Agencies for Perception in Environmental Monitoring

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***Abstract*—This paper presents the main results obtained in the Agencies for PErception in environmental monitoring (APE) Project, funded by the Italian Ministry of University and Research, and aimed at studying the employment of advanced distributed artificial intelligence techniques in developing cooperative multiagent systems oriented to support environmental monitoring applications. In particular, this paper describes issues about communication between perceptive agents and two implemented multiagent systems for monitoring electromagnetic fields and for pollutant evaluation.**

***Index Terms*—Air pollution, cooperative systems, electromagnetic fields (EMFs), mobile robots, robot sensing systems, sensor networks, smart sensors.**

I. Introduction

An "agency" [10] is a cooperative multiagent system in which the agents synergically interact to address an application. The agents are computers or robots that are intelligent (for example, they are able to perform reasoning and inferential activities). The intelligent agents of an agency cooperate to reach distributed solutions for complex problems. The agents individually adopt an approach, or paradigm, to the problem resolution. An agency, being composed of more agents, adopts a multiparadigmatic approach to the problem resolution.

Today, mankind must address serious problems connected to the natural resources exhausting, environmental pollution, and ecosystem destruction. One of the main goals of modern society consists of stopping these degenerative processes. This requires the development of systems for large-scale environmental monitoring that are able to provide high-level information to the public offices that make decisions about the environment. Efficient and affordable sensor systems that show autonomous and intelligent capabilities are needed.

Traditional research has been oriented to build sensor networks composed of a number of sensors that are independent and distributed and are able to collect information on the ground and transfer it to a central processing device that outputs high-level indications to people who can take operative decisions. This conception is based on the ability to determine *a priori* the characteristics and the placement of measurement stations, their tuning and maintenance procedures, the ranges of the instruments, the general methods for validating the data, etc. A radical shift in the conception of a sensor network for environmental monitoring is represented by the possibility of using techniques based on artificial intelligence. In this way, perceptive agents are allowed not only to dynamically adapt their measurement capabilities to the changing environmental conditions (and, thus, to autonomously configure themselves) but also to cooperate to rationalize and enrich the information gathering and to validate, by means of comparison processes, both the data and the phenomenological models. A *perceptive agency* is a multisensorial cooperative intelligent system composed of several perceptive agents [7]. The complexity of environmental monitoring applications (e.g., the pollution processes) and of their models, the large number of quantities to keep under observation, and the geographic scale of the phenomena require multidisciplinary approaches and modular solutions for collecting and processing data. This is therefore an ideal case to study the development of a perceptive agency.

This paper reports some results of the research performed in the Agencies for PErception in environmental monitoring (APE) Project which was funded by the Italian Ministry of University and Research in 2003–2004 and aimed at studying the employment of advanced distributed artificial intelligence techniques in developing cooperative multiagent systems oriented to support environmental monitoring applications.

The project was focused on the interaction among autonomous intelligent agents operating in a distributed environment. This topic constitutes the fundamental core of the new perspective on the creation of advanced, adaptive, and autonomous environmental monitoring systems in which heterogeneous components can synergically cooperate to pursue an applicative goal. In this respect, communication plays a central role; the results about communication technologies obtained in the APE Project are discussed in Section II.

An important aspect of the perceptive agencies studied in the APE Project is that they can include mobile robots equipped

Manuscript received June 15, 2005; revised April 27, 2006.

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Digital Object Identifier 10.1109/TIM.2006.877747

with different perception devices. The modular installation of different sensor equipment on board mobile robots increases the quality of the perception and, as a consequence, that of the monitoring. Mobile robots offer to the sensors the ability of moving around the environment. In this way, the perceptive agents are dynamic both with respect to time, since they can obtain a sequence of perceptions, and with respect to space, since they can obtain perceptions in different places. Hence, the perceptive agents of a perceptive agency can be, besides passive (equipped only with passive sensors) or active (equipped with active sensors),[1] mobile as well (when they are implemented as autonomous mobile robots). The modular combination of different perceptive agents gives to the perceptive agency architecture the generality needed to tackle different applications related to the monitoring of environments.

The first applicative example that has been considered in the APE Project is related to the measurement of electromagnetic field (EMF) for the analysis of environmental electromagnetic pollution, exploiting sensors that perceive EMFs. The results of this application are discussed in Sections III and IV (more details are reported in [8], [9], and [14]). The second applicative example is the analysis of the chemical–physical conditions of air to identify possible polluting elements. This application is discussed in Section V (more details are reported in [3]–[6] and [18]).

II. Communication Infrastructure for Distributed Measurement Systems

To build a perceptive agency, it appears suitable to use commercial off-the-shelf communication technologies since these products can meet the technical requirements exploiting reliable mature technologies that are supported, scaleable, and, generally, low cost.

Environmental monitoring applications usually involve a number of quantities to be observed on wide geographical areas, thus requiring various sensing and processing technologies, as well as a heterogeneous distributed interconnection structure. The identification of an optimum overall structure is a complex multiobjective optimization problem, which involves many different aspects, including technological issues, performance, and cost. Consequently, the solution is usually based on already known, possibly partial, solutions and on the experience of the designers: This leads to the need for interoperable components that can be integrated in dedicated applications.

The physical architecture of a perceptive agency is basically that of a distributed measurement system, which is a network of perceptive agents (which are examples of the smart sensor/actuator nodes of the IEEE 1451 standards). A typical sensor node may be structured in five layers [1], namely 1) physical layer, 2) data link layer, 3) network layer, 4) transport layer, and 5) application layer (note that specific components need to be added to manage sensors). With reference to this layered structure, we carried out within the APE Project an analysis of the communication technologies, hardware, and protocols, and of the related products suitable for implementing interconnected networks for distributed measurement systems, especially for environmental applications. According to our purposes, special emphasis has been put on standard technologies supported and maintained by official organizations. This analysis aimed to understand the characteristics, benefits, and limits of the various solutions, as well as to give guidance in making the most appropriate choices for specific application cases.

The communication infrastructure can be built choosing between hardware technologies (characterized by transmission range, data rate, availability, and robustness) and software solutions (such as networking and transmission applications), different purchase and maintenance costs, and different degrees of easiness for implementation and management. For each solution, we analyzed the physical interconnection characteristics, the architectural and functional characteristics of the physical transmission, the interconnection and communication models, the architecture and functions provided by the lower level protocols, the functions of the application protocols that are relevant for distributed measurement systems and finally the security issues and related security standards. In addition, general information about the products available on the market and about the organizations supporting the technologies is provided. Some applications in real and research environments supporting the most appropriate choices are reported too. The main results focus on the physical interconnection, wired and wireless network technologies, data flow, and application protocols.

The following "wired" network technologies appear suitable to implement distributed monitoring systems or specific subnetworks for dedicated tasks.

1) Serial transmission media (RS-232-C, RS-449-C, USB, Firewire) provide effective low-cost small-distance interconnection with significant transmission transfer rates (up to gigabit per second) typically between data acquisition systems and computers dedicated to manage the collected data. The technical characteristics of serial transmission relevant to distributed perception are summarized in Table I. Applications include connecting a patient monitoring system with a central system [23] and connecting remote sensing systems for relative humidity [26].
2) Ethernet (common name for the IEEE standards 802.3, 802.4, and 802.5) provides many advantages, including low cost, broad use, wide area network, constant enhancements, high data rate (up to 10 Gb/s), different interconnection topologies, and a family of protocols and a suite of applications (Internet protocols). The technical characteristics of Ethernet relevant to distributed perception are summarized in Table II. Ethernet and related protocols are suitable for Internet-based distributed measurement and control applications [24] and for high-performance measurement systems and telemetry systems [31].

[1] An "active sensor" requires input energy from a source that is different from that which is being sensed. For example, a sensor based on time of flight is active because to perceive a reflected signal, it requires an external source to transmit the signal to a target.

TABLE I
SERIAL TRANSMISSION

	Serial Interfaces		**Universal Serial Bus (USB)**	**Firewire**
	RS-232-C	**RS-449-C**		
Standard	RS-232 EIA	RS-449 EIA	USB Specification Version 2.0	IEEE 1394 – Cable Environment
Data Rate	20 Kb/s	Up to 4 Mb/s	Up to 480 Mb/s	Up to 3.2 Gb/s
Cable	9/25 conductors (multi-conductors, multi-pair)	9/37 conductors (multi-conductors, multi-pair)	4 conductors (in different cable types)	6-conductors, 4-conductors, STP, CAT-5 UTP, Plastic optic fiber, Hard polymer clad fiber, and Glass fiber
Max Cable Length	15 m	60 m	Not defined, suitable for short connections	Up to 100 m
Topologies	Point-to-point	Point-to-point	Tiered star	Point-to-point, Multiple ports allowing a branching multihop interconnection
Transmission	Serial or Parallel, Synchronous or Asynchronous	Serial or Parallel, Synchronous or Asynchronous	Control, Isochronous (real-time), Interrupt, Bulk (for large amount of data)	Asynchronous or Isochronous
Scalability	-	-	Up to 127 devices	According to the cable length
Robustness	Low	Low	Medium	Medium

TABLE II
ETHERNET TRANSMISSION

	Ethernet			
Standard	IEEE 802.3	IEEE 802.3	IEEE 802.3	IEEE 802.3
Data Rate	10 Mb/s	100 Mb/s	1000 Mb/s	10 Gb/s
Cable	Coaxial cable, Twisted pair, Fiber optic	Twisted pair, STP or UTP, Fiber optic	Fiber optic, Copper, Cat-5 TP	Fiber optic
Max Cable Length	2000 m	400 m	5000 m	10000 m
Topologies	Bus, Point-to-point, Star, Passive star	Point-to-point, Star	Point-to-point, Star	Point-to-point, Star
Transmission	Half duplex, Full duplex (not available in all technologies)	Half duplex, Full duplex (not available in all technologies)	Half duplex, Full duplex (not available in all technologies)	Half duplex, Full duplex (not available in all technologies)
Scalability	Small LAN	Large LAN	Large and fast LAN	Wide and fast LAN
Robustness	Low	Medium	High	High

3) Fiber (fiber channel standard, FDDI) provides the most effective interconnection technology to integrate and control systems when high performance, large distance (kilometers), high data rate (gigabit per second), and high reliability are required. The technical characteristics of fiber relevant to distributed perception are summarized in Table III.

The "wireless" network technologies appear to be the most appropriate technologies for sensor networks. Several efforts have been devoted to develop wireless sensor networks for environmental monitoring. At the same time, environmental monitoring and its specific sensing requirements drive the development of wireless sensor networks in many areas: habitat monitoring, environment observation, and forecasting systems. For example, wireless sensor networks for habitat monitoring research have different ways to implement sensors (size, transmission range, reliability) and to transmit data (data rate, networking) collected by the sensors [25].

Basically, available wireless network technologies for distributed monitoring systems are the following ones (Table IV).

1) Infrared Data communication (IrDA) provides short-range wireless connectivity (up to 1 m, with angles narrower than 30°) at speeds of up to 16 Mb/s and requires a well-defined protocol stack for each specific application. The IrDA intrinsic characteristics limit its effectiveness in distributed systems as a reliable and secure cable replacement for device interconnection.
2) Bluetooth provides short-range transmission for small wireless networks operating at the 2.4-GHz ISM band using frequency hop. The limit of Bluetooth consists of requiring, for each specific application, well-defined protocol stacks called Profiles. Although its limitations

TABLE III
FIBER TRANSMISSION

	Fiber Channel	FDDI
Standard	ANSI X.3.230:1994	ANSI X3.148:1988
Data Rate	Up to 2 Gb/s (in the future 10 Gb/s)	100 Mb/s
Cable	Fiber optic, Coaxial, Shielded twisted pair cable	Fiber optic, Copper
Distance	Long range	Long range
Topologies	Point-to-point, Fabric (switched), and Arbitrated loop	Ring
Transmission	Simultaneous symmetrical bidirectional	Token passing ring

TABLE IV
WIRELESS TRANSMISSION

	IrDA	Bluetooth	Wi-Fi
Standard	IrDA Specification V1.0	Bluetooth specification V1.0	IEEE 802.11
Data Rate	Up to 16 Mb/s	1 Mb/s	Up to 54 Mb/s
Distance	Short range	Short range	Short range
Topologies	Point-to-point	Point-to-point, Point-to-multipoint (Piconet/Scatternet)	Point-to-point, Point-to-multipoint (through a gateway or access point), Topology id dynamic
Transmission	Half duplex serial infrared communication	Isochronous and Asynchronous	Half duplex
Scalability	-	Up to 262 nodes in a Piconet	Small LAN
Robustness	Reliable, no secure	High reliability, built-in security	Reliable, secure

(range, data rate, small networks), Bluetooth enables the development of sensor networks for low-cost industrial or home applications with few sensors [19].

3) Wi-Fi (common name for the IEEE standard 802.11) provides fair transmission distance and data rate (up to 54 Mb/s) for wireless local networks; Wi-Fi operates in the unlicensed 2.4- and 5-GHz bands. A family of protocols and a suite of applications (Internet protocols) operate over the Wi-Fi physical interconnection. Typically, the IEEE 802.11 transmission is effective for the transmission from a gateway (sensor's interface) to a base station that collects and processes data [25]. Moreover, multiple receiver base stations can be bridged to an 802.11-based access point, enabling multiple sensor clusters to be connected to a central information gateway in a wireless sensor network [30].

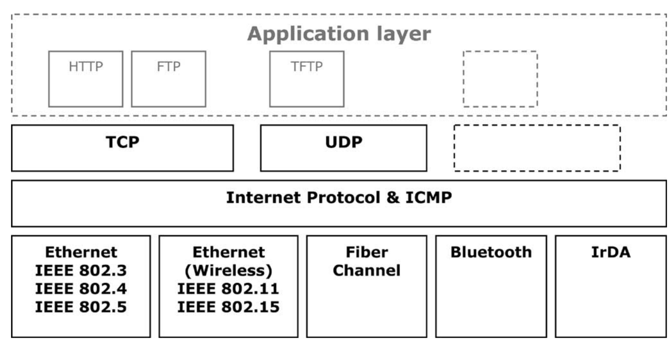

Fig. 1. Protocol stack.

The analysis of the "data flow and application protocols" we carried out aims at encompassing the protocols covering the network, transport, and application layers of the sensor network stack with particular attention to the security issues. The following main families of protocols are suitable for implementing distributed measurement systems.

1) Internet protocols (Fig. 1) are widely used to implement networks of any kind; in particular, they are suitable to implement the data flow between sensors. The most important advantages are the interoperability (by TCP/IP), the wide range of application protocols for data transfer (file transfer protocol (FTP) and simple mail transfer protocol (SMTP) are just two examples) and for building a secure architecture, and the independence from the physical interconnection (wired and wireless Ethernet, fiber channel, ...). Typically, Internet protocols provide a solution to collect and distribute data from a wide variety of sensors over the Internet [30].
2) Bluetooth protocol Profiles support several types of connections; serial transmission, file transfer, and personal area network are the typical applications providing usage protection and information confidentiality measures.
3) IrDA protocols consist of a set of mandatory protocols and a set of optional protocols. Specific protocol stacks enable exchange of objects (data), serial transmission, and interconnection with a local area network exploiting its security intrinsic characteristics.

4) Fiber channel protocols provide transmission of data, typical network, and channel transmissions; application protocols are not included in this family to assure interoperability.

Generally speaking, a complex problem can be decomposed in several specific subproblems, and for each subproblem, the best apparatus can be chosen by taking into account the optimization of performance of the entire system. As a matter of fact, multiple diverse underlying hardware technologies can be connected by providing a way to interconnect heterogeneous networks. A set of communication conventions makes them interoperate. Communication between clusters of sensors organized in subnetworks can use TCP/IP or dedicated protocols, depending on the specific application. Integration between subnetworks is facilitated by the possibility of using routers and gateways that translate the communication from a protocol to the others. To guarantee security and privacy of every subnetwork, it is also possible to take advantage of Virtual Private Networks (VPNs). VPNs are private networks established over public and shared networks, for example, the Internet. All the traffic between nodes of a VPN goes on the public network using its transmission standards. To guarantee VPN privacy, coding protocols (like IPsec, SSL, and PPTP) are used together with mechanisms that prevent security violations. Usually, an adequately designed VPN exhibits a security degree comparable with that of a dedicated network.

III. EMF Sensors

The measurement of low-frequency EMFs for verifying the levels of human exposure is an activity of great interest for its implications on the human health [21]. In this context, the APE Project carried out the design of a specific sensor for this application.

The sensor design has been oriented by the following criteria: 1) 10-Hz to 10-kHz bandwidth (which is suitable for detecting and measuring EMFs produced by transformer stations, electrical machines, high voltage lines, etc.); 2) rms values measurement and frequency spectra analysis of the three spatial components of the EMF; 3) 1-Hz frequency resolution in frequency analysis; 4) automatic comparison of the measured values with the thresholds allowed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines [21]; and 5) making costs cheaper than those of sensors available on the market.

The developed sensor is organized in two sections, namely 1) analog front-end and 2) digital processing unit.

The magnetic field signals are collected by three coils placed on three orthogonal plans (commercial probe Narda 100 cm^2 isotropic B-Field), while the electric field signals are derived from three capacitive sensing elements (one for each spatial axis) followed by a proper electrometer (custom probe). The probe signals are first amplified by programmable gate arrays (PGAs) and then filtered by fifth-order lowpass antialiasing filters, with 10-kHz cutoff frequency, according to the bandwidth requirements of this application. The resulting signals are then sent to the analog-to-digital converter (ADC) input.

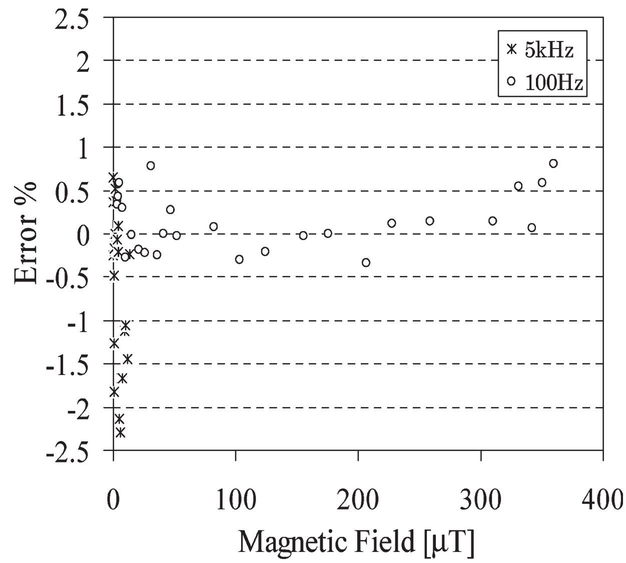

Fig. 2. Percentage error of the EMF sensor for different amplitudes and frequencies of the magnetic field.

The analog to digital conversion is based on a 12-bit ADC, featuring eight multiplexed channels, each with a proper S&H, and operating at its maximum conversion rate (62.5 ksamples/s for each channel).

The digital section is based on an ADSP-21065L EZ-LAB low-cost demo board (Analog Devices). All measurement functions (autoranging, rms evaluations, spectrum analysis, field exposure check, etc.) are performed by digitally processing the acquired data, and the results are available on an RS232 port.

Some experimental tests have been undertaken to calibrate the developed sensor. For instance, as far as the calibration of the magnetic section of the sensor is concerned, a magnetic field generator was developed based on a coil wounded around a laminated ferromagnetic core supplied by a sinusoidal current. The electric field was generated by two metallic parallel plates (2 m^2 area, 25-cm gap) supplied by a sinusoidal voltage.

Sensor calibration was performed by comparing the sensor measurement results with those performed by the reference instrument (Narda EFA 300 Analyzer). These tests were performed by operating with different amplitudes and frequencies in the sensor measurement ranges. A detailed description of the experimental activities is reported in [14].

Fig. 2 shows, for instance, the errors for a 100-Hz magnetic field with amplitude ranging from 3 to 360 μT: in this case, the maximum percentage error is lower than 1%. In the same figure, it is represented by the detected error operating with a 5-kHz magnetic field and amplitude range of 0.2–13 μT; in this case, the maximum percentage error is about 2.5%.

Starting from the described version of the sensor (which has been mounted on the robots described in the next section), during the APE Project, an improved version of the sensor has also been developed. In particular, a new board was introduced to manage multinetwork communication standards and was especially oriented to support both mobile and fixed autonomous applications of the sensor.

According to the requirements for distributed measurement systems discussed in Section II, this board, called common

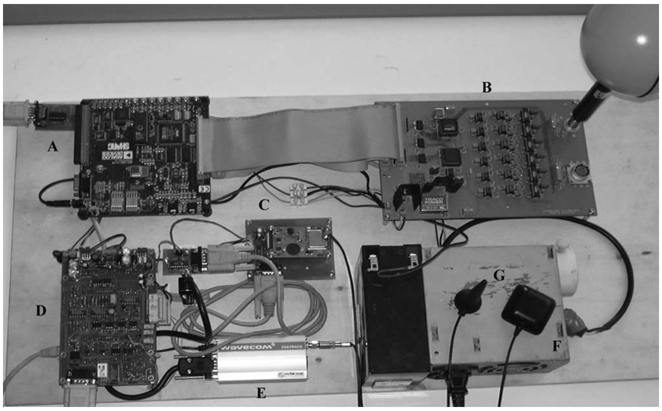

Fig. 3. Improved EMF sensor. (a) EMF sensor digital processing unit, (b) EMF sensor analog processing unit, (c) GPS sensor, (d) CIRO, (e) GPRS/GPS modem. (f) Power supply systems, and (g) GPS and GPRS antennas.

interface for remote operation (CIRO), is able to support a wide kind of wired and/or wireless network technologies (GSM/GPRS, Ethernet, Bluetooth, IrDA, and RS232) and can also be interfaced with a wide typology of sensors (via RS232, SPI, Analog voltage input, 4- to 20-mA current inputs, and digital I/O). The CIRO core is a Motorola Dragonball 68VZ328/33 MHz CPU with μClinux 2.4 operating system and has been endowed with a GPS sensor for geographical position measurement (Fig. 3).

In this way, the overall system represents an evolution, in sensor-related applications, of the machine-to-machine concept, supporting a wide typology of communication protocols, offering various interfaces for sensors connection, and a good capability of autonomous data processing. As pointed out before, this sensorial platform can be employed both for indoor and outdoor applications: A specific application has been developed for environmental monitoring in an urban area [17].

IV. Mobile Robots for Monitoring EMFs

In environmental monitoring, any system that has to detect phenomena reliably and produce detailed environmental assessments should be organized in a distributed fashion. These systems are usually sensor networks in which nodes are in fixed locations. The use of mobile robots for carrying sensors around the environment represents a solution that has recently received considerable attention [28]. Within the APE Project, we developed and implemented an architecture for a multirobot system that performs tasks oriented to localizing and characterizing low-frequency EMF sources. The monitoring of these EMF phenomena is extremely important in practice, especially to guarantee the safety of people living and working in places with power lines, motors, and other equipment. It is thus important to localize and characterize the EMF sources in an environment to assure that the EMF levels are compliant with the current legislation. This kind of activity can be naturally carried out by perceptive multirobot systems, such as the one described here.

The proposed architecture is hierarchical. A "coordinator" (a computer) supervises the activities of the system, while a number of "explorers" (mobile robots equipped with EMF sensors) navigate in the environment and perform measurement tasks. The coordinator and the explorers communicate by means of a Wi-Fi network with Internet protocols (see Fig. 4 and Section II). The main cycle of activities of the multirobot system we implemented can be summarized as follows.

1) The explorers (independently) measure the EMF in their current locations.
2) The coordinator integrates the measurements and builds a hypothesis about the location of the EMF sources.
3) The explorers move in the environment to reach new interesting measurement positions, and the cycle starts again from 1.

We explicitly note that the explorers are autonomous mobile robots that carry both "navigation" sensors (for example, cameras and sonars) and "monitoring" sensors (such as EMF sensors).

In our implementation, the representation of the EMF phenomena is limited to the representation of the estimated positions of the EMF sources within a grid map of the environment (which is known). For simplicity, we considered a single EMF source. The position of the EMF source is given by the cell of the grid map in which the source is located.

The most significant feature of our system is the task allocation at step 3) of the above algorithm (for a more complete description, see [9]). We use the "contract net" paradigm for allocating tasks to the robots. The tasks to be allocated are "interesting" cells to be visited. The coordinator proposes a cell for visit if it needs an EMF measurement from that cell, either for purposes of triangulation (to estimate the position of the source) or for determining whether the EMF is within the limits established by the law. The coordinator sends the proposed task to free explorers, waits for their proposed paths (or until a timeout expires), and assigns the goal to the explorer that submitted the best offer. A proposed path is a sequence of move actions that brings an explorer from its current pose to the center of the cell to be visited. The coordinator considers the minimum length proposed path and assigns the task to the proposing explorer. The other explorers are notified that their proposed paths have been refused.

The multirobot system we developed is a small mobile sensor network, that is, it is a sensor network in which some or all of the nodes can move around in the environment [20]. In particular, we implemented mobile nodes as autonomous perceptive mobile robots (as in [28]). The perceptive robots are more complex and expensive than nodes typically used in sensor networks, enabling them to perform complex processing and communication tasks. Some of the multirobot systems for environmental monitoring that have been proposed in the literature are only simulated (see, for example, [22]) and thus are not directly comparable with our system. The architecture presented in this paper differs from that proposed in [28] since, in our case, the coordinator is responsible for data integration and the building of the model that represents the perceived phenomenon (essentially, the locations of EMF sources), while in the general framework of Petriu *et al.*[28], all the robotic agents

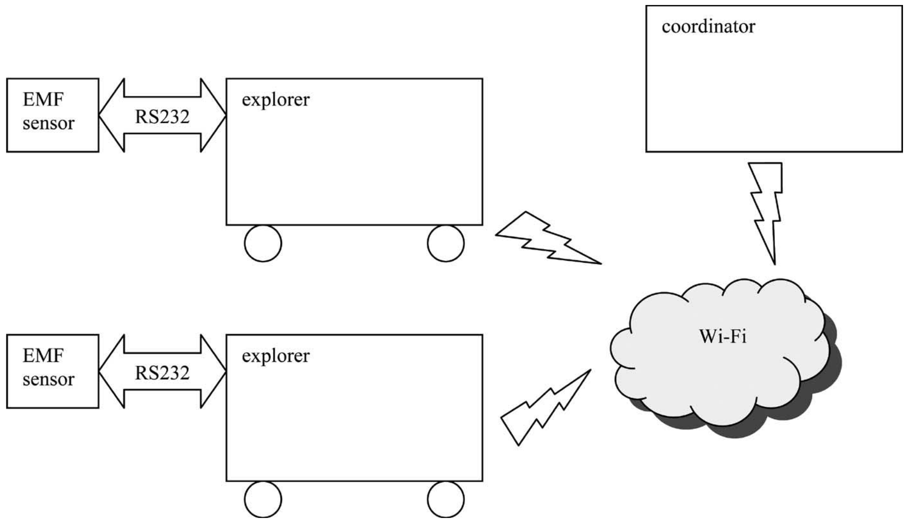

Fig. 4. Communication in the multirobot system for EMF monitoring.

are involved in the integration of the perceived data. Many approaches in the literature address a single aspect of perceptive multirobot systems: the self-deployment of mobile nodes [20], [32] (note that the deployment of nodes is a fundamental part of the activity 3 described above). Usually, all these approaches use a "local" criterion to decide the spatial configuration of the nodes: Each node adjusts its position according to those of its neighbors, for example, using optimization algorithms based on potential fields. Our architecture adopts a "global" centralized approach to deploy the perceptive robots in the environment: The explorers move in the positions that the coordinator globally evaluates as interesting. Although perceptive robotic systems have been developed for perceiving different phenomena, to the best of our knowledge, the student project presented in [2] is the only robotic system specifically designed for EMF measuring. However, that work aimed at developing a single robot, while our proposal focuses on a multirobot system.

In the following, we describe the experiments we performed both with simulated and with real sensors.

A. Experiments With Simulated EMF Sensors

In the following, the on-board EMF sensors have been simulated; they return data in accordance with the position of a simulated EMF source virtually placed in the environment via a graphical interface. In this way, we have been able to validate the general multirobot architecture without considering the specific details of the EMF monitoring application.

We present one of the several EMF monitoring tests we performed. In this experiment, we localize and characterize an EMF source that changes its position over time. Initially, the robots perform an EMF measurement in their initial locations (Fig. 5, top left). The coordinator uses the data gathered by the robots to determine (by triangulation) the estimated position of the EMF source (represented by the white trash bin in the figure). After having negotiated the allocation of the task of reaching the estimated source position, one of the robots (the closest one) moves toward the cell where the EMF source is estimated to be (Fig. 5, bottom left); each time the robot reaches the center of a cell along the path, it executes an EMF measurement (these data are used by the coordinator to confirm the hypothesis). At some point, we manually change the position of the EMF source in the environment. After the moving robot returned one of the measurements, the coordinator reacts to this change of the EMF source position by changing the hypothesis and identifying a new source position. After having negotiated the allocation of the task of reaching the new estimated source position, the other robot (closer than the first one) moves toward the cell where the EMF source is now estimated to be (Fig. 5, top right) and circumnavigates it for characterization (Fig. 5, bottom right).

This experiment shows the adaptability of task allocation performed via contract net: The multirobot system works robustly when the location of the EMF source changes.

B. Experiments With Real Magnetic Field Sensors

We also performed some preliminary experiments with the real sensor for the magnetic fields described in the previous section. The communication between a mobile robot and the EMF sensor it is equipped with is performed by means of a RS232 port (see Fig. 4 and Sections II and III). The localization algorithm we used is based on triangulation, which in turn is based on the fact that in the plane wave propagation model we adopt, the (time-variant part of the) electric and magnetic fields are always perpendicular to the line of propagation (LOP) of the wave. The LOP is the line connecting the magnetic field source to the measurement position. So, in principle, if we can extract from the measured data two different LOPs, their intersection gives the source position (assuming that the source is static). The complete procedure for localizing the magnetic source is reported in [8].

We performed a series of source localization experiments using a simple single-frequency magnetic field generator. We built this test source using 200 m of wire that was tightly wound in a cylinder approximately 15 cm in diameter and 15 cm in height with a central hollow with a diameter of approximately 8 cm. We connected this device to the 230 V–50 Hz power line

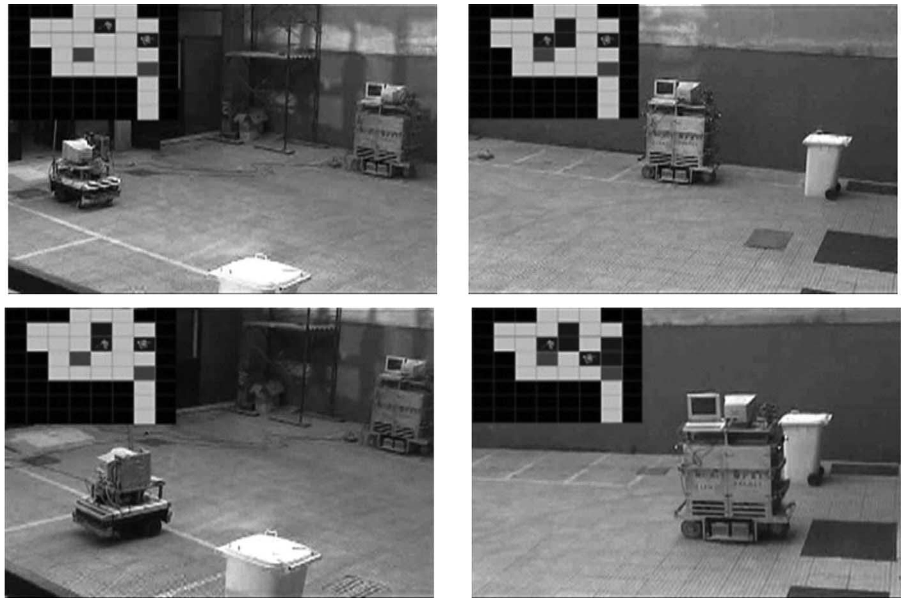

Fig. 5. Localizing an EMF source.

in series with a 500-W halogen lamp used as a resistive load. In these experiments, we used only one magnetic field sensor mounted on a robot.

The first group of experiments had the aim of assessing the real performance of the sensor when used in a university lab (i.e., in an environment neither shielded nor structured for the task and containing many EMF sources: 230 V–50 Hz power lines, PCs, monitors, pulsewidth modulation (PWM) power supplies, etc.). With the test source 1.5 m away from the sensor probe, and with the sensor powered by the robot's 12-V PWM supply, we recorded a typical amplitude ratio of 60 dB between the 50-Hz test signal and the noise and ambient background in the relevant frequency range (10 Hz to 10 kHz). This value rapidly decreases as the distance between the source and the sensor increases, leading to a maximum usable distance of around 4 m.

For the second group of experiments, we used the same source–sensor arrangement to perform localization. Each one of these experiments was organized as follows. The source was placed in a random position at about 2 m from the robot, at the same height of the sensor. Then, with the robot powered but still, we moved the source to other positions (typically five to ten times per experiment). For each position, we used the sensor to gather data on the magnetic field and manually recorded the new position of the source relative to the robot. For each new set of sensor data, we used the localization system to generate a source position hypothesis. The source localization precision was higher than we expected, considering that we manually moved the source, that the angle measurements were approximate, and that with small source–sensor distances, the plane wave model approximation is significant. Typical position errors are around 5% of the distance between the robot and the test source, for example, 10 cm with a distance of 2 m. These localization experiments give a preliminary validation of the correctness of the assumptions on which the localization algorithm is based.

V. Agencies for Air Pollutant Evaluation

The choice of a monitoring process for air pollutants depends on the type and properties of the substances that must be acquired. Pollutant concentrations depend on emissive sources, geographic conformations, and meteorological conditions capable of modifying the atmospheric dispersion of pollutants. Therefore, to evaluate the air quality properly, it is necessary to work out a sophisticated monitoring system that measures both chemical substances and meteorological quantities [12].

Environmental data recorded in several monitoring stations installed in many Italian cities are the input for our application. A typical measurement network is characterized at least by six stations in each city with more than 250 000 inhabitants. All the equipments record approximately 50 measures/min (raw data), which are processed to generate hourly medium values (valid data). These values are considered valid if at least 75% of the raw data are correct.

The considered applicative case consists of seven automatic acquisition and recording stations installed in Taranto, Italy, that are able to measure both chemical substances and meteorological quantities. The considered area has been declared by the Italian Government "territory with high environmental risk." These stations are placed on various typologies of urban areas (parks, residential areas, suburban areas), according to national law prescriptions.

The data validation process is a crucial phase for all scientific applications, especially in the environmental field where physical and biological data are strongly related.

To measure a large quantity and variety of substances, it is necessary to implement a complex measurement system composed of several chemical substance analyzers (based on photoionization, gas chromatography, IR, and UV absorption) and of many sensors for the meteorological quantities. The results are collected by a sophisticated acquisition and measurement system that, every day, automatically calibrates all devices.

The data set is characterized by several problems (which can generate errors during processing and prediction phases), including

- missing data, caused by the periodic setting or stop function of instrumentations;
- incorrect data, caused by malfunction or nonsetting of equipments;
- incorrect recording data (not interpretable symbols), caused by errors in transmission and recording.

To solve these problems and produce a suitable data set, we need to undertake two different steps:

1) generating a suitable mathematical model, based on interpolation techniques, to optimally characterize the time and space behavior of pollutants and to determine its uncertainty;
2) trying to find out the causes of possible numerical differences between stored values and those that were expected before labeling the data as invalid. The factors that are considered to explain the odd values vary meaningfully according to the type of pollutant in question and to the environment characteristics (for example, peculiar characteristic of the monitoring place, season, typology of instrumentation, human and meteorological factors, and so on).

If the validation operations cannot find a cause for the odd-looking data, or if a malfunctioning of the instrumentation has been identified as the cause, the data are definitely invalidated [11].

A. *Mathematical Model for Data Interpolation*

We used some interpolation and validation techniques to address and solve the first of the two above problems. The procedure is performed in several steps and uses data that, even if partially preprocessed and filtered by technicians employed in control of measure stations, may contain irregular values.

Incorrect and missing data are very frequent in real cases. An incorrect data can invalidate the analysis, introducing errors in the measurements of examined parameters. For this reason, some filters have been developed to point out incorrect and discordant data. They are based on the elimination of evident discontinuities in the data, namely of values outside the admissible ranges previously defined for each examined quantity. Missing data can lead to perform the processing phase using reduced data sets. This restriction can obstruct the individuation of peculiar dynamics of pollution phenomena (like daily and seasonal recurrences), distorting the obtained results. Therefore, reconstruction techniques, based on both continuity hypothesis of pollution values and interpolation methods, have been developed. By using these techniques, it is possible to work with a continuous and valid set of data, with the further aim of reducing the measurement uncertainty [13], [16], [27].

The following technique is useful to validate data coming from sensors at the instant t_0. The acquired data are compared with the trend. This is computed from historical data sets allowing for a possible margin of error. There are many

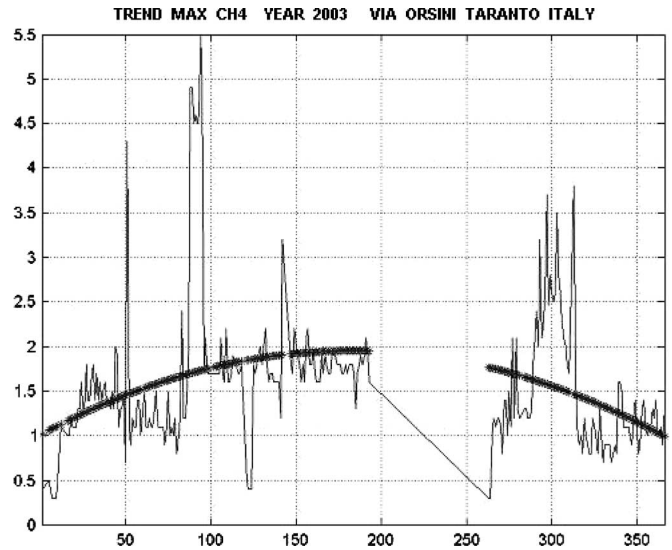

Fig. 6. Interpolation trend of a monitoring station about CH_4.

methodologies, known in the literature as autoregressive (AR) method and AR moving average (ARMA), to compute the trend [15]. In this paper, the approach of extracting the fitting polynomial curves is used, as shown in Fig. 6.

Several tests have been carried out by eliminating, from the complete time series, a subset of data in a random way to evaluate the reliability of the developed model. By comparing the interpolation polynomial function obtained using the reduced data set with the results obtained using the original data set, a measurement error lower than 4% has been obtained. An example is shown in Fig. 6 and describes the daily average concentrations relevant to the year 2003 for CH_4, in which some data are considered to be missing [4].

To highlight the basic problem, let us consider the annual trend of hourly concentrations of carbon monoxide (CO) according to the data recorded in Taranto. These data are characterized by particular recurrences in specific hours of the day and periods of year due to road traffic pollution. The availability of a large amount of data allows individuating the trend over long time periods of the concentrations of the examined substances. For example, analyzing the annual trend of hourly concentrations of CO provides information about the presence of particular recurrences in specific hours of the day and periods of year. More precisely, we notice the presence of two distinguished daily peaks of CO concentrations, corresponding to rush hours for road traffic, which are 9:00 AM and 8:00 PM, and a minimum of CO concentrations, corresponding to summer days, when it is normally possible to observe a reduction in road traffic.

By following the observations, and on the basis of an intensive measurement processing performed on data sets, we have individuated a mathematical model, based on a suitable polynomial interpolation, that describes the behavior of daily average concentrations of pollutants examined during the days of the year.

By analyzing benzene concentrations, we have obtained very similar results (same daily and seasonal trends) with respect to the CO data. After a suitable fitting of the available measured data sets, it has been possible to identify a strong correlation between the two substances (the correlation coefficient between the two interpolation curves is 0.97 [29]) and to individuate a good linear relationship between the examined pollutants.

To supply the first validation of the obtained results, we have carried out an annual reconstruction of daily average concentrations of benzene, starting from CO values and coefficients of the achieved linear regression straight line. To evaluate the reliability of the identified correlation, two indexes relevant to the mean square deviation have been defined as

$$\mathrm{ind}_1 = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_i - x_{i_1}}{x_i}\right)^2}$$

$$\mathrm{ind}_2 = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{x_i - x_{i_2}}{x_i}\right)^2}$$

where N is the number of samples in the data set, x_i is the ith sample of the collected data set relative to the values concentrations of benzene, x_{i_1} is the ith sample, relative to the interpolating curve obtained using a complete data set of benzene concentrations, and x_{i_2} is the ith sample relative to the curve obtained using the interpolating curve of CO and applying the identified linear correlation.

The percentage difference between the cited two indexes is 4.5%, and this can represent the first validation of the so-identified correlation. A more complete discussion on these results can be found in [3].

B. Tempospatial Correlation

After data integration, a perceptive agency we developed performs spatial correlation. This second treatment introduces a further check on the data set. In our case, a "temporal agent" and a "spatial agent" are defined as software components that are capable of acting to accomplish tasks on behalf of their user. Hence, in this application, the perceptive agents are software programs that perform analysis of data relative to air pollutants.

Temporal validation is based on an agent that compares the acquired and expected data (extracted by applying a forecasting model, as explained above). If the data are verified in the expected range, they are labeled as "valid" and valid for processing; otherwise, they are labeled as "suspect." If an agent with "suspect" data is recognized in the agency, a second agent analyzes the correlation between the "suspect" data and the other data collected from the other stations using a suitable proximity matrix (with a weighing function generated according to the monitoring stations relevant to near positions).

If the measured values are similar to the values obtained (at the same instant) from the other stations, the agent updates the database, and the "suspect" data are accepted; otherwise, it considers the data invalid due to malfunctioning of the instrumentation. Furthermore, there is the case in which more data of near stations are over the threshold of tolerability; therefore, these data are not wrong, but the spatial agent accepts all acquired data because there is an anomalous local environmental reason to validate the data.

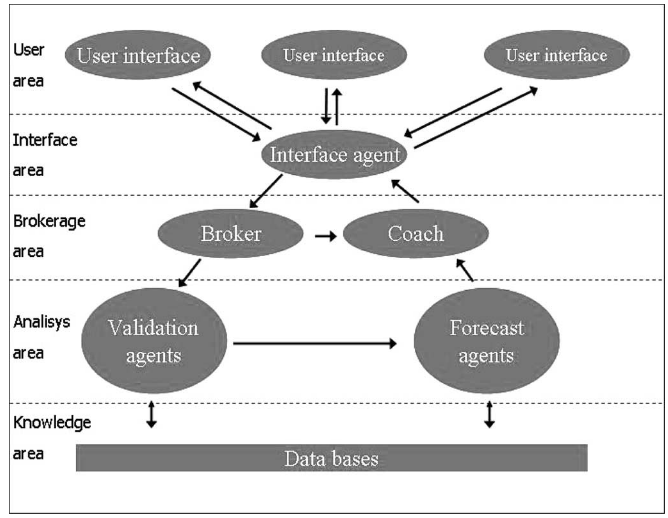

Fig. 7. Data flow of the agency architecture for environmental monitoring.

The two agents described above are integrated in an agency that answers queries characterized by a high semantic level. The basic idea is that all users (humans or computer systems), using the Web, can formulate a query to the system to obtain environmental information. Our agency is composed of classes of agents. A class collects the agents that have the same features and common goals but that are able to satisfy these goals with different approaches and with different results. This is an example of the flexibility connected to the multiparadigmatic nature of an agency.

Engineering the agency, three main classes (or areas) have been identified, namely 1) interface class (its goal is to interpret external queries according to services offered by the agency), 2) brokerage class (its goal is to manage information flows), and 3) analysis class (its goal is to satisfy environmental applications, which validate and forecast pollutant values). Fig. 7 shows the developed agency with the following agents: "interface" (one agent), "broker" (one agent), "validation" (more agents), "forecast" (more agents), and "coach" (one agent).

C. User Interface and Communication Acts

In this section, we describe the user interface of the developed agency and the communication between agents. A user can compose a query to the system by compiling a form through a drop-down menu shown at the bottom of the page.

Action	Pollutants	Place	Range	Reliability	Time	Historical data set

The "Action" requested by the user is the goal that the agency will try to fulfill. In the analysis of the environmental data, the possible "Actions" are the following:

1) to validate a datum (in the space);
2) to foresee a datum;
3) to foresee a datum with technique # 1;
4) to foresee a datum with technique # 2;
5) to foresee a datum with technique # 3;
6) to query the database on the acquired historical data;
7) to calculate the average;
8) to calculate the maximum one;
9) to calculate the minimum one;
10) to calculate the most reliable one.

The selected action must be completed by the other fields that specify the type of request. If no value for a field is inserted, it is set to a default value.

The "Pollutants" (and weather parameters) are mandatory elements to define all the queries. In the proposed menu, the cardinality of this field is 28. The first 23 values are standard chemical and weather parameters: SO_2, NO, NO_2, NO_x, CO, CO_2, CH_4, NMHC, THC, benzene, toluene, xilene, polycyclic aromatic hydrocarbons, O_3 (ozone), radiation, total suspended dusts, PM_{10}, temperature, wind direction, wind speed, rain, damp, and relative pressure. The last five values are linear combinations of different parameters to extract: industrial pollution, automotive pollution, domestic combustion pollution, general air quality level, and meteor–climatic condition. Industrial pollution is characterized by an indicator that is the average of the following products of combustion analyzed by fixed stations: SO_2, NO, NO_2, NO_x, CO, CO_2, CH_4, and PM_{10}. The obtained value is further weighed in relation to speed and direction of the wind. The indicator can produce five different results: low, middle-low, middle, middle-high, and high. Automotive pollution is characterized by the average of benzene, toluene, xilene, and polycyclic aromatic hydrocarbons. Pollution due to domestic combustion (boilers and kitchen) is the weighed average of CO, CO_2, and CH_4; the result is further weighed according to temperature. Air quality level is the average of the last three parameters of temperature, pressure, and wind (speed and direction). Meteor–climatic condition is specified by a chart that evaluates temperature, damp, atmospheric pressure, and wind (both speed and direction).

"Place" is another mandatory parameter to specify the query in relation to the spatial concentration of a defined pollutant. We give the possibility to define some global results like the average of all the stations ("town condition"); the average of the three stations of the urban center; the average of three stations in high traffic zones; and the average (weighed with the distance) of seven stations to calculate the condition of residential zones of Southern Taranto.

"Range" is an optional parameter to be used with the techniques of spatial validation. The measure acquired by a station is compared with those of the neighbors using a proximity chart. The validation task finds relations among the measured datum d and the values of the other stations using techniques of weighed average applied to some stations that are close to the station that has provided the value d. The validation values are provided by the near stations. Weight is a function of the distance. We can choose to use little (three stations), middle (four stations), or wide (seven stations) neighboring area.

The degree of "Reliability" is a parameter that is used to define the validity of data. The reliability of a measure is a parameter defined by laws, but it can be selected by the user too. The cardinality of this field is 10. The Italian normative for air quality prescribes that at least 99% of the values of a parameter must be compatible with the trend of the parameter (a forecast or an analysis relative to a specific polluting substance or environmental quantity). This verification test for air quality has been modified with the Italian D.M. on 2 April 2002 n. 60, according to the European Directives 1999/30/CE and 2000/69/CE.

"Time" of the validation is a mandatory parameter for spatial validation, forecast, or examinations about a pollutant or an environmental parameter.

The "Historical data set" allows the user to choose which data set an agent has to use for calculating a forecast. In our application, the cardinality of this field is 10. The possibilities of choice are 1 month, 3 months, 6 months, 1 year, 2 years, 3 years, 4 years, 5 years, 6 years, and 7 years.

Using a sequential model, the user sends the query to the interface agent that translates the message into a format (based on an *ad hoc* ontology) that other agents can understand. Then the interface agent forwards the message to the broker, which breaks down the query into elementary tasks. The broker sends to the validation and forecast agents as many messages as the elementary tasks. The agents reply to the coach. It waits for all messages; then, it assembles the received information and replies to the interface agent that converts the final message into a format suitable to be shown to the user.

According to Section II, the agent–agent communications are based on SMTP to carry a knowledge query and manipulation language (KQML) message. A user sends an email or compiles a dropdown menu that sends an email to the interface agent. All the above agents are written in C language and run on a Linux Pentium-based computer. Currently, 27 agents are running on 4 years of data.

We are testing this architecture, increasing the number of agents (essentially used to perform different foreseeing algorithms) in homogeneous and heterogeneous environments, to evaluate the performance and the limits of our approach.

VI. Conclusion

In this paper, we have presented the main results of the APE Project, which is centered around the notion of perceptive agency. The perceptive agency provides an approach to the development of distributed, autonomous, modular, and effective measurement systems composed of perceptive agents. We have presented two specific applicative instances of the general paradigm of perceptive agency. In the first application, perceptive agents are mobile robots equipped with EMF sensors that monitor EMF phenomena. In the second application, perceptive agents are software programs that perform, according to different methods, analysis of data related to air pollutants. Future work will address the application of the perceptive agency approach to other domains.

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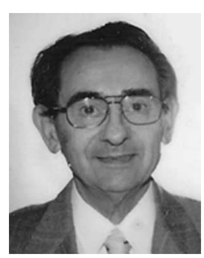

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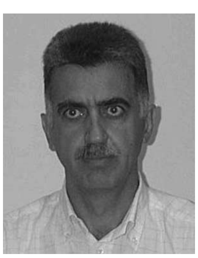

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