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Conception and deployment of the APOLLINE sensor network for IAQ monitoring

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Abstract. The long-term study of air quality inside buildings in the presence of occupants requires the deployment of low-cost instruments capable of measuring the most concerning pollutants, without nuisance to the occupants. Several laboratories within the University of Lille, France, have united their expertises within the APOLLINE project (Air Pollution and Individual Exposure). They have designed a complete infrastructure for IAQ research and education, based on chemical (NO, NO_2, O_3, CO, CO_2, COV, granulometry of PM 0.4-16 µm) and physical (P, T, RH, light, sound) sensor nodes. The nodes continuously send raw measurements through Ethernet or various wireless technologies to the APISENSE® cloud platform operated by Inria, for offsite real-time visualization and analysis. The network was successfully deployed since July 2018 within the buildings of University of Lille, with interesting results on the pollution levels and occupancy patterns.

1. Introduction

Indoor air quality (IAQ) has been recognized as a major health problem worldwide [1], with an economic cost evaluated to hundreds of billions of dollars [2]. Still, indoor air quality is far from being a mature science, and the understanding of the chemistry inside indoor environments, such as lodgings, workplace, vehicles and other transportation systems, recreational facilities, is far from complete [3]. In spite of the increasing number of studies, these are still limited and do not cover all different cases. From these studies, an even smaller number of indoor air quality models have been developed, that may not consider all the drivers of IAQ yet, or may not completely reproduce the observed concentrations of pollutants [4]. It is therefore necessary to continue the experimental investigation of IAQ, and in particular to investigate the role of the occupants and of their activities.

In order to study indoor air quality in buildings, especially in the presence of occupants, it is necessary to develop and deploy instruments that satisfy simultaneously several requirements. One set of requirements pertain to the absence of nuisance produced by the apparatus, such as bulkiness, noise, vibration, with the ideal instrument being as inconspicuous as possible, so that the occupants are not aware of its presence and therefore do not modify their behaviour. Another set of requirements is related to the performances of the instruments. They are expected to measure all or almost all the chemical species of interest, (i) with well-characterized metrological performances, in terms of

sensitivity, (ii) absence of interference from other species or from environmental parameters such as temperature, humidity, direct light, and (iii) no drift with time. In addition, in order to describe correctly possible fast-changing conditions, a response time of the order of the minute or less is necessary. Lastly, because of the many different environments and conditions to be explored, the cost, ruggedness, long time autonomy, unattended functioning, as well as real-time analysis and reporting capability of such instruments must also be considered.

While no instruments can fulfil all these criteria simultaneously, nodes composed of miniature sensors stand out as extremely interesting candidates [5]. Such sensors are increasingly used in atmospheric chemistry and indoor air quality studies, as well as for exposure studies, with an increasing number of studies published in scientific journals, establishing the performances of some of the sensors commercially available [6], or using these sensors to analyse some case studies [7].

The multidisciplinary Apolline project (Air Pollution and Individual Exposure), developed by laboratories of the University of Lille, is an experimental platform for IAQ study and education, with miniature chemical sensor nodes continuously streaming data to a server for offsite visualization and analysis.

2. Architecture overview

2.1. Sensors nodes

The sensor nodes (figure 1) are designed to accommodate all kinds of sensors for physical parameters (T, RH, P, motion, light, and sound level) and for the quantification of chemical pollutants. The chemical sensors installed so far include electrochemical sensors (Alphasense, B-series) for O_3, NO, NO_2 and CO, a PID sensor (Alphasense) for VOCs, an NDIR sensor (Alphasense) for CO_2, and an optical particle counter (Alphasense OPC-N2) measuring particles with a diameter in the range 0.3-16 µm in 16 bins. Some of the nodes have an additional SO_2 electrochemical sensor. Metrological issues such as calibration of the chemical sensors or possible long term drift in the signals are fundamental to ensure the quality of the measurements prior to deploy a fully unattended network [8]. In the present work they are addressed by periodical checks of the response of the sensor boxes in laboratory conditions, and are not reported here.

An Arduino board acquires the signals from the chemical sensors. A Raspberry Pi 3 manages the time synchronization and the real-time transfer of the data to a server with Ethernet or wireless technologies (WiFi, LoRa, Zigbee, Bluetooth), every 30 seconds. The Arduino and Raspberry programs have been developed within the laboratories members of the Apolline project.
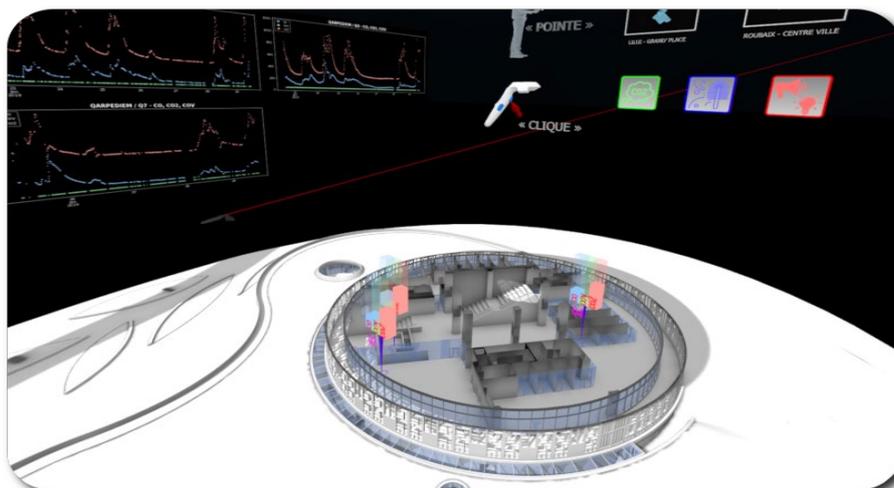

Figure 1. APOLLINE sensor node.

2.2. Server-side infrastructure

The server-side infrastructure of APOLLINE is a cloud software systems, named APISENSE® (https://apisense.io), that builds on a time-series database (TSDB) and a visualization dashboard. This solution delivers long-term storage capabilities with the ability to include new types of measurements according to the evolutions of the nodes. More specifically, we build on the InfluxDB open source software, which offers a robust database to store all our measurements on a single virtual machine. The real-time visualization of these metrics is implemented as customizable dashboards on Grafana (figure 2). Beyond storage and visualization, this software architecture also supports the automated analysis of measurements, which are implemented in Python and can be run online from a Jupyter environment. We also consider the implementation of a 3D virtual representation of indoor environments, which are enriched with visual gauges reflecting current concentrations of monitored chemicals (figure 3).

Figure 2. Screenshot of the Grafana interface. One month long measurements by one the sensor box in the Lilliad Learning Center.

Figure 3. Screenshot of the VR 3D visualization: the second floor of a 3D model of the Lilliad Learning Center is displayed, with a set of sensors from the 3 devices located on that floor.

3. Deployment of the sensor boxes

The sensor boxes have been deployed in several buildings of the University of Lille. Four are installed in the Lilliad Learning Center (figure 4), which is a multi-use facility including the science library, a food court, conference rooms, small working spaces, and the technological showcase, in addition to the library stacks and offices for the staff. This wide diversity of usage and activities renders this building particularly interesting to analyze air pollutant patterns and the exposure of patrons and staff. A fifth sensor box is permanently located in the air pollution chemistry lab, where it is used to assess the metrological performances of the sensors, in particular over long periods of time, to test and develop the necessary calibration procedures, and to study the impacts of human activities, consumer products on the air quality, under controlled conditions. A sensor box is permanently installed in the electronics laboratory, for ongoing development. Another sensor box is placed on the roof of one of the buildings of the University, collocated with many reference instruments dedicated to study atmospheric pollution, and in particular the particle concentration and composition. This sensor box therefore provides the characterization of outdoor air, necessary when studying indoor air quality.

The diversity of environments where the sensors have been deployed has allowed us to test the robustness and limitations of the communication protocols. Unexpectedly, the major difficulties encountered in the deployment were not related to the sensor boxes themselves or to the Apolline infrastructure, but to the high security level of the Ethernet network inside the Lilliad Learning Center, which prevented us at first to upload the data onto the server database, as well as the low reliability of the eduroam WiFi network, with frequent interruptions of the connection.
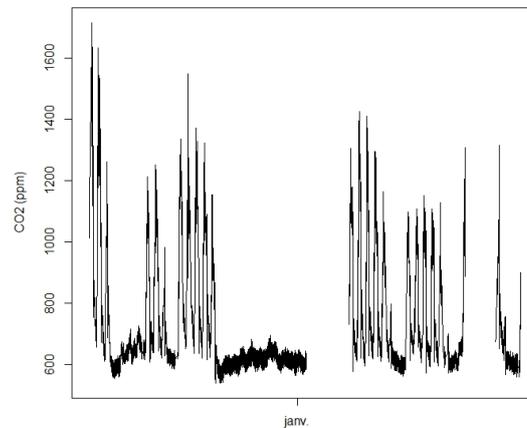

Figure 4. Sensor box in a workspace of the Lilliad Learning Center.

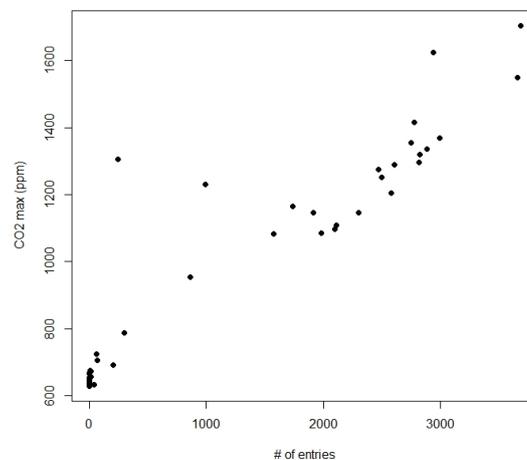### 4. Some results: CO_2 level and occupancy counting

We only consider here the CO_2 concentrations measured by the Apolline sensor boxes installed in the Lilliad Learning Center. These concentrations are displayed in figure 5 for the sensor box placed on the middle level of the main hall of the Lilliad Learning Center, between December 6, 2018 and January 25, 2019. This period includes the winter holidays with no people in the building (December 22 to January 6), as well as a period of exceptional closing between December 9 and 12, 2018.

The CO_2 concentrations show a regular pattern characterized by a sharp increase every weekday between 8am and 10pm (opening period of the building), followed a return to the baseline value of ~600 ppm. Still, this baseline value is not reached except during the weekends, because the air exchange rate of the building is not sufficient to evacuate completely CO_2 overnight. An additional weekly oscillation in the baseline can also be noticed, even during the holidays, but is not explained yet. The maximal CO_2 concentration measured with this sensor is ~1700 ppm, which might be considered too high, or at least indicative of insufficient ventilation, though no guideline or standard has been set in France for CO_2 indoor concentration. The maximal CO_2 concentrations measured within the Lilliad learning center come from the sensor box located in the food court, with values above 2000 ppm everyday around lunchtime.

Figure 5. CO_2 concentration in the Lilliad Learning Center, from December 1, 2018 to January 25, 2019.

The daily variation of the maximal CO_2 concentration can be explained by the variation of the number of occupants of the buildings. Most of the published studies on CO_2-derived occupancy focus on developing algorithms for near real-time prediction of the occupancy of well-defined, relatively small rooms, and usually require other information such as an accurate measurement of the air exchange rate [9]. Such is not the case of the Lilliad Learning Center, with a large open hall spanning three levels, and a simultaneous occupation in excess of 1500 persons. Still, we can relate the daily maximal concentration of CO_2 with the number of entries in the building, given by the counters logging entry and exit located at the entrance of the building, displayed in figure 6. The correlation between both metrics is unexpectedly good considering (i) the large volume of the building, (ii) the ill-defined shape of the hall, (iii) the calculations made with daily values, and (iv) the fact that some people may enter the building but go directly to the other spaces accessible from the main hall, such as the conference hall or technological showcase, that are quite separated from the main hall. Still, this demonstrates the feasibility of using CO_2 measurements for determining the occupancy of a whole building.

Figure 6. Correlation of the daily maximal CO_2 level with the number of entries in the Lilliad Learning Center.

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5. Conclusions – possible applications and future developments

Thanks to a close collaboration between several laboratories within the University of Lille, the Apolline network for the study of indoor air quality is fully operational. Sensor boxes have been assembled and validated for the quantification of gaseous and particulate air pollutants. The signals from the sensors are uploaded in real time to a server for offsite visualization and analysis. The sensors have been deployed in various buildings of the University. Their potential for the characterization of the indoor air quality, as well as for problems related to the management of the buildings, such as the determination of the occupancy, has been demonstrated. The future steps will consist in technical improvements to the present system, most particularly the automatization of the analysis procedure, and on the other hand in the deployment of the sensor boxes on a wider scale so as to construct a database of indoor air quality in various environments.

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