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High-Quality meets Low-Cost: Approaches for Hybrid-Mobility Sensor Networks

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Abstract

Air pollution within industrial scenarios is a major risk for workers, which is why detailed knowledge about the dispersion of dusts and gases is necessary. This paper introduces a system combining stationary low-cost and high-quality sensors, carried by ground robots and unmanned aerial vehicles. Based on these dense sampling capabilities, detailed distribution maps of dusts and gases will be created. This system enables various research opportunities, especially on the fields of distribution mapping and sensor planning. Standard approaches for distribution mapping can be enhanced with knowledge about the environment's characteristics, while the effectiveness of new approaches, utilizing neural networks, can be further investigated. The influence of different sensor network setups on the predictive quality of distribution algorithms will be researched and metrics for the quantification of a sensor network's quality will be investigated.

Keywords: mobile robot olfaction; air quality monitoring; wireless sensor network; gas distribution mapping; occupational health

1. Introduction

Occupational health is an important topic, especially in industry where workers are exposed to airborne by-products (e.g., dust particles and gases). Therefore, continuous monitoring of the air quality in industrial environments is crucial to meet safety standards. For practical and economic reasons, high-quality, costly measurements are currently only carried out sparsely [1], both in time and space, i.e., measurement data are collected according to the European standard [2] in one or few day campaigns at selected locations and by few persons only [3].

Recent developments in sensor technology enable cost-efficient air quality monitoring in real-time for long-term intervals. A better knowledge of the contaminant distribution inside industrial environments facilitates improved situation awareness and provides the means for better and more economic control of air impurities, e.g., the possibility to regulate the workspace's ventilation exhaust locations can reduce the concentration of airborne contaminants by 50% [4].

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This paper describes the concept of “Robot-assisted Environmental Monitoring for Air Quality Assessment in Industrial Scenarios” (RASEM). An implementation of this concept in the homonymous SAF€RA[1] project RASEM[2] brings together the benefits of both – low- and high-quality – measuring technologies: A stationary network of low-cost sensors, with temporally dense, but spatially sparse measurements, is augmented by mobile units, that enable spatially dense, but temporally sparse measurements with high-quality sensors. Additionally, RASEM will develop procedures and algorithms to map the distribution of gases and particles in industrial environments.

2. System Overview

The key idea of RASEM is the combination of stationary and mobile sensing platforms. The application of mobile robots for tasks of environmental sensing falls in the research field of Mobile Robotics Olfaction (MRO). These environmentally sensitive robots address tasks like gas leak detection or the exploration of areas, where hazardous gases may be present. Examples of gas sensitive ground and aerial robots can be found, e.g., in [5]-[9].

The general concept of RASEM can be seen in Fig. 1. The system will be deployed in four different scenarios, including a stainless-steel plant and a cruise ship.

2.1. Stationary Sensing Nodes

The stationary sensor network is composed of multiple custom stationary sensing nodes. Each node will be equipped with various low-cost sensors to assess gas concentration, dust particles, temperature and humidity. The nodes will be equipped with optical dust sensors (GP2Y1010AU0F by Sharp) and electrochemical gas sensors (DGS-CO 986-034 by SPEC). Temperature and humidity will be measured with a DHT22 by Aosong. Uncalibrated measurements of the dust and gas sensor, deployed in an urban area, are visualized in Fig. 2. Both sensors are able to depict the day-night-cycle, with maxima in the early afternoons and minima in the late night.

The sensing nodes will form a wireless sensor network, whose main task is the continuous monitoring of the dust and gas distribution and identification of areas of interest. These areas may be areas with high gradient or noticeable variance in the gas or dust concentration. Gas is usually dispersed through advection, which causes a gas plume to form downflow of the source. While turbulence and diffusion will cause the plume to meander and spread out, it’s centerline may be found following the increasing gradient of the concentration [5]. Experiments with gas sensitive robots further showed, that the observed variance can also serve as an indicator for a gas source [12].

2.2. Mobile Units

Mobile units (ground and aerial robots) will support the stationary low-cost sensor nodes with high-quality sensors for gas and dust monitoring, e.g., DustTrak Aerosol Monitor 8532, which can measure three different sizes of dust, namely PM1, PM2.5 and PM10. These sensors can also be used for cross-calibrating the low-cost sensors. The main advantage of the robots is the ability to collect data with a high spatial resolution and perform measurements at different heights and at areas that are not covered by the stationary network. The unmanned aerial vehicle (UAV) allows measurements at different heights. To keep disturbance due to the UAV’s induced downward airflow for workers as minimal as possible, the UAV will only be operated in appropriate areas and situations. While ground-based and aerial robots are fully controllable, the usage of semi-controllable and passive mobile units will be tested: Workers themselves (passive mobility) or forklifts (semi-controllable) can be equipped with portable sensors. The forklift could suggest the driver to drive in a certain direction because sensor readings for a specific area are desired. Similarly, the fully controllable robots could be equipped with sensor planning algorithms to autonomously investigate informative spots that are identified by the stationary nodes.

[1] https://www.safera.eu/
[2] https://projects.safera.eu/project/20

3. Research Opportunities

3.1. Gas and Dust Distribution Maps

One of the main tasks of RASEM will be the development of algorithms to create 3D distribution maps to display air quality in an intuitive way. The output will be visualized for non-experts (e.g. workers, managers, maintenance staff) and provide information of dust, gas and airflow.

Gaussian processes are widely used to represent spatially varying processes, e.g., distribution mapping of pollutants. In [10], Evans et al. leveraged Gaussian processes to estimate the temperature over an area with a sensor network, consisting of stationary sensing nodes and a flying platform. A different approach with a similar, hybrid-mobility network consisting of stationary nodes and a ground robot, was suggested by Schaffernicht et al. in [1]. They proposed the Echo State Map (ESM), which combines an echo state network, a recurrent neural network, with Gaussian processes for gas distribution mapping. As the ESM is a promising model, which is easy to train and understand, it offers further research opportunities, e.g., regarding the knowledge management of the model, i.e., deciding which data to forget or how to weight different data samples in the temporal domain. A different neural network, recently applied is the CNN-LSTM by Bilgera et al. In [11] they showed that the problem of gas source localization can be approached with a dense sensor network and a CNN-LSTM model. However, their good predictions of the locations may be the result of a relatively high-resolution sensor network. As several different sensor networks of varying spatial resolution will be set up in the RASEM project, the findings of [11] shall be verified with different setups. New answers, on how much the measurement resolution can be varied, shall be found. It could also be of interest, to what extent the CNN-LSTM can be exploited for the problem of gas distribution mapping.

While neural networks offer interesting opportunities, a standard approach to create distribution maps is the Kernel DM+V algorithm proposed by Lilienthal et al. in [12], e.g., used by Bennetts et al. [3]. These standard approaches could for example be improved by adding knowledge about the 3D structure of the environments to the models and build upon the previous work of Reggente et al [13]. It may be interesting to incorporate some aspects of land-use regression models, which predict pollution patterns on the basis of the area's characteristics and have been used for environmental monitoring at a larger scale only so far to the best of the author's knowledge.

The algorithms to be developed in RASEM should include time- and event-dependency, e.g., a dependency on periodic or non-periodic events causing a burst of dust and gas emissions. These dependencies are expected to allow extraction of temporal patterns from the maps that could be correlated with operational and seasonal changes (daily shifts, weekends). With these temporal patterns, abnormal situations, e.g., excessively high dust levels or increased temperatures, could be detected to trigger alarms or mitigation processes. Once possible events are automatically classified, it could be of interest to forecast certain trends and compare them to the measured dust distribution. Further research could then investigate metrics to quantify the contribution of a single event to the total background emission. The planned experiments in industrial environments with their periodical emission patterns, could help to verify whether or not the metrics proposed by Apte et al. [14] are able to quantify the 'freshness' of events.

Conventional models of occupational health will be compared against the developed gas distribution models. Exposure assessment methods, risk mitigation measures and human exposure will be estimated to carry out guidelines for the mitigation of health risks in industrial environments.

3.2. Sensor Planning

RASEM will build upon previous approaches of Bennetts et al. [3], to find optimal positions for sensor nodes to monitor the industrial context. Especially the combination of low-cost sensors on the one hand and high-quality sensors on the other hand is interesting from a research point of view.

When combining multiple data sources to a consistent dataset, it is of question, how to weight the individual measurements. Especially, when this fused data is used for creating distribution maps. As the true concentration level for a specific location cannot be known, its concentration level has to be estimated on the basis of samples at related locations. This means that the mobile, high-quality measurements have to be related to the stationary, low-quality measurements, while also taking the spatial and temporal domain into account. Clearly, different samples have to be taken into account (i.e. weighted) differently, however a high-quality reading might not always be 'worth more' than a low-quality reading. For example, does the reading of a high-quality sensor reflect the true concentration level of a certain location better than that of a low-quality sensor, even though the high-quality sensor may be spatially further apart from that position? How much time has to pass, so that a low-cost sensor reading is worth more than a high-quality sample taken in the past?

In effect, this leads to the question on how to quantify the quality of a sensor network. Within RASEM, different metrics to enable this quantification will be investigated. How many sensors and samples are necessary to reach a certain quality in the distribution models and forecasts? How to decide on the required amount of mobile and stationary sensors in hybrid networks? Research performed by Apte et al. [14] showed a point of 'diminishing return', after which additional samples add little information and don't significantly increase the performance of land-use regression models in an urban environment. With the data collected in RASEM, the authors aim to find answers as to whether these statements can also be applied for gas distribution mapping algorithms (see 3.1) in industrial environments.

3.3. Exposure Assessment and Control

Gas and dust distribution maps are used to create representations of airborne contaminants that allow increased situation awareness and ultimately mitigation actions if needed. By exploiting the dense sampling capabilities of the RASEM system, combined with conventional exposure assessment methods or modelling, new methods for continuous human exposure estimations can be developed. The RASEM system can also be utilized for exposure assessment in scenarios which are not normally reachable with conventional occupational hygiene exposure methods. Knowledge of the contaminant distribution can facilitate improved technical control of air impurities, ventilation systems and better safety and protection policies, and, consequently, the improvement of working conditions. Identification of contaminant sources and events causing contaminant emission can be utilized e.g. in demand-controlled ventilation. Location of exhaust openings can be redirected as the contaminant source is varying. The results of earlier studies indicate that the contaminant concentration at the occupied zone could be decreased by 50 % simply locating the exhaust opening to the position where the plume reached the ceiling [4]. The results imply that the residence time of the contaminant has to be kept as short as possible and thus exhausts should be placed where the emission is highest.

4. Conclusion

The proposed concept promises a further examination and usage of recent developments in sensor technology. While low-cost sensors enable the setup of dense sensor networks, they cannot deliver the same high-quality data as costly sensor technology can.

The system that is going to be developed in the scope of the RASEM project will be evaluated under real conditions in multiple industrial sites in Finland. The cooperation of diverse research institutes and industry partners allows to maximize the insights of how the combination of low-cost and costly sensor technology can enable effective gas and dust distribution mapping. By combining the capabilities of the proposed system with conventional assessment methods, the minimization of health risks in industrial environments is made possible. Research questions in distribution mapping, sensor planning and the quality of sensor networks can be addressed, to ultimately further close existing research gaps.

Acknowledgements

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Image Captions:

Fig. 1. The key idea of the RASEM project: Dust and gas measurements from stationary sensing nodes in combination with mobile robots and drones to create 3D dust exposure maps in industrial work environments.

Fig. 2. Uncalibrated measurements of a sensing node in an urban environment. A rolling mean (window size = 40) is applied to the dust measurements.

Figure 1

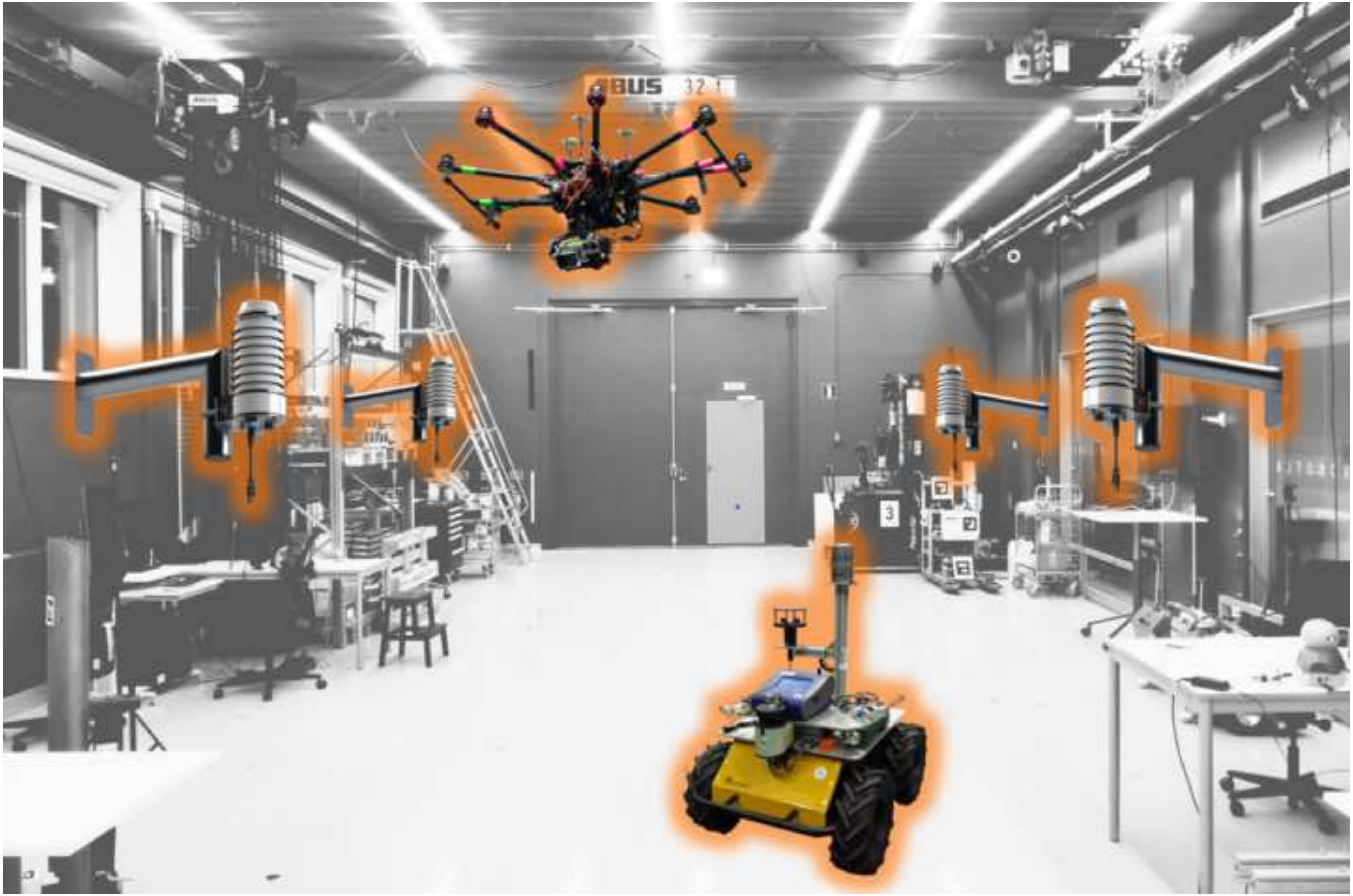
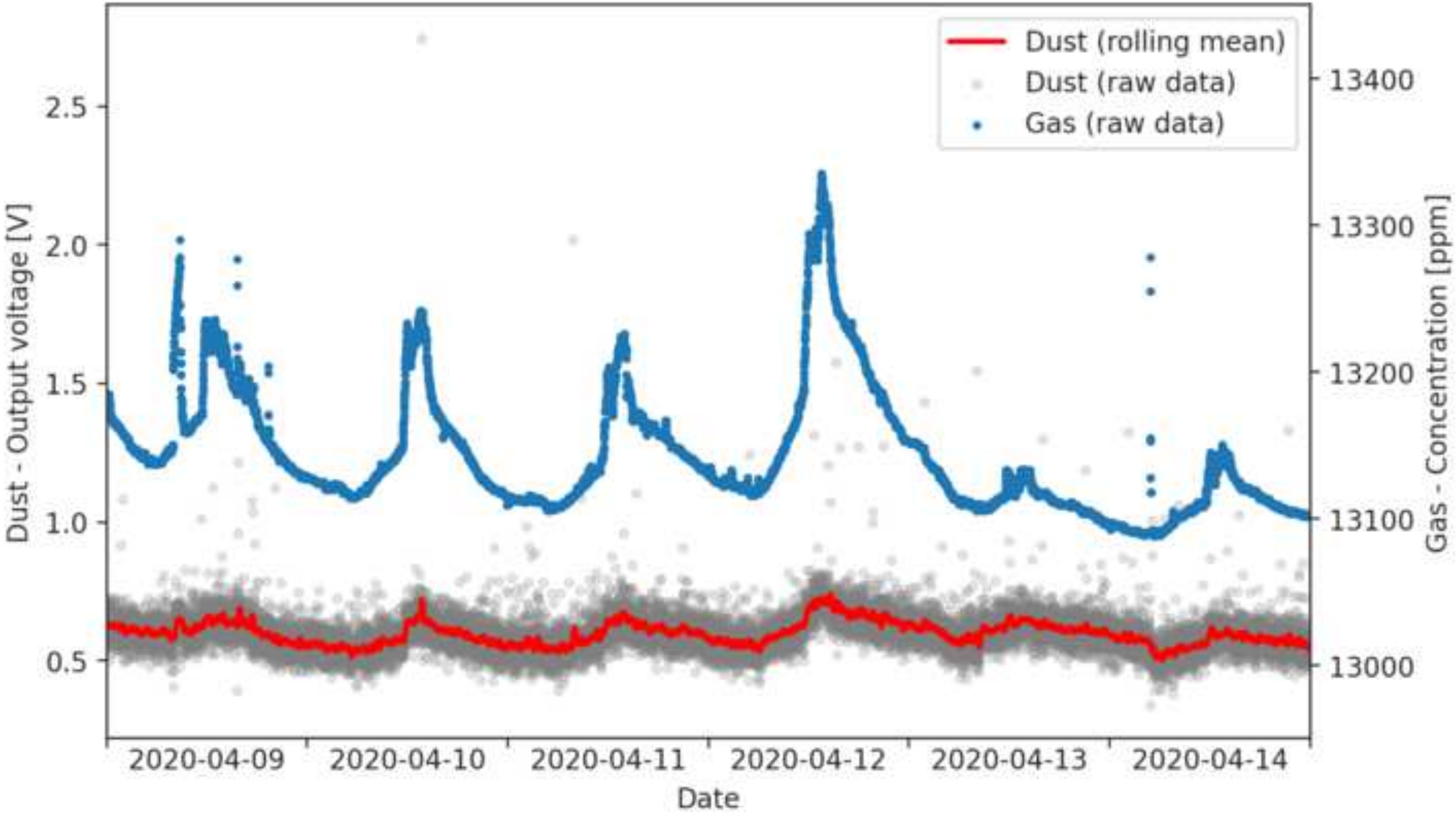


Figure 2

Click here to download high resolution image



Dear Reviewers,
Dear Editor,

First of all we'd like to thank you for your valuable remarks.

In this document first we list all your comments and describe in detail how we responded to them, and then we explain briefly the changes we applied in the text.

We deeply appreciate your consideration of our manuscript. If you have any queries, please don't hesitate to contact us.

Thank you and best regards!

Yours sincerely,

Nicolas Winkler

Reviewer #2:

1. **Please clarify the goal or the quantitative performance indicators the authors are planning to or want to accomplish in RASEM project. For example, in ref. [9], 30 stationary gas sensors were used to measure gas distribution in an area of 7.5 m x 9.5 m with a resolution of 1.5 m. How much do the authors think the number of sensors can be reduced, or the measurement area can be expanded, or the measurement resolution can be enhanced?**
   a. We took a look into the referred research paper and added, how our research can supplement previous findings: "*In [11] they showed that the problem of gas source localization can be approached with a dense sensor network and a CNN-LSTM model. However, their good predictions of the locations may be the result of a relatively high-resolution sensor network. As several different sensor networks of varying spatial resolution will be set up in the RASEM project, the findings of [11] shall be verified with different setups. New answers, on how much the measurement resolution can be varied, shall be found. It could also be of interest, to what extent the CNN-LSTM can also be exploited for the problem of gas distribution mapping.*"
2. **In the 4th line of the first paragraph in Section 2, the authors cited three research papers to refer ground and aerial robots. It would be better to add more research papers such as (1) for ground robots, and (2) for aerial robots.(1) H. Ishida, A. J. Lilienthal, H. Matsukura, V. Hernandez Bennetts, and E. Schaffernicht, "Using chemical sensors as "noses" for mobile robots," in Essentials of Machine Olfaction and Taste, T. Nakamoto, Ed., Wiley, 2016, pp. 219-245.(2) J. Burgués, V. Hernández, A.J. Lilienthal, S. Marco, "Smelling nano aerial vehicle for gas source localization and mapping," Sensors, voi. 19, paper no. 478, 2019.**

a. We added citations of the suggested research papers.

3. In the 6th line in Section 2.1, the authors said "These areas may be areas with high gradient or noticeable variance." However, I think that the authors should explain in more detail why such areas may have high gradient or noticeable variance, preferably by citing several research papers if needed. Most readers are not familiar with the characteristics of distribution of chemical substances.

a. We shortly explained the distribution of chemical substances and cited two research papers: *"Gas is usually dispersed through advection, which causes a gas plume to form downflow of the source. While turbulence and diffusion will cause the plume to meander and spread out, it's centerline may be found following the increasing gradient of the concentration [5]. Experiments with gas sensitive robots further showed, that the observed variance can also serve as an indicator for a gas source [12]."*

4. In the 5th line of the first paragraph in Section 2.2, the authors stated "The aerial platform allows measurements at different heights with minimum disturbance for present workers." As shown in Figure 1, the authors are assuming that multicopters are used as the aerial platforms. However, multicopters generally create strong downward airflow when they fly. Is there any possibility that the airflow disturbs workers and distribution measurement?

a. We clarified, that the aerial platforms will only operate in situations that allow the operation without disturbances for the workers: "To keep disturbance due to the UAV's induced downward airflow for workers as minimal as possible, the UAV will only be operated in appropriate areas and situations."

5. There seems to be several typos. For example, in the last line of the second paragraph in Section 2.2, "… informative spots that are that are identified …" should be "… informative spots that are identified …" Please carefully check the whole manuscript.

a. We rechecked the paper for spelling mistakes.

Guest editor:

1. The manuscript is lacking information about achieved results. Please include appropriate numerical data, measured or simulated, so that other authors can compare their results with yours.

a. As we are still in the early phase of the project, we do not have real or simulated data of the proposed scenarios and constellations, yet. However, we added a plot displaying the sensor data of an uncalibrated stationary sensing node: *"Uncalibrated measurements of a first prototype, deployed in an urban area, are visualized in Fig. 2. Both sensors are able to depict the day-night-cycle, with maxima in the early afternoons and minima in the late night."*

***Declaration of Interest Statement**

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

***Credit Author Statement**

Credit Author Statement

Winkler	Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization
Neumann	Conceptualization, Methodology, Validation, Investigation, Resources, Writing – Original Draft, Writing – Review & Editing, Supervision, Project administration, Funding acquisition
Säämänen	Writing – Original Draft, Writing – Review & Editing, Validation, Funding acquisition
Schaffernicht	Writing – Original Draft, Writing – Review & Editing, Supervision, Resources
Lilienthal	Writing – Original Draft, Writing – Review & Editing, Conceptualization, Validation, Supervision, Funding acquisition