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SmartAQnet – Remote and In-Situ Sensing of Urban Air Quality

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ABSTRACT

Air quality and the associated subjective and health-related quality of life are among the important topics of urban life in our time. However, it is very difficult for many cities to take measures to accommodate today's needs concerning e.g. mobility, housing and work, because a consistent fine-granular data and information on causal chains is largely missing. This has the potential to change, as today, both large-scale basic data as well as new promising measuring approaches are becoming available.

The project "SmartAQnet", funded by the German Federal Ministry of Transport and Digital Infrastructure (BMVI), is based on a pragmatic, data driven approach, which for the first time combines existing data sets with a networked mobile measurement strategy in the urban space. By connecting open data, such as weather data or development plans, remote sensing of influencing factors, and new mobile measurement approaches, such as participatory sensing with low-cost sensor technology, "scientific scouts" (autonomous, mobile smart dust measurement device that is auto-calibrated to a high-quality reference instrument within an intelligent monitoring network) and demand-oriented measurements by light-weight UAVs, a novel measuring and analysis concept is created within the model region of Augsburg, Germany. In addition to novel analytics, a prototypical technology stack is planned which, through modern analytics methods and Big Data and IoT technologies, enables application in a scalable way.

Keywords: air quality monitoring, environmental sensing, big data analytics, mobile computing, modeling

1. INTRODUCTION

The investigations of individual air pollution exposure and health risks suffer from the lack of available data. Older ground-based air quality monitoring networks are very specialized (e.g., by choosing hot spots for siting of instruments) and did not cover the entire area of a region of interest. One possibility to get higher spatial-resolved information is the use of satellite platforms for remote sensing with imaging devices or spectrometers as shown e.g. by Harbusch et al. (2005)[1], Li et al. (2011)[2], Levitan and Gross (2016)[3] or Lee et al. (2014)[4]. But a high spatial resolution cannot be provided as required in inhomogeneous terrain as e.g. in urban areas. Currently, more and more sensors on board of satellites are applied which are smaller, lighter, cheaper and more simply. This opens the door to a market for nano- and

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microsatellites which is developing rapidly (van der Wal et al., 2016)[5]. Now there is a strong focus on 2D imaging of the Earth's surface, and different innovative designs to realize advanced spectrometers for space applications in a more compact (volume of 10 x 20 x 20 cm^3) and cost-effective manner (van der Wal et al., 2016)[5]. So, more and more satellite sensors operating in the Earth orbit are available which are the basis for high spatial-resolved information.

New sensors are under development also for in-situ measurements of gaseous and particulate air pollutants, which promise similar characteristics as the advanced satellite sensors (e.g. optical measurement methods) and provide much more information than the currently used ones in air quality monitoring networks. Such sensors can particularly be installed onboard of mobile agents such as unmanned aerial vehicles (UAV) also. The trend is toward distributed measurements with large spatial resolution (Kumar et al., 2015)[6] as well as small-scale numerical simulation of pollutant distributions. This allows assessing and predicting the spatial and temporal variability of these pollutants, as well as to fuse collections of relevant data and enable their real-time analysis in a common context. This development provides the possibility for ground-truthing of high spatial-resolved satellite information too.

The project "Smart Air Quality Network" (Acronym: "SmartAQnet", http://www.smartaq.net/), funded by the German Federal Ministry of Transport and Digital Infrastructure (BMVI) and described here, is based on a pragmatic, data driven approach, which for the first time combines existing data sets with a networked mobile measurement strategy. The project goals and the work plan are described, and the project team and the expected results are introduced in this paper.

2. PROJECT GOALS

The main objective of this project is the development of an overall system for the recording, visualization and prediction of the spatial distribution of air pollutants in urban atmospheres that is relevant to the living environment of citizens. Existing data sources will be decisively supplemented by novel dynamic data sources. The "SmartAQnet" project aims to implement an intelligent, reproducible, finely-tuned (spatial, temporal), yet cost-effective air quality measuring network, initially in the model region of Augsburg, Germany. An overview of the full range of available measurement technologies is shown in Figure 1.

Figure 1. Range of measurement technology (image taken from Budde et al. (2014)[7]).

2.1 Data architecture

SmartAQnet follows a data-driven approach (i.e. gives priority to many different observations over simulation based on few precise measurements). Thus, the core component of the system is a data storage and processing architecture, which allows data to be easily imported, analysed and made available to different applications at different levels of abstraction.

The network will be designed to ensure that the data can be provided and widely used in the future for science, public authorities and citizens alike, compatible for scientific purposes as well as for user-oriented service development.

SmartAQnet employs a multi-layered heterogeneous network of sensors for the small-scale detection of air quality parameters in the model region, which allows the use of existing historical data sets to perform big data analyses for quality improvement and model validation. Research questions include novel algorithms, e.g. for distributed calibration, verification of data sources or the protection of the privacy of the citizens involved in the measurements who are to be tested under realistic conditions. In addition to the technical systems, the usable products of the system include novel data sets for the spatial distribution of air pollutants in urban areas, which are addressed to scientific operators, health researchers, political decision-makers and the general public. The entire system will be tested in a pilot study in the Augsburg model region with the participation of citizens and will be available to all regions of Germany. Based on the obtained data and the developed platform, prototypical exemplary applications and services, such as an application for air quality-related navigation, will be implemented and made accessible, in order to also demonstrate third-party exploitation possibilities.

Figure 2 shows the data architecture of the project, which implements a complete Internet of Things Stack using the latest Smart Data technologies. The underlying software architecture is a so-called kappa architecture, in which live data as well as historical data can be integrated continuously from constantly growing data sources. One important aspect of this architecture is that all incoming raw data is recorded as a log file before processing, which allows the reproduction of the results at any given time. This is important as calibrated and fused measurement will never be independent of each other and any changes made to a single part of the processing might require “replaying” of the whole analysis chain.

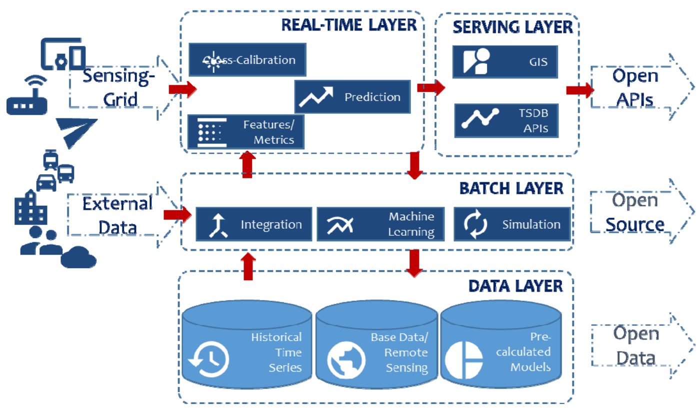

Figure 2. Data architecture of the project, which implements a complete Internet of Things Stack using the latest Smart Data technologies.

A real-time view on the data is made possible by the fact that raw data (possibly anonymous) is processed directly and stored simultaneously as a historical time series. In a data-flow oriented processing chain (red arrows), it is then merged with historical results using pre-calculated simulative and predictive models and made available almost real-time in services and applications. Thanks to the use of scaling technologies, this processing chain can easily be transferred to several larger (or smaller) regions.

The SmartAQnet Internet of Things (IoT) platform allows everyone to simply load measured environmental data into the system. The integration of various existing data sets (weather, traffic, topography, etc.) and data of stationary and mobile measuring devices of different quality, as well as the provision of useful metrics calculated using Big Data methods is another central aspect. To simultaneously increase the measurement density and the measurement quality, not only existing data are integrated, but also intensive measurements are carried out in the Augsburg model region. This also includes the development and testing of new mobile measuring instruments in order to minimize or close adaptively existing gaps of static measurement networks. The measurements should be carried out if necessary by drone or UAVs or nationwide by citizens. One important aspect of the project is that we include any “measurement” devices that provide observation that potentially decrease the uncertainty of a hypothesis in contrast to perfectly controlled measurement processes as e.g. defined by DIN 1319. It will be a challenge for the data acquisition to record the diverse contexts of each observation.

2.2 Mobile sensor network

In order to integrate a wide range of measurements with instruments of various available price and quality classes, four sensible classes were identified:

1. Highly accurate scientific measurement technology (e.g. integrated into existing measuring networks).

2. Novel, cross-linked devices ("Scientific Scouts", to be developed in the project), or existing devices (e.g. LOAC-R and Alphasense OPC-N2). Mobile and stationary units (autonomously collecting and transmitting data, for example, also for UAV monitoring).

3. Consumer-grade sensors (e.g. Dylos DC1700).

4. Low-cost measurement sensors (e.g. laser light-scattering sensors like Novafitness SD011/SD021 or smartphone attachments such as iSPEX (Snik et al., 2014)[8] or clip-on light scattering sensors (Budde et al., 2013)[9]).

The challenges in the development of new sensor systems include low investment costs (to achieve a high density), while maintaining sufficient accuracy and precision at a high temporal resolution (to globally decrease the uncertainty of a given model). For long-term research and sustainable operation, reliability of measurements and a high tolerance to environmental influences (load, temperature, pressure and humidity) is critical. Further aspects, such as network capability and smartphone connection (for integration into modern telematics systems or building monitoring systems), long-term stability and low maintenance, must be viewed and weighed against each other and with other system parameters (for example, algorithms for compensating lower precision). Methods have to be defined in order to ensure uniform time standardization (time stamp) and temporal resolution of all sensors in the network.

The development / manufacturing of stand-alone Scientific Scouts (autonomous, mobile smart dust measurement device that is auto-calibrated to a high-quality reference instrument within an intelligent monitoring network) for mobile and stationary use within the project (e.g. on public urban transport platforms, road lighting, etc.) involves the exploration of two different types of measuring instruments. These are, on the one hand, measuring instruments which primarily measure particulate mass concentrations (PM values) and, on the other hand, particle measuring devices which place their measuring focus on the particle number concentration and particle size distribution in order to obtain important information on the cause analysis of the exposure to fine dust (source identification). In doing so, it is important that the self-diagnostic tools are maintained, e.g. pollutant levels and the associated measured value drift. Depending on the measuring focus, the measuring principle is based on optical sum (nephelometry) and / or individual particle analysis (optical particle counting). Optimally, both should be covered by an inexpensive nephelometer. A major challenge lies in an extremely fast and intelligent signal evaluation, which has to be developed through extensive comparison measurements to reference devices. Such devices generally have a low signal-to-noise ratio, which can additionally be significantly altered by environmental influences. The aim of the project is to build up the test network in the model region consisting of 50 scouts + 5 reference meters.

2.3 Data Fusion

However, a new quality results from the interplay of the different measurement data at different quality and quantity levels. A major part of the project will work on investigating the plausibility of observations and derived models. The production of consistency and also the intelligent communication of the mobile measuring devices (for example validation and self-calibration) are central challenges and interesting research questions. Ultimately, it is about researching under which conditions and for what purpose also inaccurate sensor technology (used by non-experts) are used to generate valuable large high-resolution data sets. For example, it is expected that the merger with open data sources will enable us to better understand relative influences from weather, traffic or building situations. A classical evaluation of individual sensors by comparison measurements could not answer the feasibility of such analyses.

The configuration of the SmartAQnet can be modelled as a space, time and precision-dimensional feature space (large arrows) as shown in Figure 3: crowds with low-cost sensors (green) scatter irregularly in space and time at low precision, however high number. Stationary high-precision measurement (yellow) takes place at the highest quality level and continuously over time, but only at one point in space. Between the two layers, the mobile measurement is based on a medium level of precision: in one case regularly on certain routes (red) and in another case with high spatial density at a few points in intensive measurement campaigns (blue). Thus, the crowd measurements can be geo-statistically projected onto a higher quality level and the high-precision measurements (thin black arrows). This results in an overall higher information density at an elevated quality level than the sum of the individual measurements alone could provide, so that applications with continuous data are possible.

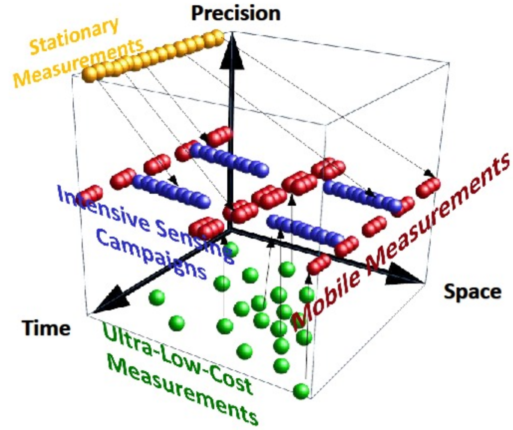

Figure 3. Configuration of the SmartAQnet modelled as a space, time and precision-dimensional feature space (large arrows): crowds with low-cost or ultra-low-cost sensors (green) scatter irregularly in space and time at low precision, however high number.

Part of the sustainability of the platform is an open and participatory approach, which requires awareness and active participation (Burke et al., 2006)[10]. In contrast to existing air quality information, the citizen (initially in the model region) should be able to record measurement data and to feed it into the platform, e.g. via smartphones, which in turn provides him with more accurate air quality information for his location or movement route. The (commercial) exploitation strategy is based both on these data-based applications and services as well as on the new technologies for the detection. This is also to ensure the long-term recording and provision of the data. The data, as well as the technology for integration and analysis, should be freely made available (as long as no rights of third parties are affected).

3. CONSORTIUM

SmartAQnet is a collaborative project of partners from business, science, civil society and public authorities.

The research group TECO of Karlsruhe Institute of Technology (KIT) is the project coordinator of SmartAQnet and has a long research tradition in the fields of pervasive and ubiquitous computing, wireless communications, embedded systems, data analysis and human computer interaction (HCI). Past research includes mobile participatory aerosol measurements in Citizen Science and distributed measurement scenarios (Budde et al., 2014)[7], the impact of non-experts and their inclusion in the measuring chain (Budde et al., 2015)[11], as well as the distributed calibration of cost-effective sensors and the protection of privacy in such systems (Markert et al., 2016)[12]. An important focus of TECO is applied research in the field of predictive analyses and big data mechanisms with a focus on sensor data and smart cities. TECO advises small and medium-sized enterprises on the use of Big Data technology in industrial applications (Borges et al., 2017)[13], and also heads the Smart Data Innovation Lab (SDIL, www.sdil.de), one of three Big Data Competence Centers funded by the Federal German Government.

At the KIT the Institute of Meteorology and Climate Research, Atmospheric Environmental Research (KIT/IMK-IFU)'s expertise is in the areas of monitoring and urban climate research. The focus of the working group is on the vertical structure of the urban boundary layer, which can be detected using ground-based remote measurement techniques (Schäfer et al., 2006[14]; Emeis, 2010[15]) or multicopter-based air sampling (Brosy et al., 2017)[16].

The group at the chair for Physical Geography and Quantitative Methods in the Institute of Geography of the University of Augsburg (IGUA) focuses on climate research, landscape research and environmental health sciences. Earlier, fundamental studies of the urban climate in Augsburg (Jacobeit, 1986)[17] are flanked by synoptic analyses (Beck et al., 2014)[18] and distributed and mobile measurements in urban areas (Seidel et al., 2016)[19]. With a working group for unmanned aerial vehicles, IGUA contributes experience from larger measurement campaigns, e.g. ScaleX (Wolf et al., 2016)[20] or the feasibility study Aerosol Supersite at the high-altitude environmental research station Schneefernerhaus.

At the Helmholtz Zentrum München (HMGU), genetic interactions as well as environmental and lifestyle factors are examined to develop individual strategies for the diagnosis, treatment and prevention of people's diseases. The focus of research at the Institute of Epidemiology II (EPI II) is on the comprehensive collection of environmental stressors (e.g. airborne pollutants, meteorological parameters, noise) as well as on the investigation of risk factors for the development of diabetes or cardiovascular diseases (Peters et al., 2015[21]; Panni et al., 2016[22]). The focus of the collaborative group Comprehensive Molecular Analytics (CMA) is the development and application of methods to capture the chemical composition of the organic portion of the aerosol with high sensitivity and accuracy. The data obtained with these methods are used to identify and quantify the sources of the environmental aerosol (Schnelle-Kreis et al. 2005)[23] and to identify and quantify the influence parameters for variability of PM concentrations in the environment (including source strengths, propagation conditions, photochemical aging (Shen et al., 2016)[24]).

The Aerosol Academy (AA) is a regional, national and international point of contact for persons and institutions from science, business, authorities and administration. It operates an interdisciplinary active network for co-operation, projects, communication and knowledge concerning aerosol technology and aerosol research. It has expertise in aerosol, gas and climate measurement techniques in general and in opto-technical signal acquisition and signal processing in particular Grimm and Eatoug (2009)[25].

GRIMM Aerosol Technik Ainring GmbH & Co. KG is one of the world's leading companies in the field of environmental and occupational health and safety surveys, whether at authorities, in research and teaching institutions, safety engineers or accredited bodies for air pollution measurements (GRIMM, 2016[26]; Edfelder and Pesch, 2016[27]). The project objectives require the modification, application and assembly of low-maintenance measurement cells, new smart signal evaluation strategies and software packages in the system. GRIMM is able to further develop the cost-effective nephelometry to an almost equivalent alternative to very complex spectrometry. A universal use, both mobile, as well as airworthy or stationary, should be possible.

The environmental office ("Umweltamt") of the City of Augsburg, Germany supports the consortium as an unsupported associate project partner. Communication with interested schools, which are already active in the field of environmental research and air monitoring, is made possible and facilitated by the Umweltamt.

4. CONCLUSIONS

The SmartAQnet research initiative focuses on the subject of data access and data-based applications. Central to this is the development and utilization of partial, already existing (but not yet combined) data on the one hand and the collection and integration of relevant missing data on the other hand. This includes the integration of third-party sources and the development of novel measuring devices, as well as an improvement of the overall data quality and the identification and implementation of meaningful interfaces between devices, databases and the end user.

On the data, new applications will be implemented. For this entire data-driven software chain, also new methods are explored. Specifically, these are big data analyses for quality improvement and model validation, as well as novel algorithms, e.g. for distributed calibration, verification of data sources or the protection of privacy of the measuring individuals. The project involves substantial novelty in several of the eligible categories: the core is a feasibility study aimed at investigating the potential of wide-spread distributed aerosol measurements with intelligent measurement networks of heterogeneous sensors in urban areas. In particular, the possibilities and dangers of bringing experts together with laypersons will also be investigated (see (Budde et al., 2017)[28] for first results). A major part of the project work is also to bundle existing scientific, technical and economic competence on the one hand, and data from various sources on the other, thereby providing a novel application for various actors, right up to the end user needs. In the course of the project, various prototypes and demonstrators will be developed: new (small or mobile) aerosol measuring instruments, new exemplary applications on the merged and newly collected data as well as new algorithms for the distributed calibration of swarm sensors and to protect the privacy of the data raising citizens. Optical measurement methods – not only – play an important role for these developments.

Finally, the project is also intended to promote industrial research. In recent years, it has become clear that air quality monitoring will change fundamentally in the future (Snyder et al., 2013)[29]. If this new generation of air quality monitoring is to be consistently pursued, in Germany, too, the expensive costly stations, which are now around 800, will not be supplemented with other high-price stations but with a spatially high resolved, heterogeneous network of distributed and possibly also mobile measuring instruments. This provides information for end users with consumer measurement technology and access to personified air quality data. This new ground-based or UAV-based air quality monitoring provides the basis for ground-truthing of satellite observations with high spatial resolution too.

For the understanding of the city climate and the spatial and temporal distribution of air pollutants, a large amount of data is relevant. For example, the mCLOUD data (www.mcloud.de) of the German Meteorological Service (DWD) with data from the fields of weather, climate and environment or the Federal Highway Research Institute (BASt) with data from the fields of road traffic and transport infrastructure are highly relevant for an integrated data set and the big data analyses that are to be developed.

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