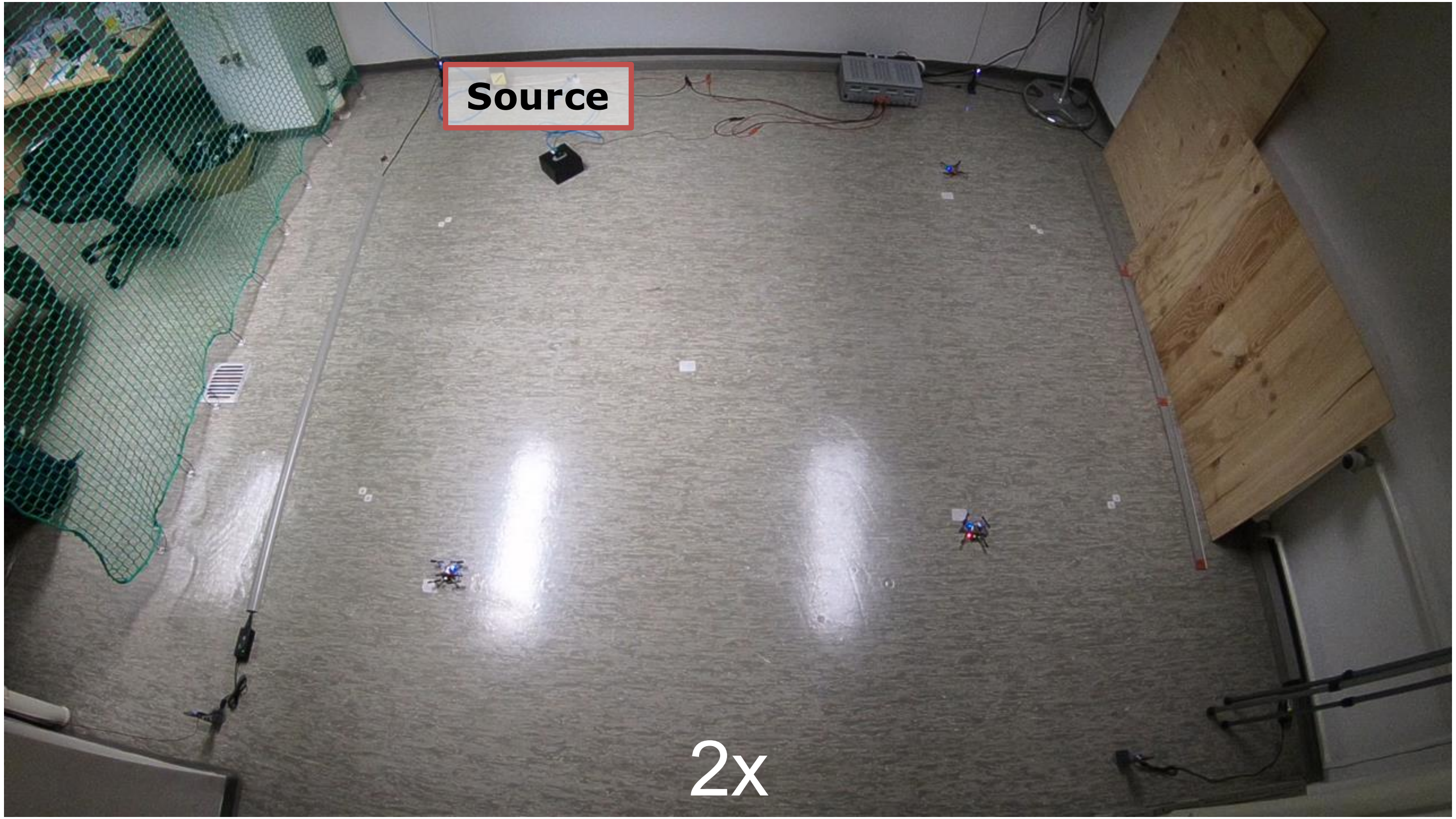
Real-World Experiment
Setup

- **Research question:**
  - » Can the pheromone-based swarm system localize a gas source in a real indoor environment?
- **Setup**
  - » Arena with defined gas source
  - » Swarm of Crazyflie nano-UAVs
  - » Pheromone system running on shared map
  - » 16 runs in total



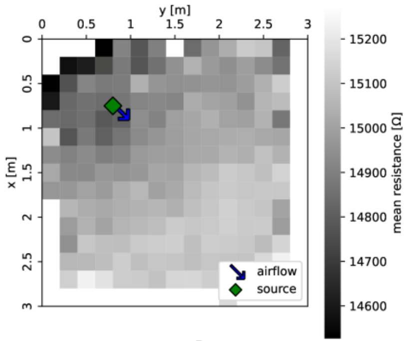
Schematic experiment setup

Experiment
Result

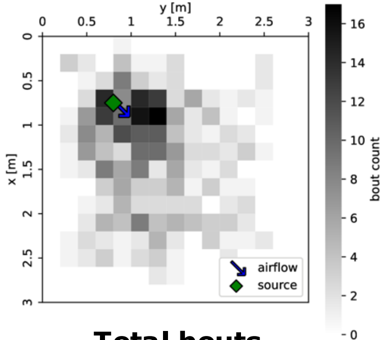


Experiment
Results

- **Key observation:**
  - » Bout cluster forms in front of source — in direction of airflow
- ❖ **One Concentration map misleading:**
  - » gas accumulates in corner behind source
- Bouts tend to indicate source direction more reliably



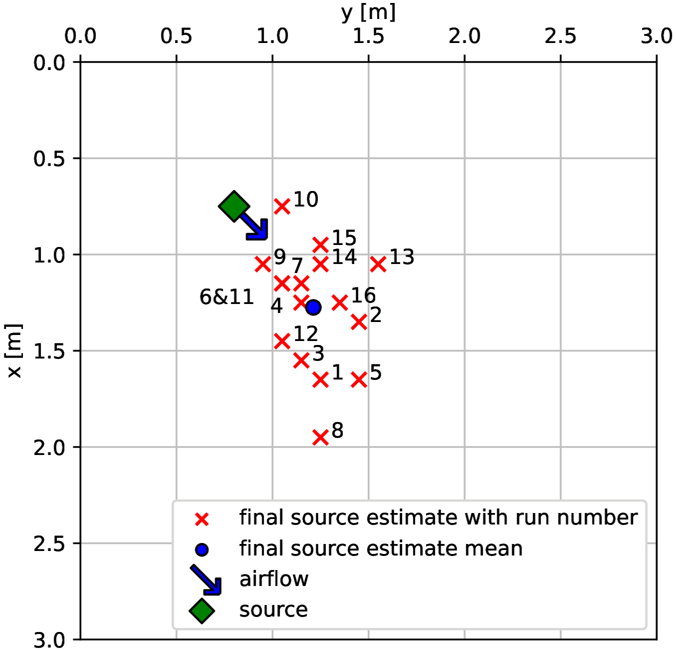
Mean resistance

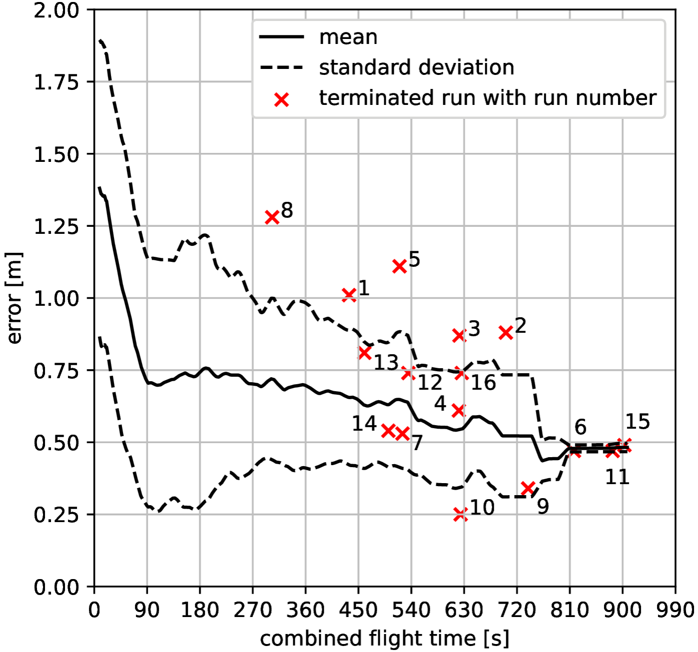


Total bouts

[Häusler, IEEE Sensors 2023]

Experiment Results
Estimation of Source Position in Space & Time



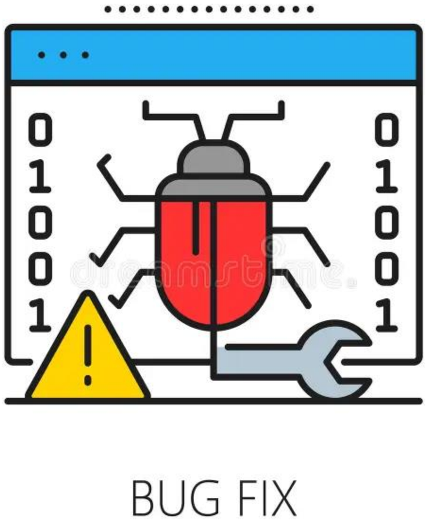


[Häusler, IEEE Sensors 2023]

Exercise: Troubleshoot the Swarm

Your swarm converges reliably, but the estimated source position is always ~2 m downwind of the real source.

→ What's the most likely cause?
→ How would you fix it — or at least correct for it?



Block F

Wrap-up & Discussion

"We have the pieces. Now let's put them together."

What Does NOT Work in ARO

✗ **Just follow the concentration gradient**
- → Block A/E: plumes are turbulent, no reliable gradient

✗ **Assuming smooth spatial gas distributions**
- → Block D: maps reflect measurement process, not ground truth

✗ **Ignoring rotor–plume interaction**
- → Block C/D: up to 80% signal reduction

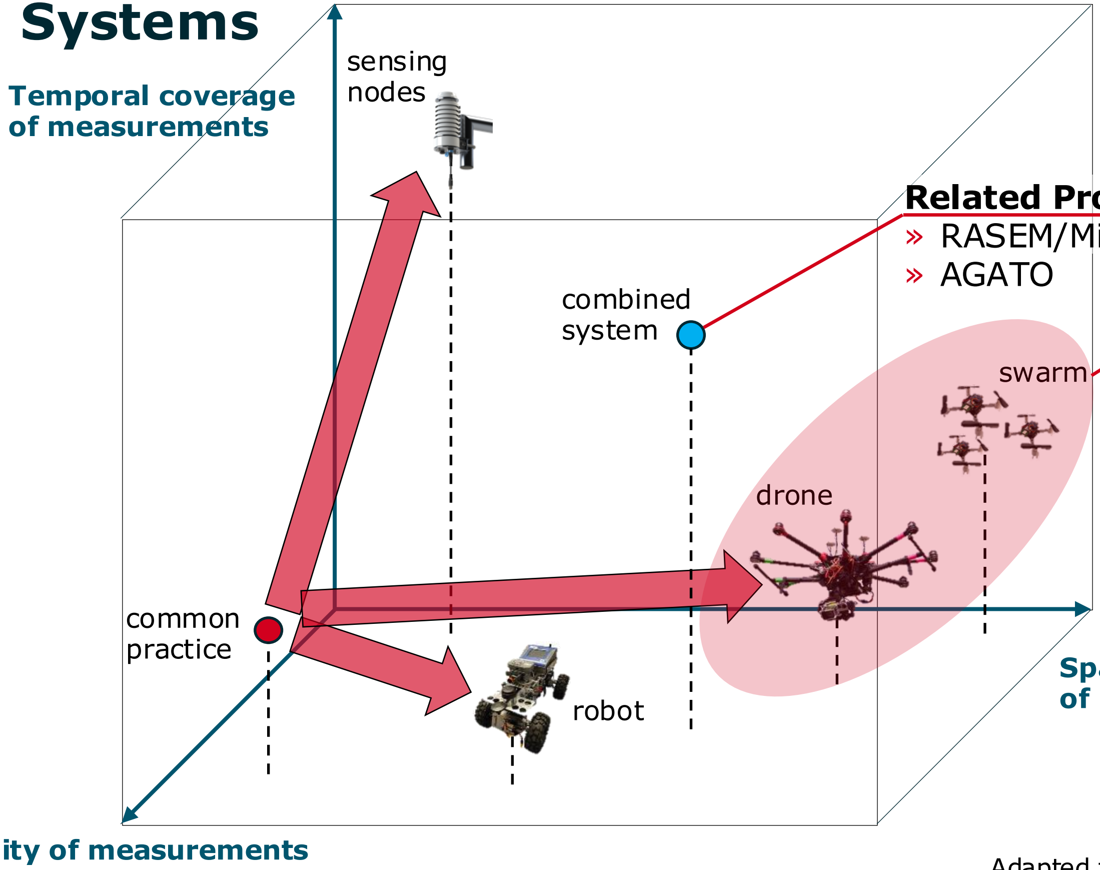
✗ **Calibrating once and assuming it holds**
- → Block C: field conditions always deviate

✗ **Single-sensor, single-drone decision making**
- → Block E: swarm + bout features outperform

Design Rules / Practical Guidelines

- ✓ **Match sensing principle to scenario**
  - → Block A/B: payload, target gas, and environment decide
- ✓ **Account for rotor downwash explicitly**
  - → Block C/D: sensor placement, trajectory, and altitude
- ✓ **Use temporal features, not only magnitude**
  - → Block E: bout frequency over raw concentration
- ✓ **Design trajectories for sensing, not just coverage**
  - → Block D: avoid drone alignment downwind
- ✓ **Validate in controlled conditions first**
  - → Block C/D: know your baseline before going to the field

Outlook: From Single Platforms to Heterogeneous Sensing Systems



Related Projects
- RASEM/Mimose-A
- AGATO

Related Projects
- Passive Smart Dust

Adapted from Achim J. Lilienthal, TUM, 2020

Final Discussion 💬

What surprised you today?

Where would you disagree?

What would you do differently?

Thank you for your attention.

Contact:

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8.1 Sensors, Measurement and Testing Methods

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Email: patrick.neumann@bam.de

References

…in order of appearance – more or less ;)

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