Contribution to the design and implementation of a reflexive cyber-physical system: application to air quality prediction in the vallées des gaves

Sylvain Poupry, Cédrick Béler, and Kamal Medjaher

Laboratoire Génie de Production, ENIT - Toulouse INP, 47 Avenue Azereix, Tarbes, 65000, France
sylvain.poupry@enit.fr
cedrick.beler@enit.fr
kamal.medjaher@enit.fr

ABSTRACT

This thesis aims to set up a scientific approach to monitor and take preventive actions on the air quality for the actors of a territory not covered by conventional measuring stations. Thus, a Cyber-Physical System (CPS) approach combined with Prognostics Health Management (PHM) methodologies is chosen to move toward a self-monitoring and self-reconfiguration system. To collect data in an inexpensive manner, measurement stations with low-cost sensors (LCS) are developed. LCS have drawbacks and the first part of this thesis is the use of redundancy and a proposed algorithm to increase their hardware and data reliability. A first station is deployed as proof of concept and the region is already receiving real-time data. The next phase is to build forecasting models to help authorities make decisions.

Keyword: Cyber-Physical System, Internet of Things, Prognostics & Health Management, air quality, citizen engagement, natural system.

1. MOTIVATION AND RESEARCH PROBLEM STATEMENT

The objective of the thesis is the proposal and implementation of an innovative scientific approach for the monitoring and prediction of air quality on the territory of the Communauté de Commune Pyrénées Vallées des Gaves (CCPVG). Located in the South of France, in the Occitanie region, in the South of the Hautes-Pyrénées department, the CCPVG is an inter-municipal territory of about 1000 km² and covered by forests and semi-natural environments as well as high mountains.

The territory of the CCPVG is confronted with peaks of air pollution linked to wood heating, firewood burning, and road traffic. These emissions of specific pollutants hide more serious risks such as background pollution, which is more dangerous for health because it acts over the long term. This is why it is important to monitor pollution throughout the year. In France, air quality monitoring is delegated to the Air Quality Associations (ASQA) under the supervision of ATMO France. In the case of the CCPVG, ATMO Occitanie is in charge of air quality monitoring and provides three tools: a real-time and continuous measurement network with conventional stations, pollution maps and daily predictions, and an annual regional emission inventory.

However, these three tools are insufficient for many territories similar to the GVCC. First, the regional inventory is an annual and global synthesis of pollution emissions and their impact on air quality. This inventory is published after a considerable time of analysis in addition to the time of data collection. Moreover, it is an estimation based on statistical data and does not allow to have a ”real-time” vision of the situation and to act quickly to limit the pollution effects. Secondly, the pollution maps and predictions are based on measurements made by the fixed stations of ATMO Occitanie and there are only two fixed measuring stations in the Hautes-Pyrénées department. As there is no fixed station on the territory of the CCPVG, the data provided by ATMO Occitanie are extrapolations collected on a reduced number of sensors which is not necessarily optimal. Indeed, this territory presents a particular topology (mountains and valleys) that generates local phenomena of pollution concentration. These local pollutions are detected by the inhabitants but escape the monitoring of the ASQA.

This thesis aims at setting up a rigorous approach that will make it possible to provide elements of scientific, tangible, and quantified knowledge to the citizens and the actors of the territory in charge of monitoring and managing the air quality. Based on these elements, the latter will be able to better apprehend the pollution problem, estimate, predict and evaluate its severity, and define preventive action plans (sensitiza-

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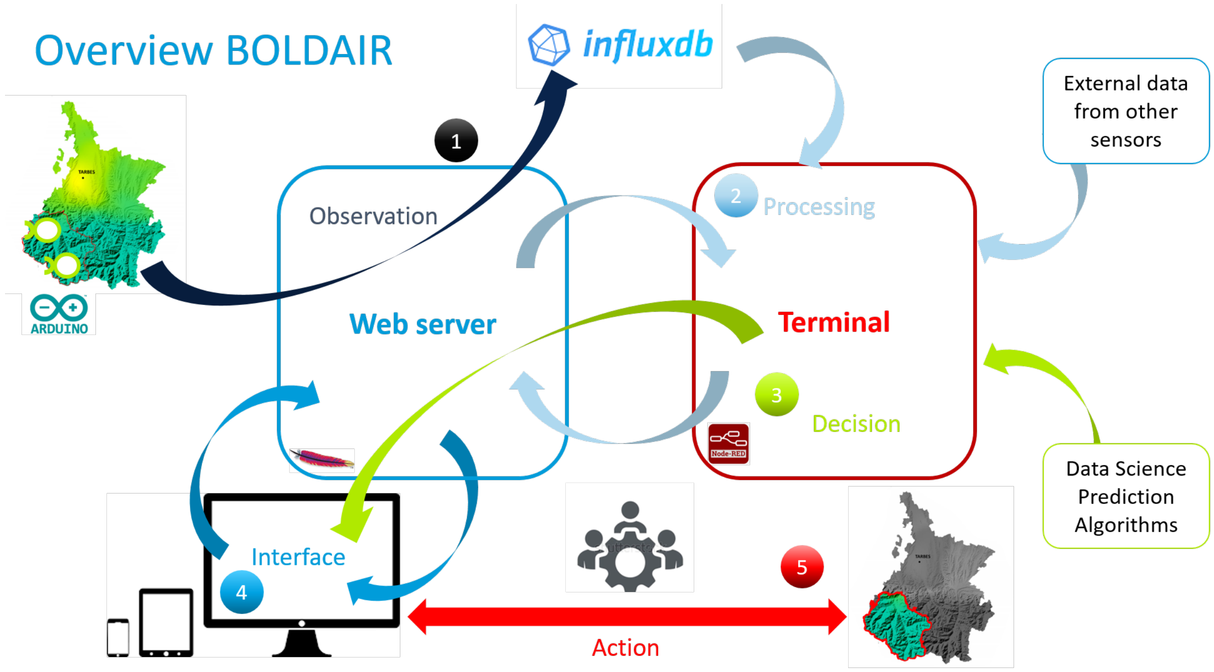

Figure 1. The five modules of the CPS

tion of the inhabitants, incitement to the use of heating fewer pollutants emissions, incitement of the stockbreeders to less resort to ecoburials, etc.), but also and especially pro-active (regulation of the road traffic and industrial pollution by anticipation of future degradation of the air quality). The proposed approach will take the form of a Cyber-Physical System (CPS) equipped with observation, processing, decision, action, and communication capabilities. For that, three axes of scientific developments will be approached:

1. Monitoring dimension: instrumentation of the territory to have a *real-time* vision of the air quality;
2. Prediction dimension: the anticipation of air quality degradation and proposal of proactive actions;
3. Societal dimension: involvement of various actors (elected officials, inhabitants, tourists, etc.).

2. A BRIEF DISCUSSION ON THE STATE-OF-THE-ART

Pillars of Industry 4.0, the CPS appeared in 2006. Heirs to the Internet of Things, they have become a priority focus. There are several definitions of CPS depending on the domain where they are used (Monostori, 2014). In this thesis, a CPS is defined as "an orchestration of computers and physical systems. Embedded computers monitor and control physical processes, usually with feedback loops, where physical processes affect computations and vice versa" (Lee, Bagheri, & Kao, 2015). CPS form a closed loop between the cyber/digital and physical worlds based on state detection, real-time analysis, scientific decision-making, and precise execution. Then, different CPS architecture are proposed in literature (Monostori, 2014; Lee et al., 2015; Shi, Wan, Yan, & Suo, 2011), and the one we will consider is the "5C" architecture proposed by Lee in 2015 (Lee et al., 2015). This article is a guide to incrementally building a high-value CPS. The first step in building a CPS is augmenting the physical system by adding computational, communication, and analytical capabilities, i.e., the territory to be observed will be augmented with a network for measuring pollution concentrations. For territories not covered by measuring stations, Low Cost Sensor (LCS) networks are an opportunity to monitor Air Quality (Castell et al., 2017). Less expensive, in the order of x10 to x100, they are easier to deploy and require few qualified personnel. Although they provide coarse measurements, their strength lies in their spatial dimension, which allows the detection of local pollution (Kumar et al., 2015). However, they have several drawbacks, notably in terms of repeatability, reliability, and lifetime (Morawska et al., 2018). Also, research works are insufficient about LCS deployment experimental duration. Indeed, the duration of the published studies varies from a few days to 4 months on average with an exception made for a study carried out over 11 months (Bauerová, Šindelářová, Rychlík, Novák, & Keder, 2020). These durations are thus insufficient especially when the study subject must be monitored continuously over several years.

3. Novelty and significance relative to the state of the art

Based on the 5C architecture, the analysis of the state of the art shows that, in practice, the total integration of functionalities within a CPS is only very rarely achieved. The goal is then to achieve a complete CPS capable of observing, processing, analyzing, predicting, acting, and communicating, but also of self-monitoring to detect any anomalies the CPS may experience and to self-reconfigure it accordingly. We get then of a *reflexive* CPS, that is to say introspective, having consciousness of itself (observe, model, and evaluate) and capable of acting on itself (switching in degraded mode, adaptation, evolution). For this purpose, we propose to integrate PHM (Prognostics and Health Management) functionalities in the architecture to assess online the health status of the CPS (Medjaher, Zerhouni, & Gouriveau, 2016; Atamuradov, Medjaher, Dersin, Lamoureux, & Zerhouni, 2017). This integration will provide greater confidence in the adaptability of the prediction system based on networked components (sensors, processing, and actuators).

At the level of the physical system augmentation, which is the first step of the CPS construction, the pollutant concentrations are measured with a measurement network deployment. However, the deployments from the literature do not take into account the relative reliability of the sensors and the possible improvements found in the sensor technologies (clustering, post-processing with Machine Learning, etc.). Novelty of the work proposed in this thesis lies in the use of modular redundancy at the measurement point. Indeed, the fact of measuring the same parameter several times at the same place with several sensors makes it possible to group the LCS to increase their reliability but also to compare them to detect their possible failures. The interest of this approach is to go further at the level of the measurement horizon and to avoid the drawbacks that are not solved during standard deployments with LCS.

4. Approach and proposed experiments

The first step consists in proposing an elementary system as modular CPS (figure 1). The CPS is composed of five linked modules (Observation, Processing, Decision, Interface, and Action) aiming to provide services.

The second step is to design and develop the first Observation module by selecting LCS and making them smart. The combination of LCS with a development board having communication and calculation capabilities allows to build a Smart Sensor (SmS). Its purpose is to measure parameters at a point, to calculate their concentration and to transmit a vector of data which is the concatenation of the processed measures with the name of the associated parameters.

The third approach is to propose an architecture composed of measuring stations that exploit SmS combined with an Aggregator. The latter element receives the vectors of data emitted from the three SmS arranged in the same measurement perimeter and measuring the same number of parameters. Then, it restructures the data and aggregates them to perform a synthesis . The next step will be to process the data in order to make this architecture reliable and resilient for air quality monitoring (Processing module in the CPS).

The final step is making the Interface and Decision modules to propose a decision-support for authorities to act on the air quality and the CPS itself.

5. Work in progress or results

The design of the SmS has been completed and they have been deployed. There are currently three of them. The acquired data are sent to a central server with a graphical interface that allows tracking the pollution evolution in real-time. This central server currently integrates the Aggregator which could have its own calculation unit depending on the calculation needs and the following deployments.
The work in progress is at the level of the functionalities of the Aggregator. The first function, as a reminder, is to receive data from the three (or more) SmS, store, and restructure them by parameters. The second function is the detection of abnormal raw data due to sensors faults. The work in progress consists in creating detection algorithms at the sensor level and at the Air Quality level. In a first step, the detection of sensor anomalies allows making the data more reliable and replacing the faulting LCS to restore the confidence in the data of the measuring station. Then, at the air quality level, other algorithms will allow to follow the air quality and to detect pollution peaks. The evolution of these abnormal concentrations over time will allow predicting the next pollution peaks. This work will help the competent authorities to take decisions and to follow the effectiveness of their actions to improve the air quality.

6. Discussion of applications and the contributions of the work

The deployment of the first measurement station validates the proof of concept of the observation part of the CPS. Other stations will be deployed and the territory will be "augmented" for the measurement of air quality. Indeed, these stations offer syntheses on two aspects: The air quality as an observed system and the CPS itself by monitoring its components. The implementation of the PHM at the hardware level and the actions to replace failing sensors add reflexivity to the CPS. This feature allows (with human intervention) an extensive horizon of measurements and reliability to the data for the final objective of monitoring and forecasting air quality on the territory of the CCPVG. Once the CPS is fully implemented, it will provide a reliable decision support to local authorities to

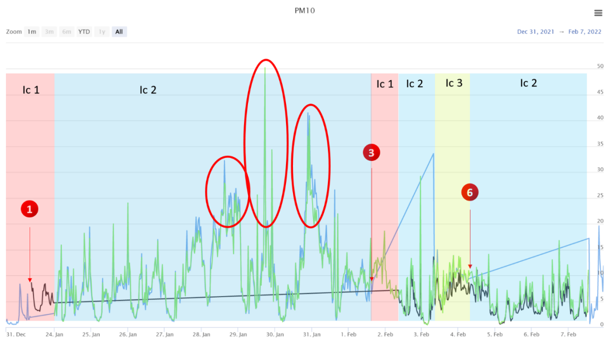

Figure 2. This is an example of output of the CPS.

act directly on pollution in case of alert and to observe on the long term the measures taken and their efficiency. It will also be able to provide a contribution to ATMO FRANCE and ATMO OCCITANIE by sharing data and thus to carry out data crossings to check if the pollution episodes detected by the association are also detected by the measurement network. These information will be exploited to specify the pollution maps and to refine the territory grid.

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