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Agencies for Perception in Environmental Monitoring

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Abstract *– This paper presents the main results obtained in the APE Project, funded by 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, we describe communication issues between perceptive agents and two implemented multiagent systems for monitoring electromagnetic fields and for pollutant evaluation.*

Keywords *– Cooperative systems. Mobile robots. Robot sensing systems. Electromagnetic fields. Air pollution.*

I. INTRODUCTION

An *agency* [9] 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 (that is typical of classical artificial intelligence); on the other hand, the agencies, being composed of more agents, adopt a multiparadigmatic approach to the problem resolution.

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

The traditional research has been oriented to build sensor networks composed of a number of sensors, independent and distributed, able to collect information on the ground and to transfer it to a central system that processes it to return high-level indications to who can take operative decisions. This conception is based on the ability to determine a priori the characteristics and the placement of the 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 such 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 together 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 [4]. The complexity both of the 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 a multidisciplinary approach 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 APE (Agencies for PErception in environmental monitoring) Project, 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 a cooperative multiagent system 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 agency approach of the APE Project is that it can include mobile robots equipped with different perception devices [8]. The modular installation of the different sensor equipments onboard of mobile robots increases the quality of the perception and, as a consequence, of the monitoring. The mobile robots offer to the sensors the ability of mobile perception, namely the ability of moving around the environment. In this way, the perceptive agents are dynamic with respect to the time, since they can obtain a sequence of perceptions, and with respect to the 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, namely with pairs passive sensor - stimulator), also mobile (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.

A first applicative example that has been considered in the APE Project is related to the support to the geometrical reconstruction of the environment and to the mobile robot navigation, exploiting telemeter sensors (detailed results are reported in [5][7]). A second applicative example is related to the environmental monitoring and consists in the measuring of the electromagnetic field for the analysis of the environmental electromagnetic pollution, exploiting sensors that perceive the electric and the magnetic fields. The results of this application are discussed in Sections III and IV (more details are reported in [6][10]). A third example is the analysis of the chemical-physical conditions of the air to identify the possible polluting elements. This application is discussed in Section V (more details are reported in [2][3][13]).

II. COMMUNICATION INFRASTRUCTURE FOR DISTRIBUTED MEASUREMENT SYSTEMS

To build sensor networks, it appears suitable and favorable to use commercial-off-the-shelf communication infrastructure technologies. Many communication infrastructure technologies were developed in the last years, with various technological features (transmission range, data rate, etc.), various purchase and maintenance costs, and various degrees of easiness to implement. Many of these technologies became a standard supported and maintained by official organization.

Within the APE Project, we carried out an analysis of the communication infrastructure technologies, hardware, and protocols, and of the related products suitable for implementing interconnected networks for distributed measurement systems, especially for environmental applications. The analysis aimed at understanding the characteristics, the benefits, and the limits of the various solutions, as well as to give guidance in making the most appropriate choices for specific application cases. For each interconnection solution we considered the physical interconnection characteristics, the architectural and functional characteristics of the physical transmission, interconnection, and communication model; moreover we outlined the architecture and the functions provided by the lower level protocols and the relevant points of the application protocols specification. Finally, security issues and related security standards have been analyzed. The analysis provided, besides general information about the specific products available on the market, the possible organizations supporting the technologies and some applications in real and research environments with reference to measurement and distributed networks.

The first focus of the analysis was on wired network technologies with specific reference to general purpose solutions and to technologies dedicated to sensing. The main results obtained on wired network technologies for monitoring systems follow.

1. Serial transmission media (RS-232-C, RS-449, USB, Firewire) provide effective low cost, low distance interconnection typically for transmission from data acquisition systems to a computer dedicated to manage the information collected in a distributed monitoring system.
2. Ethernet (the common name for the IEEE standards 802.3, 802.4, 802.5) provides many advantages, including low cost, broad uses, wide area systems network, continuing enhancements, high data rate (up to 10Gb/s); Internet Protocols, applications, and interfaces are based on Ethernet. Ethernet and related protocols are suitable for Internet-based distributed measurement and control application [16] and for high-performance measurement systems to build data acquisition and telemetry system [20].
3. Fiber (Fibre Channel Standard, FDDI) provides the most effective interconnection technology to integrate and control systems when high performance, high distance (kilometers), high data rate (Gb/s) are required.

A particular effort has been given to the analysis of wireless network technologies that are the most appropriate interconnection technologies for sensor networks for monitoring and measurement systems, especially for environmental monitoring. At the same time, environmental monitoring is a driving application for wireless sensor networks. For example, wireless sensor networks for habitat monitoring research will be the challenge for the next years. It implies a different way to implement sensors and transmit data collected by the sensors [17].

The main results obtained about wireless networks lead to the following wireless network technologies for monitoring systems.

1. Wi-Fi (the common name for the IEEE standard 802.11) provides fair transmission distance and data rate (11Mb/s and 54Mb/s) for wireless local networks; Wi-Fi operates in the unlicensed 2.4GHz and 5GHz. Internet Protocols and applications are based on IEEE 802.11. Typically, the IEEE 802.11 transmission is effective for the transmission from gateway (sensor's interface) to a base station that collects and computes data [17]. Moreover multiple receiver base-stations

can be bridged to an 802.11-based access point, enabling the concept of multiple sensor clusters connected to a central information gateway in a wireless sensor networks [19].

2. Bluetooth provides short range, low cost implementation of small wireless networks operating at 2.4GHz ISM Band using Frequency Hop. A limit of Bluetooth consists in requiring for each specific application well defined protocol stacks called Profiles. Although its limits, range, data rate, small networks, Bluetooth enables the development of sensor networks for low cost industrial or home applications with few sensors [14].
3. IrDA (the short name for Infrared Data communication) provides short range wireless connectivity (up to 1 meter, with angle narrower than 30 degree) at speeds of 9.6Mb/s and 16Mb/s, and require a well defined protocol stack for each specific application. IrDA intrinsic characteristics limit its effectiveness in distributed systems as a reliable and secure cable replacement for device interconnection.

III. THE EMF SENSOR

The measurement of the low-frequency magnetic and electric fields for verifying the levels for human exposure is an activity of great interest for its implications on the human health [15]. 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: *i)* 10Hz-10kHz bandwidth (that is suitable for detecting and measuring magnetic and electric fields produced by transformer stations, electrical machines, high voltage lines, etc.); *ii)* rms values measurement and frequency spectra analysis of the three spatial components of the magnetic and electric fields; *iii)* 1 Hz frequency resolution in frequency analysis; *iv)* automatic comparison of the measured values with the thresholds allowed by the ICNIRP guidelines [15]; *v)* making costs cheaper than those of sensors available on the market.

The developed sensor is organized in two sections: the analog front-end and the digital processing unit.

The magnetic field signals are collected by three coils placed on three orthogonal plans (commercial probe Narda 100cm^2 isotropic B-Field), while the electric field signals are derived from three capacitive sensing elements (one for each spatial axis) followed by proper electrometer (custom probe). The probes signals are firstly amplified by PGAs and then filtered by fifth order low-pass antialiasing filters, with 10kHz cut-off frequency, according with the bandwidth requirement of this application. The resulting signals are then sent to the ADC input. The analog to digital conversion is based on a 12-bit ADC, featuring 8 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 the measurement functions (auto-ranging, rms evaluations, spectrum analysis, field exposure check, etc.) are performed by digitally processing the acquired data, and the results are available on a RS232 port.

Some experimental tests have been undertaken in order to calibrate the developed sensor. 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 (2m^2 area, 25cm gap) supplied by a sinusoidal voltage.

The sensor calibration was performed by comparing the sensor measurement results to those performed by the reference instrument (Narda EFA 300 Analyzer). These tests were performed operating with different amplitudes and frequencies, in the sensor measurement ranges. A detailed description of the experimental activities is reported in [10].

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

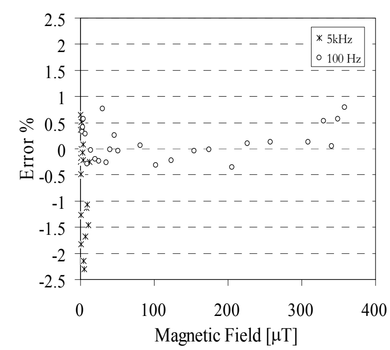

Figure 1 - Percentage relative error of the EMF sensor for different amplitudes and frequencies of the magnetic field

Starting form the described version of the sensor (that will be mounted on the robots of next section), during the APE Project an improved version of the sensors has been also developed. In particular, a new board was introduced, in order to manage multi-network communication standards, especially oriented to support both mobile and fixed autonomous application of the sensor.

This board, called Common Interface for Remote Operation (CIRO), is able to support standard protocols of communication (GSM/GPRS, Ethernet, Bluetooth, IRDA, and RS232) and can be interfaced with a wide typology of sensors (it can manage RS232, SPI, Analog voltage input, 4-20mA current inputs, digital I/O). The CIRO core is a Motorola Dragonball 68VZ328/33MHz CPU with μClinux

2.4 operating system and it has been endowed with a GPS sensor for geographical position measurement (Figure 2).

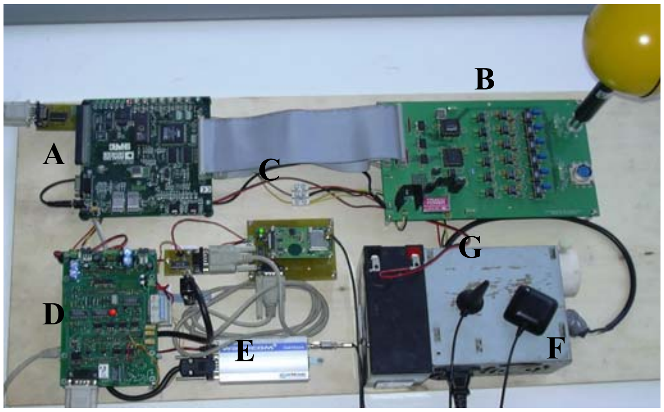

Figure 2 - The improved system; A: magnetic and electric fields sensors digital processing unit; B: magnetic and electric fields sensors analog processing unit; C: GPS sensor; D: CIRO; E: GPRS/GPS modem; G: GPS and GPRS antennas; F: power supply systems

In this way, the overall system represents an evolution, in the sensors application, of the Machine-to-Machine (M2M) concept, supporting a wide typology of communication protocols, offering various interfaces for sensors connection and also 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 [12].

IV. MOBILE ROBOTS FOR MONITORING ELECTROMAGNETIC FIELDS

In environmental monitoring, any system that has to detect phenomena reliably and to 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 [18]. Within the APE Project, we developed an architecture for a multirobot system that performs tasks oriented to localizing and characterizing low-frequency Electro-Magnetic Field (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 equipments. 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 activities 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 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 an 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 the 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 (that is supposed known). For simplicity, we considered a single EMF source. The position of the EMF source is given by the cell in which the source is located. In the following experiments, the on-board EMF sensors have been simulated; they return data in accordance with the position of a simulated EMF source placed in the environment via a graphical interface. Experiments with the real sensors described in the previous section are still ongoing.

We now describe the most significant feature of our system: the task allocation of step 3 of the above algorithm (for a more complete description, see [6]). 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 a 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 position to 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.

We present one of the several EMF monitoring tests we performed. In this experiment, we localize and characterize a EMF source that changes its position over time. Initially, the robots perform an EMF measurement in their initial locations (Figure 3 left top). The coordinator uses the data gathered by the robots to determine (by triangulation) the estimated position of the EMF source. 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 (Figure 3 left bottom); 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 refine the hypothesis). At some point, we manually change the position of the EMF source in the environment. After one of the measurements returned by the moving robot, 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 (Figure 3 right top) and circumnavigates it for characterization (Figure 3 right bottom).

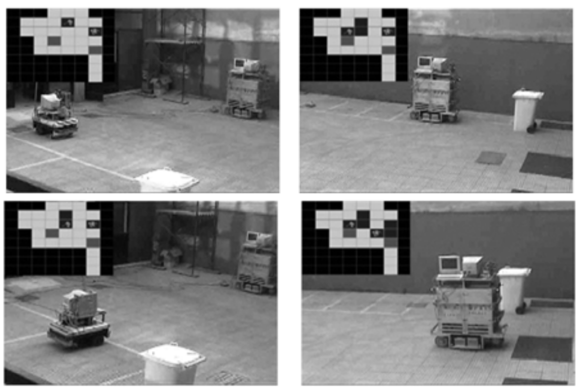

Figure 3 – Localizing a EMF source

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.

V. AGENCIES FOR AIR POLLUTANT EVALUATION

The choice of a monitoring process for air pollutants depends on the type and the relevant properties of the substance that must be acquired. Pollutant concentrations depend on emissive sources, geographic conformations, and meteorological conditions, capable of modifying atmospheric dispersion of pollutants. Therefore, to evaluate the air quality properly, it is necessary to work out a sophisticated monitoring system that measures chemical substances and meteorological quantities [1].

Environmental data, recorded in several monitoring stations, installed in many Italian cities, provide real information for our application. The monitoring stations are distributed according to the national prescriptions. The measurement network of Taranto urban area (about 250,000 people) is composed of six stations. All the equipments carry out approximately 50 measures/minute (raw data), that are recorded and subsequently processed to generate medium values (valid data) per hour.

The perceptive agency we developed in the APE Project is layered in five levels, and answers to a queries characterized by a high semantic level. Basic idea is that all users (humans or computer based systems), using the Web, can formulate a query to the system to obtain environmental information.

The general structure, that we identify by engineering the multiagent system, is based on three general classes of agents: the first one is the Interface class (agent-goal interpreting external queries according to services offered by the agency), the second one is the Brokerage class (agents with only one goal: dividing the goal in simpler sub-goals and selecting the agents that can satisfy the specified sub-goals), and the third one is the Analysis class (agents with specific features to satisfy environmental applications: to validate and to forecast pollutant values). As shown in Figure 4, five more specific subclasses have been introduced, to implement a scalable system: Interface (one agent), Broker (one agent), Validation (more agents), Forecast (more agents), and Coach (one agent).

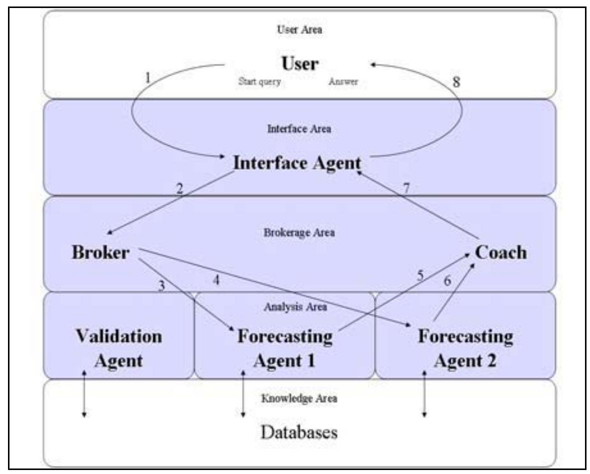

Figure 4 – Perceptive agency for air pollutant evaluation

The inter-agent and external communications are based on the well known protocol SMTP (Simple Mail Transfer Protocol), to carry a KQML message. A user sends an e-mail or compiles a dropdown menu that sends an e-mail to the Interface agent.

The Interface agent translates the message from human/natural language into an Agent Communication Language (ACL) [11]. A dropdown menu would make the integration easier in Internet.

The Broker agent decides which agents can satisfy the request. The Broker analyzes a local database in which services, offered by the agency, are stored. Starting from one query, it produces as many e-mails as the request needs. The language that Broker uses to communicate is resulted from the use of understandable and common language for all agents.

The Validation agents try to validate the data acquired by the measurement stations. These data must be treated and filtered according to measurement technique shown in [1], using the knowledge of the geographic position in which sensors are placed. Often there are missing data, this occurs because of periodic settings or stops of the instrumentations, or of incorrect data caused by bad functioning or un-setting of the equipments.

The Forecast agents have their own knowledge, based on forecasting models, which are known in literature. Each forecast agent applies its analysis method, in this way it is possible to define which is the best forecast method among the ones that are used. This is a typical example of the importance of the multiparadigm approach of a perceptive agency.

The Coach is the dual agent of the Broker, because it is able to assemble information contained in the e-mails that the Validation and Forecast agents have sent. At the end of the process the Coach sends an e-mail to the Interface, that translates the answer from ACL into human language.

The proposed approach divides a query - How will be air quality tomorrow? - in a number of simpler queries. The combination of information given by different agents to the Coach and the communication Coach-Interface-User is the solution for the problem of the apparent intelligence of the system. Some results show the time and the way in which a message is generated by a user and how it is decomposed in other simple messages that agents can manage.

All the above agents are written in C language and run on Linux Pentium based computer. At this time, 27 agents are running on 4 years data. The basic idea is to use data of the day before to foresee the current parameters.

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

VI. CONCLUSIONS

In this paper we have presented the main results of the APE Project, which is centered on the notion of perceptive agency. Perceptive agency provides an approach to the development of distributed, autonomous, modular, and effective measurement systems. Future work will address the application of perceptive agency approach to domains related to industry and security.

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