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From Sensors to Applications: A Proposal to Fill the Gap

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Abstract: In this paper, basing on the results of previous studies, we present an information processing architecture that aims to lessen the distance between sensors and applications in as much humanly unsupervised way as possible. With the impressive growth of todays computational and miniaturization technologies, it is likely that the distance between sensors and applications could be covered by one single device or system only. Practically, it happens that experts such as system integrators or engineers are often needed to fill in the gap. The proposed computational model uses the notion of 'holon', a concept that is well suited for multi-level information processing, from the raw data level up to the knowledge-oriented information level. For test purposes, a data analysis platform called H-GIS that grounds on the current proposal has been employed and a case study has been commented. *Copyright © 2013 IFSA.*

Keywords: Information processing, Smart sensors, Intelligent sensors, Holons, Applications.

1. Introduction

Traditionally, sensors have been used by practitioners and engineers as transducers of physical quantities into instrumental signals mainly for measurement purposes.

Nowadays, in the era of information technologies, sensors are becoming ubiquitous and are no more used by experts only. Most of us even ignore to bring a bunch of sensors (accelerometers, gyroscopes, gravitometers, etc.) always with them, embedded in their smartphones. Certainly, since the target users have changed, also the original idea of sensor as simple physical transducer has to be rethought in favor of an up-to-date perspective.

Modern sensors can be smart observers of the reality they are immersed in and, in the longer run, it is not so hard to think they will behave so intelligently to be proactive, understanding the context where they are actually being used and thus providing only the relevant information to the user (for example that a gas leakage has been detected and it is better to move to a safe destination).

Our credence is that for this scenario to become real sensors have to evolve in terms of 'process observers': i.e., they should be able to manifest a higher interface to the application level of the hosting system by providing a measure of the situation they are sensing more than a raw value.

In this paper, we present an information processing architecture that aims to lessen the distance between sensors and applications. This attempt is made possible thanks to a number of previous studies and is further supported by a recently developed data analysis platform that grounds on the proposal reported here.

The remainder of the paper is as follows: Section II discusses the current technological solutions employed to bridge the sensors/applications gap and a prospective view is also provided; Section III reports on research outcomes that can be applied through the information processing chain; Section IV enlightens the current proposal; Section V comments the case study of air quality monitoring performed with heterogeneous low-cost data sources; Section VI draws conclusions.

2. Problem Overview

It is a matter of fact [1] that there is a language gap between practitioners working with measurements and experts in Artificial Intelligence (AI). This is reasonable since, at a first impression, they account for very different domains. However, such domains are strictly linked in real-world situations.

To make an example, let us consider SCADA systems. They heavily rely on sensors but they also need a certain amount of human intelligence for data output to be properly used (e.g., for supervisory control purposes).

Under this view, the information processing chain from sensors to applications begins with raw data acquisition and finishes with a human action: thus, the aspects of measurements and intelligence become the endpoints. In this paper, the aim is shrinking this chain.

As a result, a new generation of scalable systems architectures has to be developed to traverse the entire information processing chain from end to end; in the sequel, the focus is on what is there in between.

2.1. The Information Processing Chain from Sensors to Applications

At the very core of any sensor, there is a transduction action permitting the transformation of measurands into analogue output. This is what exactly a traditional sensor does.

The next stage is to convert the analogue signal through an ADC into byte streams to interface the sensor with the digital world and make measurement signals available for higher-level processing [2].

At this stage of the chain, IEEE has played a pivotal role by promoting a sensors standardization process through the IEEE-1451 family of transducer interface standards [3]. In particular, the IEEE-1451 has mainly addressed the engineering aspect of connection transparency. The purpose is to aid transducer manufacturers in developing smart devices that can be interfaced to networks, systems, and instruments in a plug-and-play fashion.

Smart sensors standardization attempts to bridge the gap between measurements and information processing since these types of sensors are conceived on purpose as hardware/software transducers for bringing the measured physical signal to an application target level.

However, smart sensors do not offer support to high-level information processing requirements such as, for example, the possibility to host self-correction on board, performing data integration and fusion, managing local alarms to reduce the network and the host load. In other words, until the smart sensor embedded logic remains fixed, it is not customizable to the requirements of any specific application context.

In response to these limitations, a new family of intelligent sensors capable to deal with the increasing complexity of modern applications is required.

As of the latest couple of years, a new class of devices referred to as ‘intelligent sensor hubs’ is attracting the focus of the market and the academia. These can be viewed as sensor platforms endowed with a microcontroller unit that pre-process and aggregate external sensor data. An example of this new sensor generation is the MMA9550L motion sensing platform from the Freescale company, housing a 14-bit 3-axis accelerometer together with a 32-bit CPU, I2C, SPI and other GPIOs. The low-power and small size enable applications in mobile phones, portables devices and also medical and industrial applications.

However, the bare availability of a microprocessor does not suffice to provide an intelligent framework alone. Sensory data, in fact, have to be processed in accordance to an interpretation model (ontology) shared with the potential end-users of the information processing task.

Typical limitations related to application-level tasks such as (to cite a few) effective customization, data fusion and self-calibration require to employ some kind of ‘software intelligence’ currently not addressed by the available standards.

2.2. The Information Processing Chain as will be

It seems that nowadays there is a “gray zone” where hardware-oriented and knowledge-oriented approaches are mixing up to fit the requirements of complex real-world applications.

As a proof to this assumption, it suffices observing that in the last couple of years there has been a growing debate on the adequacy of the term “smart sensor” to functionalities typical of intelligent information processing [4]. The debate is a cue to our confidence that the concept of sensor is broadening in the direction of AI [5] and intelligent agents technologies [6].

Moving towards software-oriented approaches, the conundrum is the availability of a standardized sensory data interpretation model having the same efficacy as smart sensor standards have for hardware-oriented issues.

As of 2012, the Semantic Sensor Network (SSN) ontology addressed by W3C answers the need for a domain-independent and end-to-end model for sensing applications by merging sensor-focused, observation-focused and system-focused views [7]. These standards support the development of services-based architectures, but do not provide semantic interoperability, which is generally left to ad-hoc engineering solutions. These heavily depends on the state-of-the-art of technology and research and, ultimately, on application designers' and developers' skills.

When dealing with information processing at the semantic level, one major problem is semantic ambiguity because there can be multiple ontologies available; furthermore, a reference knowledge [8] crafted by domain experts may not be always at hand. Unfortunately, semantic disambiguation is considered to be one of the most relevant and difficult problems in AI [9] with entailments also in the sensor research field [10, 11].

In the hopefully foreseeable view, a new generation of technological solutions will endow sensor embedded logic with semantic interoperability and scalability. Fig. 1 displays the predicted technological trend.

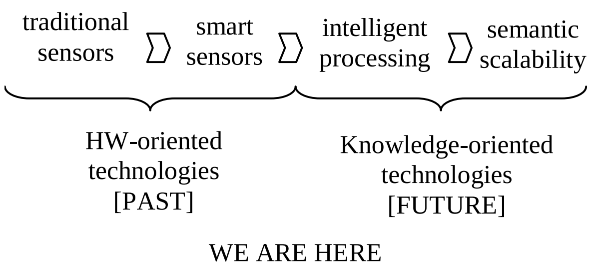

Fig. 1. The evolution path of sensor technologies as envisioned in this paper.

3. Related Work

Research in AI is not new to the previously presented sensors/applications information processing chain.

For example, as shown by early works on sensor-equipped mobile robots in 80s [12], the problem of organizing and traversing different granularity levels according to both enrichment or abstraction criteria is a central issue from the system engineer's point of view.

In more recent years, the aspect of knowledge granularity has been intensively studied in the framework of granular computing (GrC) [13].

According to Bargiela and Pedrycz [14], GrC as opposed to numeric computing (which is data-oriented), is knowledge-oriented and accounts for a new way of dealing with information processing in a unified way.

Since knowledge is basically made of information granules, information granulation operates on the granule scale thus defining a sort of 'pyramid of information processing' where low levels account for ground data and higher levels for symbolic abstraction.

Even A/D or D/A conversions can be revisited and generalized in the framework of GrC. In fact, after the A/D conversion process, digitalized measurement values become containers of information granules that need to be given sense by means of some computational task.

3.1. Agent-based Approaches

As previously seen, another central aspect of sensors technology in view of effective applications is the interface with the hosting system. It is worth saying that the aspect of communication is a major issue also in the AI field.

Knowledge-oriented communication protocols and architectures have been extensively studied in the field of multi-agent systems (MAS) [15, 16] and human-machine interaction (HMI) [17, 18].

Since late '90s, MAS have blossomed a countless variety of engineering applications, ranging from comparatively small systems for personal assistance to open, complex, mission-critical systems for industrial applications [19-21].

Although MAS have been largely proven to be a relevant methodology in distributed intelligence systems modelling, a number of challenges arise in their design and implementation [22]. The most important are: problem decomposition, communication, global coordination, technology issues, decision-making.

To deal with these problems, in [23] a MAS-based multi-layer communication architecture was introduced. The rationale was that, by using an adequate ontological approach [24], it is possible to define a system having the ability to both perform knowledge extraction and provide information to unskilled users. Communication flow starts at the top-level, in consequence of the user query submission, and propagates down the hierarchy toward database level, where data are structured, confronted and used to make predictions. Then, information flow is pulled back to the high level of the hierarchy to provide a suitable response to the user.

Despite its effectiveness, the architecture dependence on the application-specific ontology remains troublesome. Changes occurring either in the problem semantics or in the granularity level description have a significant impact on the overall system re-engineering process. In other words, this architecture is "flat" with respect to the problem description: in case ontology was granulated in a different manner, this would require rewriting some or every single agent of the architecture. At this stage, the concept of 'holon', introduced by Arthur Koestler in late 60s [25], comes into play.

3.2. Holons

Holons and holonic systems can be considered as a recent evolution of agents and MAS. In particular, holon is a recursive agent [26] with peculiar computational aspects such as self-modularity and self-organization.

Since the offspring, several holon-based systems have been presented in the literature, especially in the last decade [27-31]. However, the impact of the holon paradigm in the scientific literature goes beyond application and regards a radical paradigm shift [32] in complex systems modeling.

In 1998, Thompson and Hughes [33] introduce a theoretical model to describe (human and computer) activities within a given organization. The work was led by the aim of finding an improved solution to the design of computer integrated manufacturing systems.

According to the authors, a manufacturing enterprise can be represented as a network of semi-autonomous cells, “alike and fractal in nature”, with the common purpose to satisfy the ‘supply=demand’ equation. Interesting enough, the cells have a dynamic existence: they exist as long as they have a role to play; their specialization depends on the process involved.

This kind of ‘cooperation in autonomy’ capitalizes on the property of emergence: some complex system behaviors are evident only at a higher echelon, as it happens in biological systems. Granularity levels are then properly accounted for without the need of an external top-down decomposition imposed by a hierarchy of commands/control, but only referring to a system-subsystem part-whole decomposition.

The use of this paradigm as a conceptual means for describing complex systems is properly called ‘holonic modeling’ and leveraged a number of subsequent studies especially in both Business Process Engineering [34] and Computational Intelligence [35].

3.3. Holarchies

Self-nested hierarchies of holons are called 'holarchies': with respect to MAS, they account for a more general concept of agent organization comprising multiple nested granularity levels. At the base of a holarchy, atomic holons are found, i.e., holons that cannot be further decomposed according to the problem context.

It is noteworthy that holons and holarchies, due to holon intrinsic recursiveness, can be considered as two faces of the same coin viewed at two adjacent granularity levels [36]. Consequently, holon encapsulates in a single concept that of system of arbitrary complexity thus overcoming the part/whole and abstraction/enrichment dichotomy [37] that traditionally impedes Reductionist approaches [38]. As a result, the holonic view is highly suitable for modeling complex problems under a multi-granularity levels holistic [32] perspective.

3.4. Holonic Information Processing Architecture

The same recursive concept of holon encompassing multi-level agent-based architectures can be used to setup an information processing framework for dealing with data interpretation at an arbitrary semantic granularity.

In [39], an abstract architecture for processing sensor data at multiple granularity levels has been introduced. Each level accounts for a different scale of information granules (in the Zadeh’s sense [40]) that can be represented by means of linguistic descriptions (whatever fuzzy [41] or categorical), i.e., ultimately by words [42]. The architecture can be viewed as a composition of two layered parts:

- the holonic transduction layer (HTL) and
- the holonic ontological layer (HOL).

The HTL is the computation-oriented layer. It works with numbers and implements all the transduction functions necessary to map a measured input signal into an output digital value and vice-versa. The HTL interfaces directly with the hardware level (i.e., sensors) for data acquisition.

The HOL is the knowledge-oriented layer. HOL works with symbols and operates in between the user and the underneath computational model managed by the HTL. It is convenient to think to the HOL as an agent-based architecture where agents are able to perform information processing tasks at different granularity levels.

As an example, let us suppose that the HOL accounts for the concepts of ‘ppm’ and ‘ammonia’ and is able to answer the query about the concentration of ammonia at a given sampling time. When asked for this information, the HOL calls the function PPM(ammonia) that is present in the HTL. The function outputs a number representing the part-per-million concentration of NH_3 at a given sampling time k. Such number is thus encoded in a reply message produced by the HOL as a response to the querying user.

It could happen that ammonia computation cannot be performed by one single function call with an acceptable accuracy due to high cross-sensitivity of the ammonia sensor. In this case, the HOL could ask for data coming from other sensors, collect all data, and infer on the presence and accurate concentration of ammonia basing on the holonic-based computational inference mechanism introduced in

[43] and applied in [44][45] for the case study of low-cost gas sensors.

4. Proposal

Our proposal is summarized by the model depicted in Fig. 2. It is an evolution of the abstract architecture based on the two previously mentioned information processing layers, namely: HOL and HTL.

HOL and HTL together can be viewed as the super-holon representing the entire system holarchy. The two layers are now characterized as follows:

In the HOL (upper part of the holarchy) there is a holon managing the problem ontology;

In the HTL (lower part of the holarchy) there is a recursive MAS made of an encapsulation of holons at the lower levels. The MAS supervises information coding/decoding between adjacent levels.

The novelty lies in that an agent (being it a human user or a machine) is put explicitly *inside* the model, thus becoming part of it. This allows complementing hardware-oriented issues with knowledge-oriented ones within one single conceptual framework.

One important feature of this model is the scalability gained thanks to the intrinsic recursivness of the employed holonic model. In particular, holons should be considered as knowledge-oriented computational objects acting all through the information processing task from numeric to symbolic levels and vice-versa.

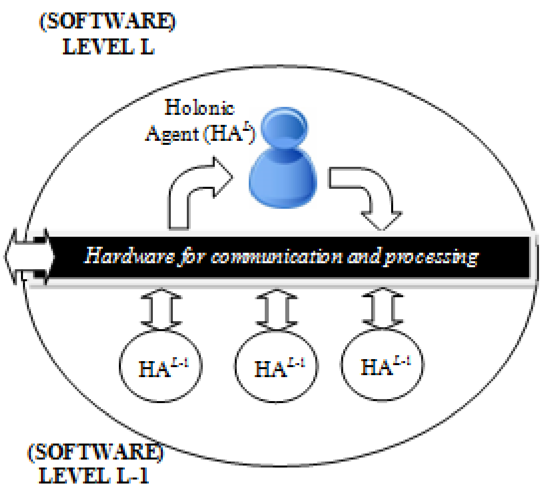

Fig. 2. Proposed holonic architecture (extension of a previous work [39]). The backbone is represented by the hardware enabling both communication and computation. Knowledge-oriented information processing is performed recursively by the MAS at different granularity (software) levels.

As the figure shows, the model is built around the dialogue among holons at any possible granularity level. At the maximum possible abstraction level there is, generally, a human user who queries the subordinate levels for knowledge-oriented tasks.

When a holon receives a query from the higher level, it decodes the message, eventually asks subordinate holons for fresh data or new actions, then performs computation at its level and finally encodes results to reply to the querying holon.

The holons at the lowest level receive data from the real world using a set of sensors. Furthermore, these holons can handle various actuators to operate in the real world. As a result, information processing is operated across different granularity levels in both bottom-up and top-down fashion: from the sensors/actuators lowest level to the application-dependent level to produce effective information and from the upper level back to the lowest level to perform numerical computation.

This multi-level information processing model has been the driver for developing a data analysis platform called H-GIS (Holonic-Granularity Inference System, website: http://www.hgis.it). The tool is specifically conceived to focus on measurement data interpretation at multiple granularity scales by employing the modeling framework of the holonic systems. Practically, H-GIS main feature is to extract unsupervised inferential models from data according to a computational intelligence technique basing on the heuristics presented in [43]. The next section will be devoted to present an H-GIS case study as a validation test for the current proposal.

5. A Case Study

According to our experience gathered in previous research projects (see [46] for more details), air quality monitoring systems characterized by strong heterogeneities (different operating conditions, unobservable variables affecting measurements, etc.) pose a challenge to the data analyst.

As representative case, it is useful to consider air pollution in an industrial and densely-populated area. In this context, pollution can be ascribed to different factors such as traffic jam in main roads and gaseous emissions of neighboring factories. However, it is difficult to state with certainty which pollution source is responsible for the actual value, say PM10, measured both at a given time and at a certain location. The underlying dispersion model is utterly difficult to estimate due to changing atmospheric conditions (e.g., wind direction and strength, temperature and relative humidity). In fact, semantic heterogeneity additions to the information processing gap between sensors raw data and application requirements: as a consequence, human intervention is generally needed to supervise the monitoring process.

Here we report on a test performed in a real-world scenario, the industrial city of Taranto (south Italy) chronically affected by high pollution especially in proximity of the industrial area.

The area hosts one of the biggest steel factory in

Europe, an oil refinery, a cement factory, a port; all these facilities are located at the borders of the residential district of Tamburi. Recently, Taranto's court imposed to suspend the neighboring steel production due to studies of experts stating that factory emissions are being causing above-average cancer rates in the area. This further testifies the importance of technologies to enable and support effective air quality monitoring policies.

With specific reference to our experiments, the aim was to understand if data obtained from air pollution low-cost sensors placed few miles away from the industrial area could be correlated with nearby weather stations information. For this objective to be achieved, we employed the H-GIS data analysis platform based on top of the theoretical model presented above.

5.1. Experiment Setting

The data acquisition system was placed at the first floor of the II Faculty of Engineering of Politecnico di Bari, in a room of the Computer Science Laboratory approximately (2 miles away from the industrial area, direction N/W), with a ventilation system driving air flux from the outdoor.

The weather station is placed in proximity to the industrial area (approximately 4 miles north from it, in the town of Statte); data are displayed on a Web page where they are taken from periodically by a Web crawler that stores results in a database hosted in our Laboratory.

5.2. Methodology

From our point of view, it was interesting to answer the following question: can two monitoring stations measuring the same phenomenon from different observation points (e.g., different locations and sensors) be combined together to obtain more valuable information than the one provided by that sources considered apart?

In order for the answer to be found, experiments have been organized as follows: a data acquisition campaign has been run for approximately one year throughout 2011, thus obtaining two dataset clusters, one for the weather station and the other one for the air pollution sensors. Then, the cluster of air pollution sensors has been analyzed with H-GIS, and the relative model has been extracted. Afterwards, the weather data have been also considered and a new analysis has been performed with H-GIS to obtain a new model. Data fusion between the two clusters consisted in putting the data matrices (rows for data and columns for measurement variables) together in a data file. Data synchronization was guaranteed by a pre-processing step mapping air pollution sensors data and weather data into the same time window.

5.3. Example Results

In this sub-paragraph, we report on an experiment run across two days from 06-15-2011 at 15:59:47 to 06-16-2011 at 19:09:39.

As for the air pollution sensors dataset is concerned, we considered the three low-cost gas sensors, namely Figaro TGS2602 (air contaminants), Hanwei MQ131 (ozone), Hanwei MQ136 (sulfur dioxide).

In all these sensors, the sensing material is a metal oxide semiconductor (generally tin oxide). When their sensing layer is heated at a certain temperature in the air, oxygen is adsorbed on the crystal surface with a negative charge. By withdrawing electron density from the semiconductor surface, adsorbed oxygen gives rise to Schottky potential barriers at grain boundaries, and thus increases the resistance of the sensor surface. Reducing gases decrease the surface oxygen concentration and thus decrease the sensor resistance. The overall process causes a decrease in the resistance Rs of the sensing layer that can be measured against a standard value R0 gathered at optimal test condition. Sensor datasheets are given as Rs/R0 values against part-per million (ppm) concentrations.

In sum, due to their manufacturing process, the employed sensors show a high cross-sensitivity, i.e., they respond to multiple contaminants at once, making it difficult to discriminate which gas has been actually measured. Fig. 3 shows the datasheet provided by manufacturers: it is easy to notice that a measured resistance value corresponds to more than one possible outcome in terms of ppm.

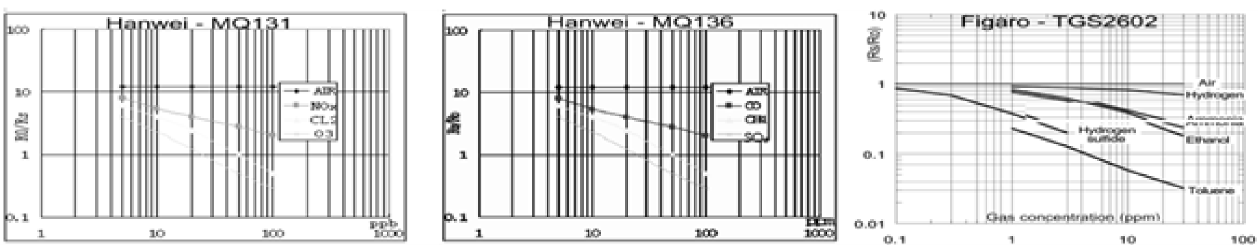

Fig. 3. Datasheet of the employed sensors. Notice that multiple curves are needed to characterize each sensor behavior due to their sensitivity to multiple gases (low selectivity).

Despite the high cross-sensitivity, the chosen triplet is sufficient to disambiguate certain contaminants (carbon dioxide, ammonia and sulfur dioxide) with acceptable accuracy, in accordance with results presented in [10]. As counterproof, H-GIS has been run on the sensors data and relations among sensors have been found (view Fig. 4a for details) as expected.

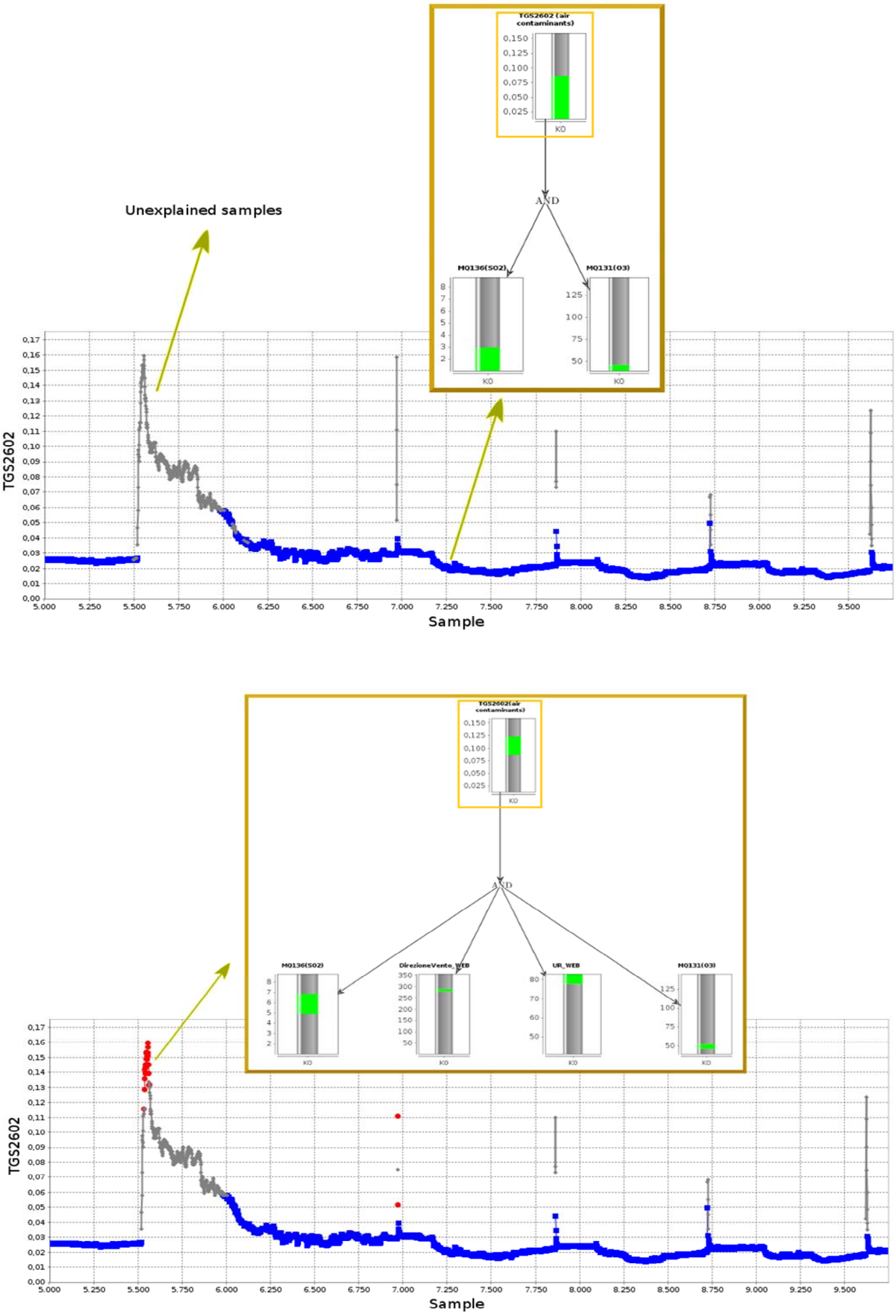

Fig. 4. Above (a): TGS2602 interpretation obtained by H-GIS using only sensors data for the model extraction phase. Gray points represent unexplained samples; blue points represent samples interpreted by means of the logic-numeric condition displayed in the brown box. Sensor values are expressed in ppm (part-per-million); Below (b): TGS2602 interpretation obtained by H-GIS using both sensors and weather data for the model extraction phase. Notice that now certain peak points have been interpreted. Sensor values are expressed in ppm (part per million).

In non-peak zones, TGS2602 behavior can be explained in terms of numeric conditions involving other sensors values in accordance with results in [10][11] (blue points). The found condition corresponds to the following logical pattern:

IF
MQ136 value is between [0, 3] ppm *AND*
MQ131 value is between [0, 4] ppm
THEN
TGS2602 value is between [0, 0.08] ppm

Unfortunately, we notice that the extracted model is not capable of explaining the peaks measured by the TGS2602 sensor (gray points).

On the contrary, when also weather data are considered and the model extraction process is run, single peak emissions can be interpreted in terms of numeric conditions involving both gas sensors and weather variables. An example pattern is the following:

IF
MQ136 value is between [5, 7] ppm *AND*
MQ131 value is between [45, 55] ppm *AND*
Relative Humidity value is more than 78 % AND
Wind direction value is between [270, 290] deg°
THEN
TGS2602 value is between [0.08, 0.12] ppm

Fig. 4b reports this example where the presence of the wind direction variable allows inferring on the district possibly causing the measured emissions, which is compatible with the position of the industrial area.

6. Conclusions

In this paper, a computational model that fills the current information processing gap between sensors and applications has been introduced.

At the theoretical level, the model is based on the concept of holon, a self-modular entity spawned in the field of AI as an evolution of agents and MAS technologies.

At the practical level, a knowledge discovery platform called H-GIS that implements the proposed model philosophy has been used for test and validation purposes.

Primary results show that our proposal may leverage knowledge-oriented applications in the sensors field.

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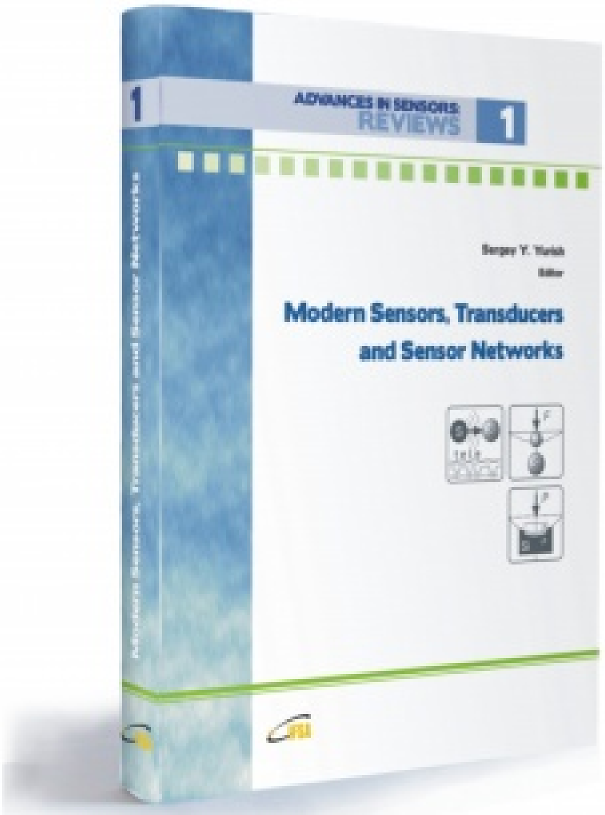

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