Pre-Deployment Testing, Augmentation and Calibration of Cross-Sensitive Sensors

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Active Research and Development

• Numerous research projects and start-ups

• Similar approach
  • Small and low-cost air quality monitoring systems
Low-cost Air Quality Sensors

• **Pro’s:**
  • Small
  • Cheap (1$ - 100$)
  • Low power consumption

• **Con’s:**
  • Low target pollutant concentrations, often at sensitivity boundaries
  • Environmental conditions affect sensor output
  • Low selectivity, i.e. sensors are cross-sensitive to multiple substances
  • Need frequent re-calibration
Limiting Effects

- Datasheet information
  - Sparse or not provided at all
  - Laboratory results do not cover deployment conditions

<table>
<thead>
<tr>
<th>ENVIRONMENTAL</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity @ -20°C (%) output @ -20°C/output @ 20°C @ 2ppm NO₂</td>
<td>40 to 70</td>
</tr>
<tr>
<td>Sensitivity @ 50°C (%) output @ 50°C/output @ 50°C @ 2ppm NO₂</td>
<td>120 to 135</td>
</tr>
<tr>
<td>Zero @ -20°C</td>
<td>±10</td>
</tr>
<tr>
<td>Zero @ 50°C</td>
<td>60 to 380</td>
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</table>

<table>
<thead>
<tr>
<th>CROSS SENSITIVITY</th>
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</thead>
<tbody>
<tr>
<td>H₂S</td>
<td>sensitivity % measured gas @ 5ppm H₂S</td>
</tr>
<tr>
<td>NO</td>
<td>sensitivity % measured gas @ 5ppm NO</td>
</tr>
<tr>
<td>Cl₂</td>
<td>sensitivity % measured gas @ 5ppm Cl₂</td>
</tr>
<tr>
<td>SO₂</td>
<td>sensitivity % measured gas @ 5ppm SO₂</td>
</tr>
<tr>
<td>CO</td>
<td>sensitivity % measured gas @ 5ppm CO</td>
</tr>
<tr>
<td>H₂</td>
<td>sensitivity % measured gas @ 100ppm H₂</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>sensitivity % measured gas @ 100ppm C₂H₄</td>
</tr>
<tr>
<td>NH₃</td>
<td>sensitivity % measured gas @ 100ppm NH₃</td>
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<tr>
<td>CO₂</td>
<td>sensitivity % measured gas @ 100ppm CO₂</td>
</tr>
<tr>
<td>O₃</td>
<td>sensitivity % measured gas @ 100ppm O₃</td>
</tr>
<tr>
<td>Halothane sensitivity</td>
<td>% measured gas @ 100ppm Halothane</td>
</tr>
</tbody>
</table>

Datasheet, NO2-B4 Nitrogen Dioxide Sensor, Alphasense

secondhand smoke, smoke generated from burning of wood and paper, volatiles of wine (alcohol) and cosmetics, ammonia, hydrogen sulfide, hydrogen, carbon monoxide, propane, methane, styrene, propylene glycol, phenol, acetone, thinner, insecticide, correction fluid, benzene, formaldehyde and so on.

Datasheet, TP401-A Indoor Air Quality Sensor, Shenzen Dovelet Sensors Technology CO., LTD

- Ignoring these effects limits performance
- **Goal**: Understand sensor characteristics under deployment-related conditions
Example: Alphasense NO$_2$-B4 Sensor

- Deployed at high-quality monitoring station
- Ordinary Least-Squares (OLS) calibration to nitrogen dioxide (NO$_2$) reference measurements

![Graph showing NO$_2$ concentration over time with calibrated and reference measurements]

- Root-Mean-Square-Error (RMSE) = 12.4 ppb (50%)

Sensor is highly cross-sensitive to ozone (O$_3$), temperature and humidity
Sensor Calibration

Simple sensor calibration

Reference \hspace{1cm} Sensor

Ordinary Least-Squares (OLS):
\[ r = \beta_0 + \beta_1 s_1 + \varepsilon \]

Sensor array calibration

Reference \hspace{1cm} Sensor array

Multiple Least-Squares (MLS):
\[ r = \beta_0 + \beta_1 s_1 + \beta_2 s_2 + \beta_3 s_3 + \varepsilon \]

Used to compensate for cross-sensitivities
Example: Alphasense NO$_2$-B4 Sensor revised

- Multiple Least-Squares (MLS) sensor array calibration
  - NO$_2$-B4, SGX O$_3$, humidity and temperature

- RMSE = 4.6 ppb (18%)
Challenges

**Testing**
- Identify ALL
  1. cross-sensitivities and
  2. environmental dependencies
  3. under deployment-related conditions.

**Augmentation**
- Select low-cost sensors and augment to optimal sensor array

**Calibration**
- Sensor array calibration for
  1. accurate measurements
  2. with long-term stability
Challenges

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Sensor Testing: Signals

- **In-field measurements**
  - Measurements next to high-quality monitoring stations, e.g. run by governmental authorities

- **Sensor-under-test** \( s \)

- **Various reference signals** \( r_i \epsilon R \), e.g. pollutants, temperature, humidity...

- **Standardization for scale-invariant results**
Sensor Testing: Inverse Calibration

- Inverse calibration

\[ s = \beta_0 + \beta_1 r_1 + \beta_2 r_2 + \beta_3 r_3 + \varepsilon \]
Sensor Testing: Regression Error

- Regression estimation $\hat{u}$
  - *Explained* part of the sensor signal with given references
- Regression error $\varepsilon$
  - *Unexplained* part of the sensor signal
- Reason for substantial error can be two-fold
  - Uncaptured cross-sensitivities
  - Sensor noise
Sensor Testing: Error Decomposition

- FFT of typical $O_3$ concentration

- Error decomposition: Low-pass filter (cut-off: $\frac{1}{24h}$)
  - Low-frequent part $\varepsilon_P$: Uncaptured cross-sensitivities
  - High-frequent part $\varepsilon_N$: Sensor noise
Experimental Evaluation

• Various low-cost sensors
• Governmental high-quality station (NABEL) in Duebendorf, Switzerland
  • 20 different reference signals
• 15 months of data
Alphasense NO₂-B4 Sensor

Decreased error and increased explained signal components when adding O₃, temperature and humidity

Extending the used references

Root-Mean-Square
\[ \text{RMS}(\cdot) \in [0,1] \]

High error components when using only NO₂ reference

Decreased error and increased explained signal components when adding O₃, temperature and humidity
SGX O₃ and Alphasense CO-B4

Similar results: Highly sensitive to target gas. Adding T & H reduces error components.
Dovelet Air Quality Sensor

Not sensitive to any pollutants.
Unqualified sensor for outdoor air quality measurements.
Testing Conclusion

1. Need $O_3$, humidity and temperature measurements to compensate for cross-sensitivities of the $NO_2$ sensor

2. $O_3$ and CO sensor depend on humidity and temperature
Identify ALL cross-sensitivities and environmental dependencies under deployment-related conditions.

Deployment goal: Monitor pollutants O3, CO and NO2.

Select low-cost sensors and augment to optimal sensor array.

Sensor array calibration for accurate measurements and long-term stability.
Identify ALL
1. cross-sensitivities and
2. environmental dependencies
3. under deployment-related conditions.

Deployment goal:
Monitor pollutants O3, CO and NO2

Select low-cost sensors and augment to optimal sensor array

Sensor array calibration for
1. accurate measurements
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Identify ALL
1. cross-sensitivities and
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Select low-cost sensors and augment to optimal sensor array

Sensor array calibration for
1. accurate measurements
2. with long-term stability

Deployment goal: Monitor pollutants O3, CO and NO2
Calibration Stability: \( \text{O}_3 \)

- Calibration error vs. different training frequencies over 12 months
- Training time: 4 weeks

Calibration to \( \text{O}_3 \) reference

- Decreasing error with increasing calibration frequency
- OLS requires monthly recalibration to achieve same error when calibrating the array every 4 months
Calibration Stability: CO

- Increasing error at f = 2: Unstable parameters during summer
- Sensor array calibration beneficial
Calibration Stability: NO$_2$

Calibration to NO$_2$ reference

- Decreasing error
- MLS outperforms OLS

![Graph showing RMSE vs Calibration Frequency](image-url)
Conclusions

• Low-cost sensors suffer from cross-sensitivities and meteorological dependencies
• In-field testing using reference measurements to explain sensor-under-test
• Quantify amount of captured and uncaptured cross-sensitivities and sensor noise
• Improved accuracy and stability when calibrating an augmented sensor array
Thank You!