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Agent-based Theory Applied in Mobile Robotics

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Abstract: This paper presents our experience in building complex autonomous systems through modularization and task specialization. As the test-bed, mobile devices were used. Some insights regarding the integration of agent-based theory in the framework of biological intelligence are presented. The obtained results approach the the definition and implementation of the intelligent activities and their realization in the framework of agent-based theory, namely, problem solving and planning, search, decision making, and learning. The experiments presented in this work specifically describe a framework of defining navigational tasks based on artificial intelligence methods.

Keywords: agents, mobile robots, perception, intelligence, autonomy

1. INTRODUCTION

The purpose of this paper is to present important results in mobile robot control by using artificial intelligence techniques like fuzzy logic and artificial neural networks in certain areas of *mobile robot control* in the framework of *agent-based theory*. The validity and performance of such an approach on a real world control problem were demonstrated by examples at hand. These results were tested in simulation, by using software agents, and on real mechanical structures with locomotion abilities. As we consider today, autonomous mobile robots are one of the closest approximation of *intelligent agents*, that people dreamed of from centuries. For centuries people have been interested in building machines that mimic living beings. From mechanical animals, using clockwork, to the *software* and *physical agents of artificial life* the question regarding a complete definition of life and the understanding of life mechanisms always motivated research. Mobile robots are mobile devices with tight coupling between *perception* and *action*, as happens with the living beings.

On the other hand, *an agent* is a computer system that is *situated* in some environment, and that is capable of *autonomous action* in this environment in order to meet its design objectives. An agent will typically sense its environment (by physical sensors in the case of agents situated in any part of the real world, or by software sensors in the case of software agents), and will have available a repertoire of actions that can be *executed* to modify the environment, which may appear to respond non-deterministically to the execution of these actions. This set of possible actions represents the agents capability to *modify* its environment. An agent should *decide* which of its actions it should perform in order to best satisfy its design objectives. Therefore an agent needs suitable *software architectures* for *decision making* systems embedded in an environment.

An agent is a system that is immersed into some environment. It has "perceptions" as inputs and "actions" as outputs. The main functions of the intelligent agent include *perception* (**SP - Sensory Processing**), *learning* (**WM - World Modelling**), *planning* (**BG - Behaviour Generation**), *thinking* (**VJ - Value Judgement**) and *communication* (figure 1). The *perceptions* are given by the **SP** module by using a lot of sensors and the *actions* generated by the **BG** module are sent to the environment by the actuators.

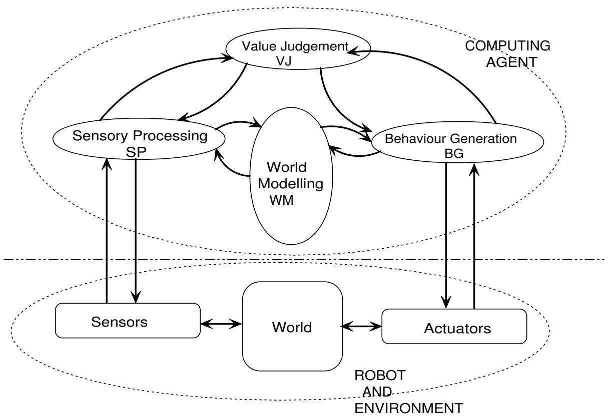

Fig. 1. The main functions of an intelligent agent

The hierarchical architecture of the intelligent agents generate behaviour at many levels of resolution simultaneously including both *planning* and *reactive actions*. **Feed-forward control** and **feedback control** are included into an intelligent agent as *deliberative* and *reactive actions*. In this respect, *intelligent agents*:

- should be able to perceive their environment, and to respond in a timely fashion to changes that occur in it in order to satisfy their design objectives;

- should be able to exhibit goal-directed behavior by taking the initiative in order to satisfy their design objectives;
- should be able to interact with other agents (and possibly humans) in order to satisfy their design objectives.

A mobile robot can be considered a *situated agent* whose configuration depends on the characteristics of an incert environment. Conceptually, the software architectures for controlling such a physical device are developed by means of *software agents*. When an intelligent mobile robot acts, it interacts with its environment because it is situated in that environment (as an integral part of the environment). By taking action, this situated agent agent changes things in the environment or changes the way it perceives the environment (e.g. move to a new viewpoint, etc). Therefore the agent's perception of the world is modified. This new perception is then used for a variety of functions, including both *cognitive activities* like *planning* for what to do next as well as reacting. Therefore, an *intelligent mobile robot* should operate autonomously being able of :

- moving in its environment;
- adapting to the changes in the environment;
- learning from experience;
- modifying its behavior;
- building internal representations of the surrounding world that may be used for the decision making process.

The *intelligence* is the property of a system that emerges when procedures of *focusing attention*, *combinatorial search* and *generalization* are applied to the input information so as to receive the output results (Dumitrache [2000]). When referring to mobile robotics, these concepts transforms into mechanisms of *perception*, *processing* and *behavior generation*. The attributes of intelligent behaviour that a system may acquire through different methodologies would further provide autonomy in fulfilling tasks (Antsaklis et al. [1993]).

Autonomous control systems are a whole new generation of control systems that could benefit from the modularization of software applications and their special organization to achieve an intelligent and autonomous behavior (Lagerberg [1996]), as previoulsly stated. These modules could be seen as agents. Being given the above mentioned desired properties of the special intelligent mechanical devices (intelligent mobile robots), using agent-based theory for the design of software architectures for mobile robot control is very challenging, because it could enable these systems with a certain degree of intelligent behavior.

The rationale of our reseach is that, for the last 20 years, since the study of (multi)agent systems began in the field of distributed artificial intelligence (DAI), these systems are not simply a research topic, but are also beginning to become an important subject of academic teaching and industrial and commercial application. Combining *agent-based technology* with the most recent advances in *information technology*, *biology*, *neurophysiology*, *ethology* and *cognitive psychology*, we can design complex autonomous systems. Since then, thousands of articles were written and today there is a huge pile of work related to the application of agent technology in different areas.

The computer science has designed algorithms for agent interactions from a theoretical point of view. This paper presents our experience in building complex autonomous systems through modularization and task specialization. As the test-bed, mobile devices were used. Section 2 of this article presents some insights regarding the integration of agent-based theory in the framework of biological intelligence. Section 3 presents our own results regarding the definition and implementation of the *intelligent activities* and their realization in the framework of agent-based theory, namely, problem solving and planning, search, decision making, and learning. Transferring animal models of behavior to robots, would help to formalize different aspects of behavior. The following sections introduces the reader to some real world examples of mobile robot control. Section 4 gives some conclusions and directions of further research.

2. AGENT-BASED THEORY AND BIOLOGICAL INTELLIGENCE

The integration of advanced environment perception and communication devices into mechatronic structures facilitates the development of strongly associative information systems. Consequently, by the modal fusion at the different presentation and multisensor processing levels, object and event recognition and classification in open environments could ensure the robustness of the perception function. Another important function that can be implemented in these robots is the environment adaptability by means of perception, representation, reasoning and action (figure 2). Conceptualizing the different aspects of intelligence by exploring biological and cognitive sciences for insights in intelligence, one intelligent mobile robot could be defined as being an artificial system which integrates the main attributes of the intelligence, that means *perception*, *learning*, *planning*, *reasoning* and *communication*. Following this definition, an *intelligent mobile robot* can be an agent (Dumitrache [1996]). As already mentioned, an agent is self-contained and independent, it has its own "brain" and can interact with the world to make changes or to sense what is happening (Murphy [2000]).

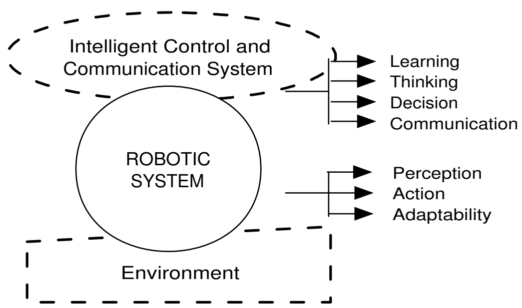

Fig. 2. Intelligent Communication Systems for Mobile Robotics

If the learning function is also integrated, one can speak about the *humanoid robot*, capable of *communication* and efficient *adaptation* in *a priori* undefined environments. In this context groups of autonomous mini-robots could be defined that can ensure a *collective intelligent behavior* by communication (Drăgoicea [2005]).

This type of organization of the adaptation and communication functions in a mobile robot control system assures the fact that the robot is able to:

- communicate in an intelligent way with the environment and with the other robots;
- react in hostile environments and to adapt to a variable evolution context by learning and behavior generation;
- communicate by means of natural language, being flexible in the process of decision making;
- integrate the informatic system with multiple facilities that are specific to the intelligent agents and to communicate in an intelligent way with the mechatronic structure;
- assure the hardware and software reconfiguration capacity, that means a complete fault detection ability.

Under the above description, one can speak about a *cognitive robot*. Therefore, a new era is opened in the field of **Intelligent Communication Systems** by the cooperation between *cognitive robots*, as *intelligent agents*, and, respectively, between robots and human operators. The integration of heterogeneous members into an intelligent behavior entity with specific abilities as *adaptation*, *self-organization*, *cooperation* and *evolution* towards the accomplishment of some global objectives becomes possible as long as attributes as robust *perception*, *learning*, *interaction* and *evaluation* could be associated with a new generation of mobile robots, capable of interactions with intelligent beings.

3. AGENTS AND INTELLIGENT BEHAVIOUR

Working with mobile robots allows us to artificially attach an agent-type software structure to a physical, pure mechanical entity (the mobile robot). We can work now with abstract concepts where agents can be used in order to analyze complex behaviors that our surrounding world usually deal with. The entire mobile robot control problem is based on presenting different methodologies for developing complex techniques of providing a desired degree of autonomy fulfilling different tasks more or less accesible to the living creatures. They should take into consideration the fact that the only information available is the subjective (egocentric) perspective of the autonomous mobile robot, constructed from a sequence of measurements, considered as their observable dynamics. In this respect, a general architecture of an intelligent agent could be used, that furher allows a straight integration of intelligent control techniques with biological insights.

3.1 A General Architecture of an Intelligent Agent

The **G**eneral **A**rchitecture of an **I**ntelligent **A**gent - **GAIA** includes two elementary functional units (figure 3). The first elementary unit is a computational automata which processes information (perception, **P**) and knowledge (**K**) in order to produce actions through the **BG** unit, while the second elementary unit connects the computational automata to the real world by using sensors (**S**) and actuators (**A**).

$(\mathrm{EFU})_1 \Longleftrightarrow (EFU)_2$

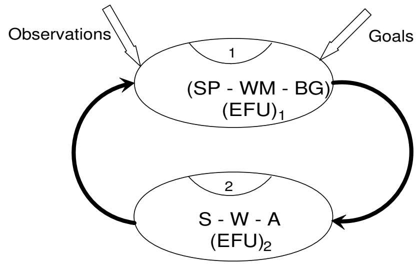

Fig. 3. **GAIA** - The **G**eneral **A**rchitecture of an **I**ntelligent **A**gent

or

$(\mathrm{P} \rightarrow K \rightarrow DM) \longrightarrow A$
$(A \rightarrow W \rightarrow S) \longrightarrow P$

where **A** means action, **W** is the real world, **S** is the set of sensors.

Along with the decision making process (**DM**) we can define a *decision policy* (**Dp**) based on a representation of knowledge by using the main operators of intelligent behaviour: **G - F- S** (*generalization*, *focusing attention* and *combinatorial search*) as follows:

$$\mathrm{R}_g[K_j, i] \rightarrow R_a[K_g, i] \Rightarrow D_p[R_a(K_g, i), J_{g,i}] \rightarrow ACTION$$

The catagories of knowledge include the structural model of the world with some planning information and global reactive information. For each level in hierarchy we define certain procedures in order to represent the knowledge categories and we use the operators G, F and S to realize a proper behaviour. For each level we have to define precision and grade of intelligence.

3.2 Intelligent Control Techniques with Biological Insights

Intelligent control techniques with biological insights, such as artificial neural networks, fuzzy control, genetic algorithms or synergetic combination of them can be successfully used in building control systems for autonomous operation of mobile robots. Therefore, following the biological traces, inside the control system of a mobile robot intelligence can be organized in a deliberative, reactive or hybrid deliberative / reactive way (Drăgoicea [2007]). All these techniques make use of the situated agent's ability to observe its environment (*percept* - **SENSE**), whereas the agent's decision making process is implemented by an action type function (**ACT**). In the context of the mobile robotic terminology, a mapping of *sensory inputs* to a *pattern of motor actions* which are used to achieve a task is called **behaviour**. Given a description of mobile robot's sensing abilities, its task and environment, a set of behaviors will be further defined using *schemas* to accomplish the task. A behavior could be composed of two schemas, a *perceptual schema* and a *motor schema* (Arbib [1990]). In this work, perceptual schema embodies the sensing, while the motor schema represents the template for the physical activity (figure 4), Drăgoicea et al. [2003].

The experiments presented in this work specifically describe a framework of defining navigational tasks based on artificial intelligence methods. The research focused specifically on automated learning techniques (artificial

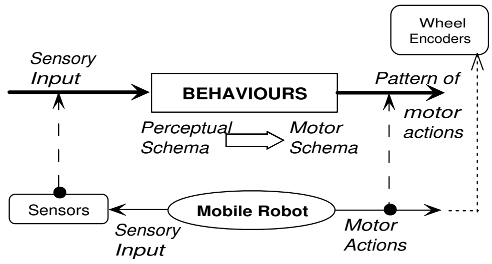

Fig. 4. Behavior based navigation by using schemas theory

neural networks) and process knowledge based techniques (fuzzy systems). Basically the methods used through these researches (Dumitrache et al. [2004]) specify and parameterize a process non-linear function **F** with parameters **p**, which maps inputs **x** to outputs **y** and represents the knowledge as shown in figure 5.

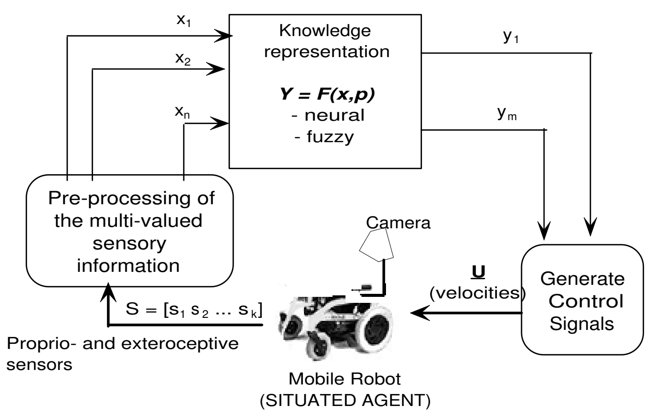

Fig. 5. Intelligent Control System for Mobile Robots

A propulsion controller acts as the brain of the unit by collecting data and replacing the joystick usual control signals. The proposed experiments used mobile robots as a special test bed for emulating the behaviour of such a mobile device. Automated learning techniques and process knowledge based methods were successfully used in order to test specific autonomous behaviours. Such an artificial brain should be able to *acquire*, *process* and *generate* behaviours for navigation. Typically, the sensory situations to which a behavior can react are limited. Only a portion of the information supplied by all sensors triggers a behavior, and all the behaviors that are triggered may react differently. The reactions of all behaviors together contribute to the action finally executed in the actuators (figure 6).

A mechanism is needed to mediate all reactions suggested by behaviors that respond to the current sensory input and to formulate one action to the actuators. Distributed execution of behaviors leads to fast decisions making, so the agent can react to sensory input quickly. Each behavior fully implements a control policy for one specific sub-task, like following a path, avoiding sensed obstacles, or crossing a door. The arbitration strategy decides which behaviors should be activated depending on the current goal and on the environmental aspects. As shown in figure 6, a behavior may have several sensory situations, a set of actions and a mapping between the two sets.

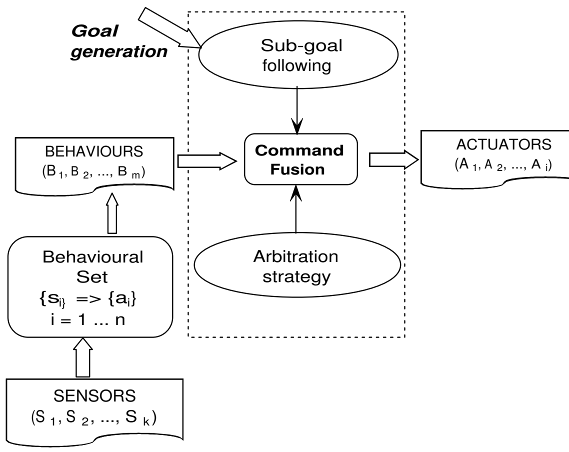

Fig. 6. Behaviour-based organization; {si} is the set of sensory situations, {ai} is the set of reactions

3.3 *Purely Reactive Agents*

Certain types of agents decide what to do without reference to their history. They base their decision making entirely on the present, with no reference at all to the past. These purely reactive agents simply respond directly to their environment. Formally, the behavior of a purely reactive agent can be represented by a function that implements an application from sensing to action. In case of process knowledge based methods like fuzzy systems the information about the process is mapped into a specific representation, the influence of single input values on specific outputs being formulated with quantitative or qualitative statements. In these cases a couple of single input-output relations or relation between inner variables of the process serve to model the complex input-output behaviour called **F**. The input-output relations are represented by sets of parallel fuzzy rules (Drăgoicea et al. [2003b]). A fuzzy control system for behavior-based robotic systems would start with crisp sensor readings (e.g. numeric values from proximity sensors), translate them into linguistic classes in the fuzzifier, fire the appropriate rules in the fuzzy inference engine, generating a fuzzy output value, then translate these into a crisp values representing actuator control signals (see figure 7).

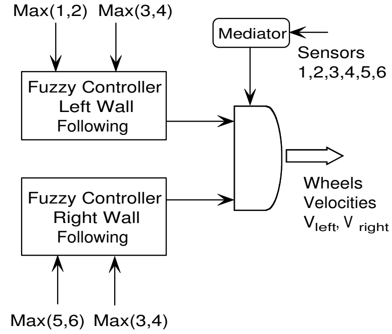

Fig. 7. Fuzzy logic control system architecture for behavior implementation

The main advantage of the proposed reactive multi-control strategy based on elementary behaviors is that the arbitration mechanism (i.e. a function of type **PLAN**) is under users control, that means it is possible to give more importance to a specific behavior or even rule according to the context in which the robot evolves (i.e. task to be fulfilled and environment conditions). In this approach fuzzy rules of the general form are used:

IF *path_cond* **THEN** *command1*
IF *obstacle_cond* **THEN** *command2*

The fuzzy controller that implements complex behaviours may consist of many controllers, one for each sub-task. The mediator for the main behavior (figure 8) realizes a weighting action of the control signal generated by component fuzzy controllers.

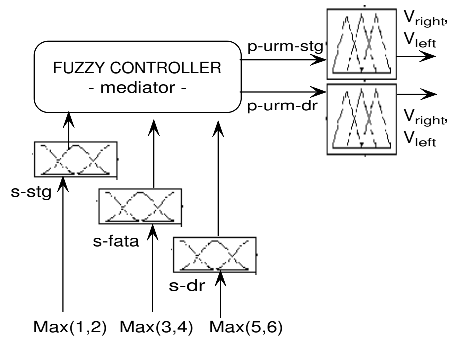

Fig. 8. A fuzzy mediator for the wall following behavior

The weighting strategy will influence one of these two controllers, according to the context in which the robot evolves (i.e sensors measurements). The inputs to the fuzzy mediator are the values of the (left, right and front) sensors, and its outputs are the weights for the component fuzzy controllers for each sub-task. For more details, notations, and results, see (Drăgoicea et al. [2003b]). Therefore, following a more general *deliberative / reactive* approach, the robot has the possibility to plan (in a deliberative way) the most suitable way to split its global task into subtasks, i.e. to make a mission plan. Then it can determine the suitable behaviors in order to fulfill the sub-tasks. These behaviors are to be executed in a reactive way, as it was previously mentioned. Based on this strategy, more complex behaviors could be accomplished, like position tracking (figure 9) and position tracking with collision avoidance behaviors (figure 10).

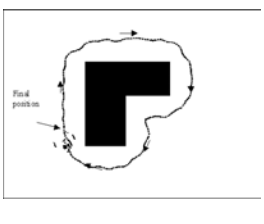

Fig. 9. Complex behaviors with fuzzy implementation (a)

3.4 Agents with Memory

These agents have some internal data structure, which is typically used to record information about the environment state and history.An agent's decision making process is then based, at least in part, on this information. The set of all internal states of the agent could be coded when a suitable coded method is provided. Learning is one way

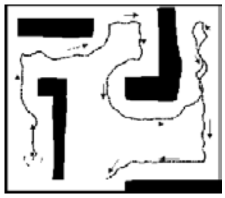

Fig. 10. Complex behaviors with fuzzy implementation (b)

of memorizing information and artificial neural networks proved to succesfully integrate information by learning. Supervised or unsupervised learning mechanisms could be used as well for each of these tasks.

Using artificial neural networks for the clustering of the environment and for the generalization of landmarks representation in the environment naturally allows the integration of a learning dimension into the navigation ability of the mobile robot. This requires that some generalization regarding the internal representation within the navigation mechanisms is possible. *Generalization* is one specific ability of the artificial neural networks. By learning raw sensory perceptions of certain landmarks the robot might learn to recognize landmarks on subsequent visits. In (Drăgoicea [2007]) a navigation strategy based on landmarks recognition for autonomous navigation of the mobile robots was proposed. An ART2 neural network (figure 11) is used in order to implement the perceptual part of a behavior in the framework of schema theory.

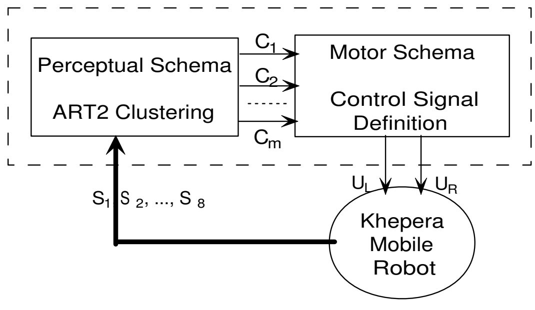

Fig. 11. Neural controller based on perceptual clustering by an ART2 neural network

The ART2 neural network learns to classify the sensory patterns that the sensory system produced during a reactive exploration stage. The motivation for choosing self-organization is that clustering the robot's perceptions autonomously using a self-organising classifier helps to avoid the problem of matching individual environmental features against an internal world model. There is no attempt to recognize specific objects in the robot's environment, rather the raw sensor readings are grouped according to their similarity. In each of the conducted studies the mobile robot showed useful learning in an impressively small number of trials. The evolution of the robot was tested on a number of simulated worlds as well as on the real Khepera mobile robot (see Drăgoicea [2007]) for more details. Different results were obtained based by using a neural ART2 controller (figure 12 and figure 13) and they are compared with the results obtained by using a "blind" Braitenberg controller (figure 14 and figure 15).

A *landmark* was defined as being a *set of raw sensory patterns*, based on which a motor decision was made. In

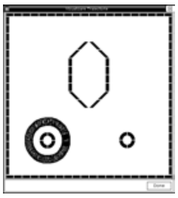

Fig. 12. Mobile robot evolution with supervision (ART2 controller) (a)

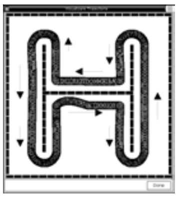

Fig. 13. Mobile robot evolution with supervision (ART2 controller) (b)

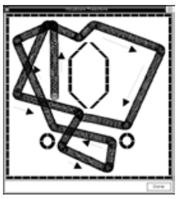

Fig. 14. Mobile robot evolution with a Braitenberg controller (a)

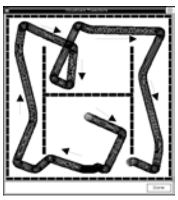

Fig. 15. Mobile robot evolution with a Braitenberg controller (b)

this way, each place (or pattern) in the environment is defined by a specific set of sensory patterns. The main advantage of this approach is that the representation is dynamic in order to allow structure expansion for the incorporation of newly identified places.

4. CONCLUSION

At the beginning of a new millenium scientists are closer than ever to the human cognitive model and, as a consequence, to the deeper understanding of life mechanisms. We can speak now, with a sufficient scientific reason, of a new generation of robots whose essential characteristic is the capacity of interaction with the intelligent beings.

Communication, a*lgorithm configuration*, *learning* and *decision* are possible through a two layer organization of the control system. Agent-based theory can be used and autonomy could be achieved at a certain level. This paper tries to do a short presentation of our research results for the mobile robot control systems with some results applications of our team. We consider that the cognitive and intelligent techniques could be applied with real success to develop a new generation of mobile robots as an intelligent information system highly adapted at the variable and uncertain environments. The parallel view between mobile robots and biological systems gives us the opportunity to identify the limitations of the actual advanced control systems for robots to realize a complex behavior into uncertain and variable environment taking into account the hybrid paradigm deliberative-reactive. Some applications of the automated learning techniques and process knowledge based methods were obtained and presented here that implement the main attributes of the intelligent systems in robotic applications. They were successfully used in order to test specific autonomous behaviours.

This paper is only a short synthesis of our research activity in this very dynamic field of mobile robot control systems and agent-based theory and it is sustained with proper references and literature.

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