Artificial Intelligence in Science of Measurements: From Measurement Instruments to Perceptive Agencies

Francesco Amigoni, *Associate Member, IEEE*, Arnaldo Brandolini, Gabriele D'Antona,
Roberto Ottoboni, *Senior Member, IEEE*, and Marco Somalvico

***Abstract*—This paper motivates, from historical, philosophical, and industrial points of view, the adoption of a novel scheme for developing complex measuring systems as perceptive agencies. The general concept of agency, a cooperative multiagent system defined within distributed artificial intelligence and robotics, is discussed together with its particular application to the field of intelligent instruments. An embryonic example of perceptive agency applied to the field of environmental monitoring is reported.**

***Index Terms*—Artificial intelligence, cooperative systems, intelligent systems, knowledge-based systems, measurement.**

I. INTRODUCTION

MEASUREMENT techniques always presuppose a theoretical model of the phenomenon under observation. Usually, the construction and the validation of the model underlying the measurement process is based on *a priori* knowledge. When a measurement process concerns complex phenomena, it is extremely difficult to identify an adequate and satisfactory model that does not need to be continuously updated. As a matter of fact, the phenomena can be often modeled only by a set of (interconnected) partial models, each one embedded in an independent measurement system. A sort of cooperative intelligent activity needs to be included in the measuring system when it is conceived and organized as an apparatus composed of a number of perceptive systems [1], [2]. This new idea of complex measuring systems leads naturally to consider them as *perceptive agencies*, namely as instances of the cooperative multiagent systems or agencies extensively studied in distributed artificial intelligence and robotics.

This position paper motivates, from historical, philosophical, and industrial points of view, the adoption of the above mentioned novel scheme for developing complex measuring systems as perceptive agencies. Since the purpose of the paper is to show a tendency that is emerging in the field of measurement systems, it mainly gives theoretical argumentations grounded on some practical examples. In this perspective, the paper does not present any particular system, in order to concentrate the attention on the main abstract, methodological, and architectural ideas without diverting into many technological details. Therefore, given the purpose of this paper, we will not focus on the implementation techniques and technologies that can be adopted to develop distributed measurement systems (see [3] and [4] for two examples of these issues). Also, a survey of the distributed and multiagent measurement systems is outside the scope of this paper. Instead, the general concept of agency, intended as a cooperative multiagent system within distributed artificial intelligence and robotics, is discussed together with its particular application to the field of intelligent instruments. An embryonic example of a perceptive agency applied to the field of environmental monitoring is also reported.

The major original contribution of this paper lies in the argumentation it provides about the importance to conceive a distributed measurement system as a *unique* system, even if it is composed of several intelligent perceptive agents. The idea of conceiving single measurement instruments as independent agents has been already presented in [5]. This paper goes beyond [5] in three different ways. First, we put the attention not only on software agents that manage the measuring equipments and that provide information or expertise, but also on robotic perceptive agents on which measurement instruments can be mounted. Second, we argue that a modern measurement system should be conveniently conceived not as a set of independent and interacting agents but as a complex system which is considered as *unitary* in its nature. Third, with respect to [5], our approach is set in a broader historical and philosophical background.

The paper is organized as follows. In Sections II–IV, we illustrate how the concept of perceptive agency naturally emerges from the history of measurement systems, from the philosophy underlying these systems, and from the current industrial practice, respectively. In the Section V, we briefly survey the main concepts about multiagent systems and agencies in distributed artificial intelligence and robotics. In Section VI, we describe the features of perceptive agencies, while a preliminary study of their practical application is presented in Section VII. Finally, Section VIII concludes the paper.

II. HISTORICAL BACKGROUND

In this section, we present the historical evolution of measurement systems from which the concept of perceptive agency emerges. In past times, the instrumentation for measuring electrical quantities was of electric or electromechanical type [6]. The analog electronic instrumentation had not enough time to

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F. Amigoni and M. Somalvico are with the Dipartimento di Elettronica e Informazione, Politecnico di Milano, Milano, Italy.

A. Brandolini, G. D'Antona, and R. Ottoboni are with the Dipartimento di Elettrotecnica, Politecnico di Milano, Milano, Italy.

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complete its evolution because it was overcome by the digital instrumentation. In both cases, the instrumentation was always devoted to measure one or more specific electric quantities (even in a complex way) [7]. In the mid 1970s, it appeared the digital programmable instrumentation [8], based on the use of "firmware structure" (although some examples of analog systems with programmable logic had already appeared on the scene). It was possible to reprogram and reutilize this kind of instruments for different purposes in a short time, even if their performances were somehow restricted with respect to hardware and software points of view. The digital programmable instrumentation was also called "intelligent instrumentation," simply because it was based on *processing*; this "intelligent" processing activity increasingly extended from the acquired data to the higher level software components that manage more abstract information and knowledge.

This high-level processing activity can be considered as the first application of artificial intelligence concepts to the measurment systems, that has lead in the 1980s to the generalized use of the intelligent instrumentation. The attribute "intelligent" was adopted when the measurement instrument (or, better, the measurement system) was capable to exhibit an abstract logical management (based on logical inference procedures) of the information acquisition and processing activities, previously directly managed by human operators [9]. Furthermore, the techniques of artificial intelligence have continuously evolved and improved over the years. In this way, the devices employing reasoning techniques have reached unexpected results. This has an impact also on measurement systems whose nature and conceptual interpretation have radically changed as illustrated in Sections III–VII.

III. PHILOSOPHY OF THE MEASUREMENTS

In this section, we illustrate how the main ideas underlying the theory of measurements have shifted toward the concept of perceptive agency. It used to be a widespread belief that, in the physical sciences, the experimental results were decisive for giving the final answer in doubtful matters. Everybody was convinced that, as Eddington affirmed [10], the theoretical physics should make its way toward the experimental evidence of a physical law.[1]

On the other hand, in more recent times, some researchers have pointed out an opposite hypothesis: the formal outcomes of theoretical physics are the *a priori* structures in which the experimental results must fit. The possible lack of agreement between theory and experiment is considered mainly due to the way in which the experiment is carried out. Therefore, the effects that can be reasonably considered "false" with respect to the adopted theoretical model must be removed from the experimental data. The ISO Guide to the Expression of Uncertainty in Measurement [11] points out this hypothesis both when it prescribes to eliminate any systematic effect and when it suggests to model some effects as random variables on the basis of reasonable hypotheses. Starting from these assumptions, it is natural to put the question if, when we make a measurement, we may think to already know (at least some properties of) the result and, as a consequence, we may behave as if we knew it [12, p. 32].

This dual conception of the experimental processes and of the measurement results interpretation is also philosophically and anthropologically supported by one of the mainstreams within the philosophy of the nature from ancient times. In fact, the philosopher Plato [13] postulated that the physical reality imitates the ideas, which are absolute models. He thus recognized an absolute value to the intellectual models (namely, to the Platonic ideas) rather than to the mere sensible reality. Closer to us, Kant [14] stated that all the human knowledge about reality is filtered through some logical categories (the twelve categories, including space and time), which constitute a logical model *a priori*. Thus, the theoretical importance of models is rooted in a well-established philosophical tradition.

With respect to the ability of developing intelligent machines, Alan Turing stated (by his Turing Test [15]) that "intelligent" is a property that can be assigned to a machine that gives answers we are expecting to be given only by a human. This conception is implicitly adopted also when we consider as intelligent those measurement instruments exploiting data processing capabilities that (until that time) were thought as a human prerogative. The technical progress of artificial intelligence has brought to systems that are able to suggest problem solutions (starting from assigned knowledge bases and sets of rules), which go beyond the direct expectations of the operators [16]. It is necessary, therefore, to deeply analyze the new conceptual perspective of measurement systems imposed by the modern technological developments.

According to the Turing approach, we consider a machine as intelligent when it acts in a rational way by planning its actions and by adapting to its environment. In particular, this applies to measurement systems. The intelligent measurement systems can eliminate, from the perceived signals, the effects considered useless (for instance, the effects of some sources of uncertainties). This means that the machine has a (limited) capability to discriminate between conceptual aspects. Of course, it does so on the basis of a theoretical model of the phenomenon under observation previously given by the designer. Nevertheless, it is a fact that these sophisticated instruments offer some interpretative logical capacities. The intelligence is thus put at the core of the measurement process: this approach leads also to overcome the differences between real and virtual instruments.

The previous considerations pave the way to complex and articulated intelligent measurement systems, able to cooperate among them and to perform an autonomous control of the measurement process and of the perceptive reliability. To this end, a measurement equipment can be conveniently conceived and developed as a perceptive multiagent system composed of cooperating intelligent measurement systems, or perceptive agents. Consequently, we shifted from a conception of the measurement system as a simple tool to validate a phenomenological model (namely, as a system with advanced metrological qualities but with limited reasoning contributions) to a conception of the measurement equipment as capable to give increasingly

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[1] Regarding the law of distances in regime of gravitation, rewritten on the basis of experimental results, Sir Arthur S. Eddington wrote: "In this form the law appears be firmly based on experiment, and the revision or even the complete abandonment of the general ideas of the Einstein's theory would scarcely affect it."

complex high-level rational contributions to the measurement process, by being directly engaged in the formulation and in the refinement of the model which can be experimentally validated and checked.

IV. INDUSTRIAL PRACTICE OF MEASUREMENT SYSTEMS

Recently, the quality control for an industrial product has moved from a final (qualitative or quantitative) test, usually performed in a dedicated test-room, toward a testing activity distributed both in time and space and devoted to verify the on-line properties of the production process. A number of quality parameters can be measured in different stages of the production process, making the classical final conformity test useless and also avoiding both expensive measurement equipments and the possibility of product rejection at a final stage.

Let us consider an example. An electrical power transformer is designed according to standard criteria, built, and finally tested. The production process in a classical scheme is organized as follows:

- executive design;
- purchase of the materials (electric, magnetic, and dielectric materials);
- execution of the work for the construction of the electrical power transformer;
- final conformity testing.

Given the guarantee of the quality of every step of the productive chain, a more modern technological-managerial approach would lead to the following production process:

- checking the electrical characteristics (resistivity, permeability, specific losses, etc.) of the materials at purchasing;
- checking and testing the structural characteristics of the components (size of the components/elements, geometrical uniformity of the parts, etc.);
- progressive implementation and development of the electrical power transformer (including the arrangement of the parts according to geometries prescribed by the project).

Following this new scheme, the resulting product is guaranteed and the final conformity test could be avoided. This is also in accordance with the basic concept of *total quality management*, extensively adopted in modern industry.

It may appear that the final testing is cheaper and less demanding than the distributed testing of the whole process; however this is not always the case. Indeed, the modern technologies make the acquisition of partial guarantees easier than the global verification, early assuring the final result. Moreover, with the classical scheme based on final testing, in the case some errors occur during the production process, the final product might be totally rejected, causing serious economic disadvantages. Therefore, in the classical scheme, the designers undertake a remarkable intellectual effort to be sure that the testing of the final product is constantly performed in a real time fashion.

It is clear that the control and the supervision of a production process is subordinated to an efficient distributed sensorial monitoring activity. This activity could be improved by metrological processes effectively carried out by articulated and cooperating systems which can be reconfigured both in space and time. In this scenario, the single measurement system (programmable or not) is not considered as isolated but it behaves as a component of a more complex and articulated measurement equipment. In this way, each measurement system enhances its metrological capabilities by interactively collaborating with the other components of the measurement equipment, whose architecture may be vertical (hierarchy) or horizontal (heterarchy). Consequently, the new concept of distributed measurement equipment extends far beyond and overcomes the traditional concept of instrument.

Later in this paper, we show how these measurement equipments can be suitably implemented as perceptive sensorial agencies.

V. MULTIAGENT SYSTEMS AND AGENCIES

In this section, we briefly illustrate the concepts of multiagent system and of agency as they have been established within distributed artificial intelligence and robotics.

In the mainstream of artificial intelligence, a new modern discipline has impressively evolved in the last years: *distributed artificial intelligence* [17], [18]. Whereas the focus of artificial intelligence is on the development of systems that emulate the intellectual and interactive abilities of a single human being, the focus of distributed artificial intelligence is on the development of systems that emulate the intellectual and interactive abilities of a *society* of human beings. For example, a typical artificial intelligence system exhibits some performances such as making diagnoses, proving theorems, allocating resources, scheduling activities, and planning and performing complex sequences of actions. On the other hand, the performances of a typical distributed artificial intelligence system are negotiating prices of goods, sharing knowledge about a subject, competing for resources, and cooperating toward a global goal (e.g., the construction of a model of a given environment or the movement of a set of objects in a factory).

A modern paradigm to develop distributed artificial intelligence systems is based on the notion of *multiagent system*. A multiagent system is composed of a number of intelligent agents that interact [18], [19]. An intelligent agent is a (traditional) system of artificial intelligence, maybe performing inferential activities, that can be implemented as a software program or as a dedicated computer or robot [16]. The intelligent agents (in the following simply called agents) of a multiagent system interact together to organize their structure, assign tasks, and exchange knowledge. For example, competition and cooperation can be viewed as two extremes of a range of possible forms of interaction. From the designer's perspective, there are two opposite approaches to develop a multiagent system. According to the first approach, the designer has in mind a global goal to be accomplished and designs both the agents and the interaction mechanism of the multiagent system. In the second approach, some designers conceive and build a set of self-interested agents that are then left to evolve a stable interaction structure through the use of evolutionary and learning techniques.

We consider in this paper a particular class of multiagent systems developed according to the first approach, called agencies. An *agency* [20] is a multiagent system in which the agents

Fig. 1. Three mobile robots employed in the robotic agency we developed.

and the interaction mechanism have been designed and built with cooperation in mind. The agents of an agency cooperate together to achieve a global goal. For this reason, the agency can be considered as the machine of cooperation. It is important to underline that, although it is composed of complex components like agents, the fact that the agents cooperate toward a global goal allows to appropriately consider an agency as a *unique* machine. The significance and the nature of an agency and of its conception as a unique machine are enlightened when we consider the origin of the word "agency." It was introduced by Marvin Minsky [21] under the metaphor of "the society of mind." Minsky's goal was to overcome the difficulties posed by the complex nature of the phenomena of human intelligence in order to reach their deep understanding and their satisfactory representation within given models. Minsky considered an agent as an individual entity where a particular and specific way (*paradigm*) of modeling a given phenomenon of intelligence is embedded into the functional architecture of the agent itself. Both the plurality of the phenomena to deal with and the variety of reasonable paradigms that can be adopted for modeling a given phenomenon suggest a scenario in which a high number of agents coexist and collectively contribute to set up a rich comprehensive precise description of the human intelligence. Minsky adopted the term "agency" to denote such system of agents, each one representing a descriptive paradigm of a given phenomenon. Starting from this initial characterization, the concept of agency has been employed, as already explained, in distributed artificial intelligence and robotics.

One of the main advantages of adopting an agency lies in its possibility to offer a multiparadigmatic approach to problems. Following the initial conception of Minsky, an agency can address an application by exploiting a number of different paradigms, each one embedded in an agent. The application is thus efficiently tackled with the cooperative composition of all these paradigms.

Let us consider an example of an agency we developed [22], [23] composed of robotic agents for mapping an unknown environment. In this case, the agency comprises different kinds of robots (see Fig. 1) that are distinguished on the basis of their sizes, of their locomotion structures (e.g., two differential driving wheels versus a single steering and driving wheel), and of their perceptive abilities (e.g., binocular vs. triocular vision systems). All the agents are connected with a IEEE 802.11 wireless network. The cooperation mechanism we designed for the agency solves the possible conflicts that can arise between the actions proposed by the agents (for example to reach the next area to explore). This mechanism is essentially a negotiation [24]. Moreover, the agents have to share the acquired information; this is accomplished by a shared memory area (a sort of blackboard [23]) where the perceived data are stored and retrieved. We point out that, although it requires somehow complex cooperation mechanism, the presence of a number of different specialized agents (embedding particular paradigms) extends the range of applications that the agency can successfully tackle.

Another important property of an agency is its flexibility. Consider again the agency of the above example: the insertion of a new agent that carries a new paradigm for the exploration of environments can be performed without modifying the other agents of the agency. This is because usually the cooperation mechanisms of agencies, like negotiation, are (almost) independent from the number of interacting agents. Furthermore, the flexibility of an agency is enhanced when the architectural structure of each agent provides a clear-cut division between the operative part and the cooperative part (see Fig. 2). The operative part is the specialized part of an agent that interacts with the environment where the agent acts, namely it contains the distinguishing functions and the capabilities of the agent. The cooperative part is the uniform part of an agent that integrates it with the other agents of the agency by providing a set of cooperative functions (e.g., negotiation). If the operative and cooperative parts of an agent are clearly separated both in design and in implementation, it is possible to reuse the same operative functions in different agencies that address different applications, by simply substituting the cooperative part of the agent. The flexibility of an agency is even more improved when the cooperative parts of the agents are automatically spread and inserted on the corresponding operative parts. This can be achieved by employing the modern software technique of mobile code systems (provided that the operative parts are connected by a communication network) on which the methodology of *dynamic agency* [22], [23] is based. In this case, the cooperative parts are the results of the evolution of a unique mobile code that travels and replicates itself on the operative parts. Hence, the designer of an agency has to develop the mobile code and its evolution mechanism. According to the dynamic agency approach, the cooperation mechanism (resulting from the interaction among the cooperative parts) can be automatically built and also easily substituted, even during the activity of the agency. Moreover, the operative parts on which the mobile code installs its replicas can be automatically selected, thus envisaging a situation in which the components of an agency are recruited on the basis of the task at hand. The need of differentiating the operative and the cooperative parts is envisaged (although in a primitive form) in distributed measurement systems based on client-server architectures [4], where both the client and the server components are logically split into two layers: the layer that deals with the network interconnection (that is similar to the cooperative part) and the layer that deals with instrument management and user interface (that is similar to the operative part). Finally, we re-

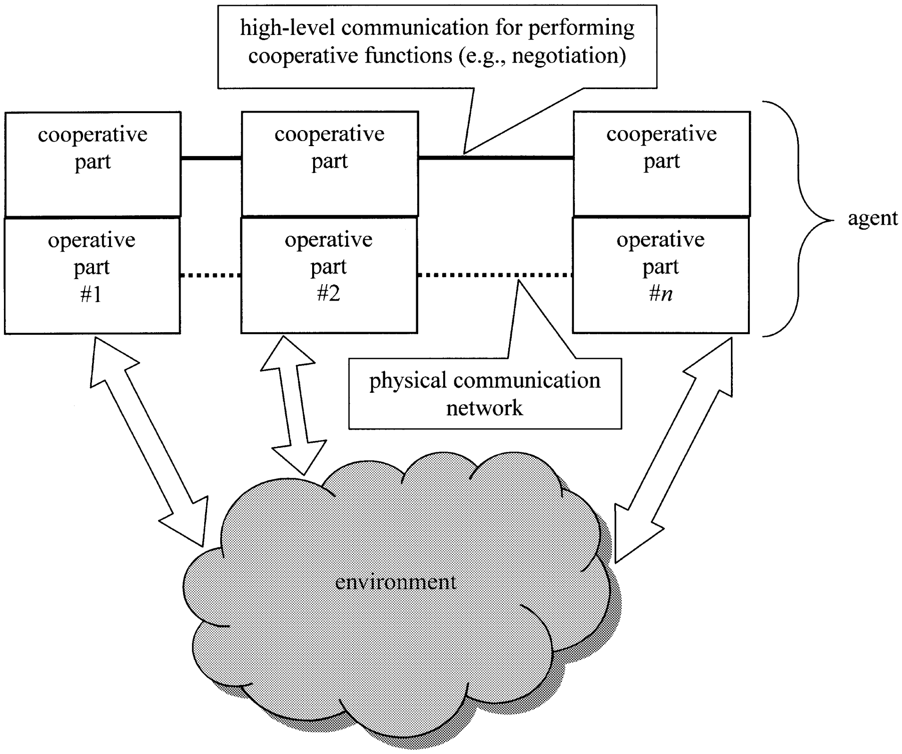

Fig. 2. Architecture of agents as divided in two parts: the operative one and the cooperative one.

mark that an interesting application of mobile code systems to measurement systems, although not as sophisticated as the dynamic agency approach, is reported in [25].

The agencies described in this section represent the way to implement modern powerful and flexible measurement systems, as discussed in the following.

VI. Perceptive Agency

As emerged from the discussion of the Sections II–IV, complex systems to measure and monitor physical phenomena require the distribution within a *chronos-topos* framework. The variability versus space (*topos*) and versus time (*chronos*) are related to the similar variability of the measured data; this variability is also reflected on the information and the knowledge obtained by the perceptive process. The methodological and architectural solution for these highly sophisticated, complex, and advanced distributed perceptive systems is provided by the *perceptive agency*.

Each monitoring station that perceives, measures, processes, and interacts with the users is oriented to provide a unitary support to the phenomenon monitoring and to the information management. The basic idea is to conceive each monitoring station as an agent; while the global monitoring system, made up of a network of interconnected stations, is conceived as a distributed perceptive agency, a particular instance of the modern multiagent approach described in Section V. We deem that agencies provide the best tools for the architectural conception of distributed measuring systems. In fact, they capture the complexity of the phenomena to perceive by means of an architecture that allows for the presence of different complementary partial models of the phenomena. Moreover, the whole system is oriented to a single perception task, in accordance to the conception of the perceptive agency as a unitary machine.

Relying on what discussed in Sections II–V, it appears now clearly how the perceptive agency can be seen as the last step of a progressive evolution (that has boosted in the last years) of artificial intelligence techniques applied to measurement, which followed this path.

1) Measurement sensor aimed to measure an elementary physical parameter and to return a corresponding electric parameter. For instance, gas sensors and microphone pickups devoted to monitor powders, gases and acoustic pollution in a limited urban zone.
2) Measurement system aimed to provide, in addition to the measurement sensor, the digital-based reprogrammable functions. For instance, sensors equipped with analog front end for the acquisition and with digitalizing devices devoted to extract rough measurements data from sensors output signals.
3) Perceptive agent, which improved the measurement system by providing the (computer-based) signal pre-processing and measure post-processing functionalities that allow complex phenomenological evaluations. A perceptive agent can also be considered as a white robot, namely as a robot having only sensorial interaction with the external world. For instance, a perceptive agent, based on the previous sensorial structure, is also able to perform the spectral analysis of the acoustic signals and to detect and classify the different powder and gas types.
4) Intelligent perceptive agent aimed to provide, in addition to the perceptive agent, the reasoning abilities (im-

plemented as logical inference procedures) on the knowledge representing the perception, according to a model, of a phenomenon. For instance, an intelligent perceptive agent is able to analyze all the collected data and, by inference procedures, identify the pollution sources and their characteristics (traffic intensity, gases produced by cars, gases produced by buildings heating, etc.).

5) Perceptive agency aimed to integrate together in a cooperation process, oriented to a global modeling task, several intelligent perceptive agents into a synergic system. For instance, a perceptive agency is able to integrate the information of the previously described agents with those of other types (agent devoted for weather forecasting, agent devoted to monitor highway traffic, etc.) to provide a better definition of the overall environmental status of the city.

The perceptive agency has the global goal of performing the various cooperation processes required for bringing together the various sources of sensorial information and of symbolic knowledge, in order to provide the resulting performances of monitoring, supervising, controlling, and managing the phenomenon, its parameters, and its properties. Each perceptive agent is equipped with (smart) sensors able to model the world by means of the technologies that support the necessary intelligence for an efficient behavior of the whole perceptive agency. For example, when considering a perceptive agent we can distinguish between *mobile* (when sensors are mounted on mobile robots) and *fixed* sensors and, orthogonally, between *active* (when the phenomenon to be perceived is stimulated, as in the case of a camera that perceives the edges projected on environment objects by a laser beam) and *passive* sensors. Intelligent sensors and sensor fusion activities take care of reliable data processing at the bottom level within the operative part a perceptive agent [26]. At an higher level, basic control tasks are performed by agents (actually, by their cooperative parts) exploiting artificial intelligence techniques, such as reasoning and learning. For instance, the distributed cooperation processes that take place in a perceptive agency include knowledge sharing and task allocation (recall the example of Section V). Both of these aspects are closely related to the type of cooperative organization according to which the perceptive agency is designed. For example, in a hierarchical cooperative organization, the sharing of the knowledge (obtained by agents perceiving the phenomena) could be conveniently performed by message passing between agents and their supervisors; while, in a heterarchical cooperative organization, it could be better based on a blackboard shared memory area [27], [28]. In the hierarchical case, the tasks can be allocated to agents with a centralized planning technique [18]; while in the heterarchical case, the tasks can be negotiated among agents with the contract-net paradigm [24].

The advantages that are expected to be provided from the perceptive agency approach and its related intelligent technologies and architectures are the following ones (these issues could also be considered as desiderata in the development of perceptive agencies).

- Reactivity: the architecture takes into account the evolution of the observed phenomenon and is able to adapt autonomously both the system composition and the agents behavior to the new environmental conditions. For example, the robotic agency for exploration of Section V can exploit this flexible architecture to insert a new smaller robot to map a newly-discovered narrow part of the environment.
- Efficiency: in each situation, the system is able to schedule efficient action plans involving one or more agents. For example, the negotiation mechanism used for allocation of areas to explore in the robotic agency of Section V is scalable to a significant number of agents.
- Reusability: the system development is carried on in such a way that the agents can be considered as reusable components. The dynamic agency methodology outlined in Section V is intended to take a step in this direction.
- Reasoning explanation: the perceptive agents act in order to understand the behavior of the external world and to improve the system knowledge. For example, the robotic agents of the exploration agency of Section V are devoted to perceive the segments (extracted from the images returned by the vision systems) that represent the features of the surrounding environment and to integrate these segments in a single global and coherent map of the environment.
- Operator interface: during the definition of the activities of the system all the knowledge is easily inserted (a knowledge description language must be available); moreover, during its activity, the system reports information about the monitoring task. In this case, the flexibility of the perceptive agency and the availability of widespread communication networks could allow users to interact with (for example, to give commands to) the perceptive agency from almost everywhere.

VII. ENVIRONMENTAL MONITORING: AN APPLICATION FOR PERCEPTIVE AGENCY

In this section, we outline an embryonic practical example of perceptive agency devoted to environmental monitoring. In particular, we discuss an environmental monitoring agency as an instance of a perceptive agency oriented toward the environmental applications that are today of fundamental importance.

A system for environmental monitoring is an extremely complex measurement system, in which a very large number of perceptive agents are present. These agents differ in many aspects including typology, functioning principle, measurement quality, and geographical location. Each monitoring agent is usually equipped with an autonomous perception capability (provided by sensors or by networks of sensors) and with a capability of processing the measured data, able to produce a well-defined high-level information about the specific physical phenomenon under observation.

Several pollution-related quantities (such as temperature, radiation, chemical substances, noxious gasses) can be directly measured by dedicated measurement sensors. There are several physical phenomena that can be utilized to indirectly characterize the distribution of polluting materials in soil, water, and air. These include electrical conductivity, magnetic susceptibility, dielectric permittivity, rigidity, and mechanical density. These physical parameters can be detected by perceptive agents equipped with suitable sensors that are thus able to detect the target substances. Then, indirect measurements can be inferred from a large amount of sensor data. The relationships between indirect measurement uncertainties and the values of the parameters of interest may thus be critical, requiring a high-level intelligent analysis for their validation. Reasoning on knowledge is provided by the intelligent abilities of the perceptive agents.

As discussed in Section V, the fundamental elements in a perceptive agency are represented, on the one hand, by its communication capabilities that allow an effective and unitary cooperation process between agents and, on the other hand, by artificial intelligence techniques that support the reasoning activity on the acquired knowledge. Recent developments in microelectronic sensors and wireless communications enable to design and manufacture very sophisticated devices that simplify environmental measurement, tracking, and monitoring. Microelectronic technologies offer also sensors and transducers for physical and chemical measurements, besides the wireless connections to form networks. Agents can provide self-diagnostic capabilities along with the functions of data analysis for appropriate prevention and reactive response to the dynamically changing environmental conditions. Packaging oriented to hostile environment protection may be adopted for the development of reliable systems.

In general, the ability of capturing in the best way the significance of an environmental process is obtained by integrating the active role played by each individual perceptive agent within an environmental perceptive agency. For instance, given an urban area, both $\mathrm{CO/CO_2}$ concentrations in air and acoustic noise levels represent two quantities of great interest for environmental monitoring. If the measurements are correlated together, a further information can be gathered: the status of the traffic in the area. This information would not be retrieved with only a single type of measurement.

The role of artificial intelligence in the environmental perceptive agency is to support the various cooperation processes required for synergically bringing together the different sources of sensor information and knowledge, in order to assign to the perceptive agency an unitary environmental goal. An example of this role is represented by data mining [29], a technique that can be useful in signal processing to handle large amounts of data by automatically extracting high-level knowledge (such as implicit relations between parameters and hidden tendencies) from them. In general, the introduction and the enhancement of artificial intelligence techniques within perceptive agencies are among the most important goals in the field of environmental monitoring.

VIII. CONCLUSION

In this paper, we have made clear the increasing role of artificial intelligence in the conception of measurement systems. In particular, we have presented the motivations that drive toward the adoption of multiagent systems for developing modern measurement systems. The motivations have been arranged in three classes.

- Historical motivations: the measurement systems are evolving to embed increasingly more "intelligence."
- Philosophical motivations: the complexity of the models of the phenomena to be perceived requires the availability of both several complementary partial models describing the phenomena and the abilities to carry out logical reasoning within each perceptive system.
- Industrial motivations: the total quality management requirements must be supported by adequate distributed measurement systems.

Starting from these motivations, we argued that the most suitable way to develop a modern measurement system is to shape it as a perceptive agency, namely as a unitary system composed of several cooperating perceptive agents. We have presented the general concept of agency and its particular application to the field of measurements. As an applicative example, we outlined how an environmental monitoring perceptive agency can be built. It is our opinion that in modern applications (and more and more in the future) the required complex and articulated measurement systems should be developed as perceptive agencies.

Future work will be oriented to the (currently ongoing) implementation of perceptive agencies for environmental monitoring, according to the guidelines discussed in Section VI. Moreover, we are working on the development of a perceptive agency for monitoring the human physiology. When the pollution problems are considered, this last agency will provide a control of *effects*, while the perceptive agency for environmental monitoring will provide a control of *causes*. From the analysis of a number of real implemented perceptive agencies we aim to assess, both in qualitative and in quantitative way, some general properties about the advantages (and the disadvantages) provided by their employment for building distributed measurement systems. More broadly, the future research on measurement systems will address the hardware integration among perception, actuation, and processing elements to obtain pervasive but not invasive distributed measurement systems.

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Francesco Amigoni (S'98–A'00) born in Soresina (CR), Italy, in 1971. He received the Laurea degree in computer engineering and the Ph.D. degree in computer engineering from Politecnico di Milano, Milano, Italy, in 1996 and 2000, respectively.

From December 1999 to September 2000, he was a Visiting Scholar at the Computer Science Department of Stanford University, Stanford, CA. Since February 2002, he has been a Research Professor at the Dipartimento di Elettronica e Informazione, Politecnico di Milano. His main research interests include agents and multiagent systems, mobile robotics, and the philosophical aspects of artificial intelligence. He is author of about 20 papers published in international journals, books, and conference proceedings.

Arnaldo Brandolini was born in 1930 in Calolziocorte, Italy. He received the M.S. degree in electrical engineering from the Politecnico di Milano, Milano, Italy, in 1955.

In 1958, he joined the Politecnico di Milano as Assistant Professor of electrical measurements, where he became Associate Professor in 1968. Since 1980, he has been the Chair of Electrical Measurements. Research activities and scientific interests include electrical and electronic measurement topics, such as design and development of digital computer-based measuring systems, new A/D testing methodologies, advanced sensors and sensing systems for robotics, and remote sensing in geophysics. He has published about 100 papers on these subjects and five textbooks in the field of electrical and electronic measurements.

Prof. Brandolini is a founding member of the North Italy Chapter of the IEEE Instrumentation and Measurement Society and its first Chairman from 1990 to 1992.

Gabriele D'Antona was born in Milano, Italy, in 1964. He received the M.S. degree in electrical engineering and the Ph.D. degree in electrical science from the Politecnico di Milano in 1991 and 1994, respectively.

In 1991, he joined the JET Laboratory. Since 1998, he has been a Researcher in electrical measurements at the Department of Electrical Engineering, Politecnico di Milano. His current research interests are principally concerned with ill-posed inverse problems for electrical measurements and diagnosis of distributed systems.

Roberto Ottoboni (M'90–SM'01) was born in Milano, Italy, on April 1, 1961. He received the M.Sc. degree in electronic engineering and the Ph.D. degree in electrical engineering from the Politecnico di Milano in 1988 and 1992, respectively.

From 1992 to 1998, he was Assistant Professor of electrical measurements at the Politecnico di Milano. From 1998 to April 2002, he was Associate Professor and since May 2002, he has been Full Professor of electrical and electronic measurements. His scientific activity deals with the digital signal processing techniques applied to electrical measurements. In particular, he is concerned with the application of DSP techniques to the experimental analysis of the electric systems under distorted conditions, the investigation of synchronous sampling techniques. He is also involved in research activity for the development of industrial sensors and tactile sensors for robots.

Marco Somalvico was born in 1941 in Como, Italy. He received the Dottore Ingegnere degree in electronic engineering from the Politecnico di Milano, Milano, Italy, in 1965.

Since 1980, he has been Full Professor of artificial intelligence at the Politecnico di Milano. From 1969 to 1972, as well as 1977 and 1986, he was Visiting Scholar at the Artificial Intelligence Laboratory, Computer Science Department, Stanford University, Stanford, CA. In 1972, he was British Research Council Fellow at the Department of Computational Logic, School of Artificial Intelligence, University of Edinburgh, Edinburgh, U.K. His research interests include automatic and parallel problem-solving, factory of the future, multiagent systems, robot manipulation and programming, robotic vision, natural language processing, virtual museums, application of artificial intelligence to disabled people, and the relations between philosophy and artificial intelligence. He was a member of the editorial board of the *Journal of Robotic Systems* from 1975 to 1990.

Dr. Somalvico received the "Joseph F. Engelberger Robotics Award for Education" of the USA Robotic Industries Association for "contributing to the advancement of the science of robotics in the service of mankind" in 1998. In 1987, he was Chairman of the Local Arrangement Committee of the International Joint Conference on Artificial Intelligence.