

# Robotic control systems based on bioinspired multi-agent systems

## Application of the principles of neuroscience to robotics

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**Abstract**— Robotics is a field that presents a large number of problems because it depends on a large number of disciplines, devices, technologies and tasks. Its expansion from perfectly controlled industrial environments toward open and dynamic environment presents a many new challenges, such as robots household robots or professional robots. To facilitate the rapid development of robotic systems, low cost, reusability of code, its medium and long term maintainability and robustness are required novel approaches to provide generic models and software systems who develop paradigms capable of solving these problems. For this purpose, in this paper we propose a model based on multi-agent systems inspired by the human nervous system able to transfer the control characteristics of the biological system and able to take advantage of the best properties of distributed software systems.

*Multi-agent systems; Bio-inspired system; Human nervous system; Service oriented architectures; Web Services*

### I. INTRODUCTION

Robotics is a field in which converge factors such as the rapid evolution of the technologies involved, be very interdisciplinary, the great diversity of missions and solve different technological levels (there are issues from physical or electronic level until the more abstract and conceptual levels) [1]. This requires that the robotic systems interact with their real environment to maximize their sensing and action, to process and combine the information received and produce plans of interaction with the world. This means that multiple tasks have to be developed in parallel with different time and resource requirements of both cognitive and reactive nature, and that tasks produce results of different types and with different frequencies, and everything should be combined into a single coherent and harmonized system. Because many of the problems addressed in the design and development of robotic systems are related to control systems, biological neuroreguladores have become a source of inspiration. These systems solve many of these problems in a natural way and are therefore they are being thoroughly studied the structures, mechanisms, organization and models of biological systems to incorporate them into robotic systems [2].

In addition, systems must be maintainable and valid at medium to long term. This requires a sufficiently flexible robotic system both conceptually and physically to allow

replacement of elements after the break down or when are obsolete, or add new elements to bring more functionality to the physical system, thus taking advantage of new advances in technology and incorporate new knowledge into the system, without reschedule part or the whole system [1].

In this paper, we propose to extract the main features of nervous systems through a multi-agent system for collecting its peculiarities, its organizational and functional structure in order to propose a robotic control system based on this model. In addition, we present the instantiation of such a system for autonomous mobile robots in an open environment and proposes its implementation using services to make viable the development of the model. Finally, we extract the main conclusions and future lines of work.

### II. BACKGROUND

Biological systems have been a rich source of inspiration for solutions to various problems. The study of these systems has led to progress on issues such as computer animation [3], the simulation of agents [4], the simulation of environments [5] or robotics [6].

Overall, the nervous system is a complex network of neural structures that control the activity of the organism. From a functional point of view, nervous system collects, processes and transmits nerve signals through different structures in order to control both somatic and autonomous activities. At first glance, the activities that develops the nervous system may seem contradictory. For example, the sympathetic system is responsible for the activation of visceral activity and the parasympathetic system is responsible for the relaxation of internal activity. The sum of both is that regulate the activity of internal organs. Separately are not valid [7].

Looking at the autonomic nervous system, it consists of different nerve centers distributed throughout the whole body. These centers produce states more or less complex regulation. In addition, each of these centers has its own activity. These stages of regulation are hierarchical one over the other. The less evolved centers are located in the periphery while the more integrative centers are located at the central level. Regulatory functions have two main levels of control: an intrinsic level of regulation, consisting of poorly developed nerve centers that generate a small motor activity that allows a certain functional autonomy in those

organs which are located; and an extrinsic level of organization, consisting of ganglionic structures and the central nervous system, that organize regulation between or inside organs [8].

The nervous system was formed through the process of evolution that has lasted thousands of years. In this process have been added many control centers at the neuroregulatory system. These new elements modulate, monitor, enhance, inhibit, suppress or substitute the underlying functionality [9] [10]. This development is done incrementally, adding elements to the nervous system or creating specialized areas [11]. Moreover, these new control centers have been organized as new layers of the nervous system [12].

The sum of all the influences of regulatory structures triggers a behavior, action, reaction or stabilization of the entire system without having a specific center commissioned to produce an action. The interaction of all structures and the sum of its influences is essential to produce the overall behavior [7].

In addition to the nerve centers of control, neuroregulatory system is affected by the hormonal brain. Compared with the precise circuits of the wired brain, the hormonal brain is like a diffuse soup. But this contrast is only theoretical. In real life, the two complement each other admirably well. This influence of diffuse-projection neurons in the brain is called neuromodulation. Neuromodulation does not change the nature of the connection between two neurons, but instead modifies its intensity and gives it a different coloration [13].

Neuroregulatory biological system therefore has a distributed nature, where each element carries out its control independently, producing emergent behavior as the result of the sum of the actions of each of the elements of the system. Furthermore, one or several centers can modify their activity due to the influence of neurotransmitters. To model this behavior we need to use paradigms that can provide sufficient expressive richness to reflect all the characteristics described. It is in this context that the agent paradigm offers a high level of abstraction appropriate to address the complexity of the problem [14, 15, 16, 17]. Multi-agent systems provide a framework capable of providing sufficient expressive capacity to address the modeling of these distributed systems, taking into account the emergent behavior and the possibility of modifying the structure of the model as further progress in the system, either by technological innovations or advances in research.

### III. FUNCTIONAL VIEW OF THE ROBOTIC CONTROL SYSTEM

Our proposal is to establish a correlation between the biological system and the robotic system so that we can see the elements of control of the robotic system as if it were regulatory centers. We can establish several similarities or equivalence between the two worlds. Although both systems are physically very different, one has cells and organic material, and the other has chips and metal, if observed from a functional point of view, both worlds contemplate creatures that perform tasks in a certain environment with which they must interact, understand and make decisions accordingly.

In this case, the main point of interest is in the way that resolves the organization, control, hierarchy and dependencies of the elements involved in human neuroregulatory system. If we are able to assimilate the operations and organization of robotic systems to biological systems, then it is possible to emulate the mechanisms of control, decision making, parallel execution, ability to multi-target system, possibility of increase or decrease the control centers and other features exhibited by biological systems.

A robotic system can be viewed as a set functional elements  $ef$ , where each function as the sensing of speed, path tracing, collision checking, and so on, is seen as an expert element in control of that particular task. The biological system controls a mechanical system, the physical body, and likewise a robotic system must also control a mechanical system, the robot, with which it interacts with the environment. In addition, the physical robot largely shall condition the control system because the functional elements of control depend on the devices that make the robot's body [18]. This conditioning factor is similar in biological creatures, because the neuroregulatory system is different in each type of living creature. The control elements of a biological system are interconnected using neural connections, which are organized hierarchically according to the development of the nervous system over time. The functional elements that make up the robotic system must also establish connections among themselves and also these connections follow the same organizational principles that the biological system, ie, reactive control centers close to the physical elements and control centers with more cognitive complexity at higher levels of control. Finally, nerve impulses that transmit information between biological neuroregulatory centers are viewed as messages in a robotic system. These messages are exchanged between the functional elements. These messages can be electrical signals in reactive centers or can be complex structures in cognitive centers. Table 1 shows the equivalences between biological systems and robotic systems.

TABLE I. EQUIVALENCE BETWEEN THE HUMAN NEUROREGULATORY SYSTEM AND ROBOTICS CONTROL SYSTEMS

<i>Biological control system</i>	<i>Robotic control system</i>
Neuroregulatory centre	Functional element - $ef$
Biological mechanic system	Robotic mechanic system
Neuronal conexions	Connections between $ef$
Nervous impulse	Messages

Following the analogy between both types of systems, we see that the biological system comprises a set of nerve centers at different levels. There are some low-level nerve centers located in the lower spinal cord responsible for collecting the afferent signals from the proprioceptive or exteroceptive sensory organs such as temperature, state of the muscles, information on internal organs, and so on. These centers processed and relay information toward centers of medium level. These centers produce semi-autonomous tasks, processed information and relay it to the centers

responsible for high level cognitive tasks. When a response has been generated, the information being relayed back from the upper centers to the lower centers so that they end up sending the right signals to the mechanical system and thus interact with the world. The robotic system can be structured similarly to the biological system, dividing their functions in control centers: the functional entities *ef*. Each entity perform functions at different levels depending on the task to be performed: to collect or emit signals and reactive tasks at a lower level, signal processing and semi-autonomous tasks in a middle and cognitive and social tasks at a higher level.

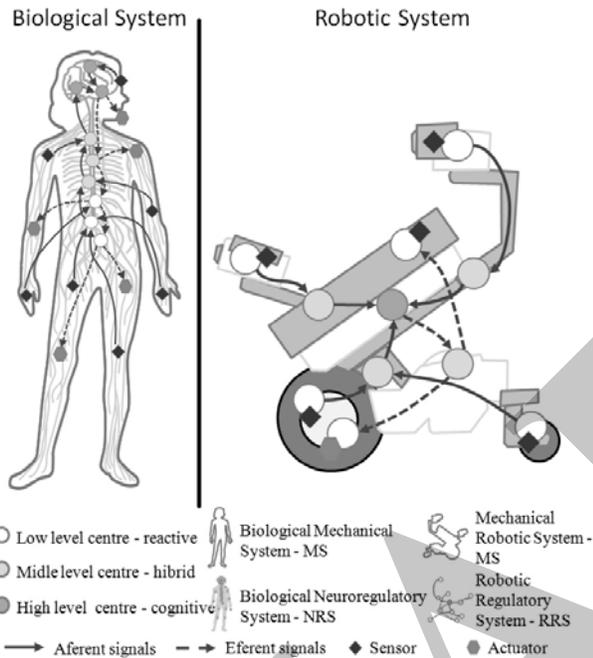


Figure 1 shows the human neuroregulatory system and robotic control system based on the architectural principles of biological system. This figure graphically represents the characteristics described.

Figure 1. Human neuroregulatory system and robotic control system based on the architectural principles of biological system.

#### IV. MULTI-AGENT SYSTEM MODEL FOR ROBOTIC CONTROL

Based on the action and reaction system described in (Ferber, 1999) we can describe the elements that form a robotic system using the structure  $SR = \langle MS, RRS, {}^{MS}I_{RRS} \rangle$ . SR represents the complete robotic system, MS defines the mechanical system, RRS the regulatory robotic system comprised of all functional entities and  ${}^{MS}I_{RRS}$  represents the interface between both systems, basically the complex system of connections and afferent and efferent signals.

The interface is defined by the structure  ${}^{MS}I_{RRS} = \langle \Sigma, \Gamma, P \rangle$ , where  $\Sigma$  represents the set of possible states of the system, P is the set of all possible actions that can be carried out in RRS to modify the state of the robot and  $\Gamma$  identifies the set of possible intentions to actions in the system by the

functional entities. The functional entities do not have a complete control of the system and have to combine their objectives. The result of each action is represented as an intention to act on the system.

The system states  $\Sigma = \{\sigma_1, \sigma_2, \dots, \sigma_n\}$  can be expressed by a list of pairs (signal, value) with the values of the different signals in the system, that is,  $\sigma_i = \langle (\text{sig}_1, \text{val}_1), (\text{sig}_2, \text{val}_2), \dots, (\text{sig}_{\text{Card}(C)}, \text{val}_{\text{Card}(C)}) \rangle$ , where C is the domain of structural elements (the different possible signals). In our robotic system C corresponds to the set formed by afferent signals (AS), the efferent signals (ES) and internal signals between elements of the system (IS). And the possible values of each signal corresponds to the real numbers. To indicate the source and destination of a signal we symbolize as  ${}^{\text{source}}S_{\text{destination}}$ .

Each functional entity tries to modify the state of the system. To do this executes actions on the system. These influences are defined as  $\Gamma = \langle \gamma_1, \gamma_2, \dots, \gamma_n \rangle$  where each  $\gamma_i$  is a list of pairs consisting of an element and its value, i.e.:  $\gamma_i = \langle (\text{sig}_1, \text{val}_1), (\text{sig}_2, \text{val}_2), \dots, (\text{sig}_{\text{Card}(C)}, \text{val}_{\text{Card}(C)}) \rangle$ . In this case, C correspond with  $ES \cup IS$  and the possible values with the set of real numbers. When a center does not want to change the system provide the empties influence  $\gamma_0$ . This influence will act as the neutral element of the set  $\Gamma$  and can be provided by any functional entity that does not want to change the system state.

To change the system state to a new state, ie to evolve, it is imperative that the functional entities perform actions, and to this end, the centers execute actions on the system. The set of all possible actions that can be performed on a particular system is defined as  $P = \{p_1, p_2, \dots, p_k\}$ . Each action can be described by  $P = \langle \text{name}, \text{pre}, \text{post} \rangle$  where name is an expression  $f(x_1, x_2, \dots, x_k)$  and each  $x_i$  is an authorized variable for *pre* and *post* formulas, and *pre/post* are sets of formulas like  $g(a_1, a_2, \dots, a_n)$  where g is an n-ario predicate and each  $a_i$  are constants or variables. *pre* describe the conditions that must be verified to perform the action and *post* refers to the set of influences that occur when executed actions.

In our system we define two actions:  $p_s$  and  $p_0$ . The action  $p_s$  is defined by  $p_s = \langle \text{SetSignalValue}(), \text{True}(), \text{Value}() \rangle$ : *SetSignalValue()* has an input list  $\tau_i$  and output with the results of *Value()*. *Value()* sets the new value to the signal from each of the pairs indicated in the list specified in the action. The action  $p_0$  defines the empty action that acts as a neutral element:  $p_0 = \langle \text{EmptyTask}(), \text{True}(), \gamma_0 \rangle$ . This action can always be done and will not alter the system state.

Because all the functional elements of the system act simultaneously as in the human neuroregulatory system, there will be different influences at the same time and thus we define the union of these influences  $\cup^{\Gamma}$  as the function that combines the influences of functional elements. This function provides a vector of influences combining the influences provided by each element  $\cup^{\Gamma}: \Gamma^n \rightarrow \Gamma$ .

The set of all functional entities forms the robotic regulatory system RRS, as they all are responsible for controlling physical and cognitive activity of robot as if it were biological neuroregulatory system using afferent and efferent signals.

Each functional element receives a set of afferent signals ( $AS_{ef}$ ), these afferent signals may come from both the mechanical system MS and other functional elements  $ef$ . It processes and transmits the results ( $ES_{ef}$ ) to other functional elements or mechanical system. The set of all functional entities that make up the robotic controller is defined  $RRS = \langle ef_1, ef_2, \dots, ef_n \rangle$ .

Each functional entity  $ef$  is represented by a PDE architecture (perception-deliberation-execution) and is incorporated memory capacity to be able to maintain its internal state and ensure a function similar as biological. With this, the structure of each functional entity will be described using the structure  $ef = \langle \Phi_{ef}, S_{ef}, Percept_{ef}, Mem_{ef}, Decision_{ef}, Exec_{ef} \rangle$ , where  $\Phi_{ef}$  is the set of perceptions;  $S_{ef}$  is the set of internal states;  $Percept_{ef}$  provides information to the functional entity of the state system;  $Mem_{ef}$  to store information about the entity's internal state;  $Decision_{ef}$  selects the next task to execute;  $Exec_{ef}$  represents the intent of the functional entity to act on the system.

The perception is the ability to sort and distinguish system states that are interesting for  $ef$ . Perception is defined as a function that associates a set of values, called perceptions or stimulus, with a set of system states  $Percept_{ef}: \Sigma \rightarrow \Phi_{ef}$ , so the perception is associated with the possible states of the system and is expressed as  $\Phi = Percept(\sigma)$ .

The set of possible perceptions associated with a particular functional element is defined as  $\Phi_{ef} = \langle v_1, v_2, \dots, v_n \rangle$ , where  $v_i$  comprises a list of pairs (signal, value) as defined above and by extension, we define the empty perception  $v_0$  as a list of null pairs. Empty perception occurs when an item is not in any afferent signal destination or origin of an efferent. The set of efferent signals to a functional element is the set of all efferent signals of the signals.

Each functional entity has an internal state that can remember, which allows more complex behaviors. The set of internal states of a functional entity is defined as  $S_{ef} = \langle s_1, s_2, \dots, s_n \rangle$ . In the case of our robotic regulatory system consists of a list of pairs (signal, value) of all signals inside the entity.

The decision function defines a task using the perception of the system state and past experience (internal state)  $Decision_{ef}: \Phi_{ef} \times S_{ef} \rightarrow P$ , so we define  $p = Decision(v, s)$ . Using the actions defined above,  $Decision()$  function is:  $Decision_{ef}(v, s) = SetSignalValue(FunD_{ef}(v, s))$  if  $PreD_{ef}(v, s)$  is true, and empty action  $p_0$  if  $PreD_{ef}(v, s)$  is false.

$PreDef(v, s)$  defines the precondition that must be satisfied to run  $SetSignalValue()$  and depends from perception and internal state  $PreD_{ef}: \Phi_{ef} \times S_{ef} \rightarrow Boolean$ .  $FunD_{ef}(v, s)$  associates a perception and internal state with an influence for system  $FunD_{ef}: \Phi_{ef} \times S_{ef} \rightarrow \Gamma$ .

Following hormonal peculiarities of the nervous system, we introduce the variable  $\beta$  in the function  $PreD$ . Increasing or decreasing the variable can affect the operation of an entity.  $PreD$  analyzes how important is a change of state to produce a new state and influence the robotic system. This importance is provided by  $\beta$ .  $PreD$  is defined by:  $PreD_{ef}(v, s) = True$  if  $s_{t+1} \pm \beta \neq s_t$  and is false in other cases.

Increasing  $\beta$  the control system remains relaxed and decrementing  $\beta$  is excited.

The memory function associates an internal state of the functional entity with its current perception of the environment and past experience  $Mem_{ef}: \Phi_{ef} \times S_{ef} \rightarrow S_{ef}$ . The  $Mem$  function works when a precondition is met:  $Mem_{ef}(v, s) = FunM_{ef}(v, s)$  if  $PreM_{ef}(v, s)$  is True, and produces  $s_0$ , the empty state or neutral state, if  $PreM$  is False.

As before,  $PreM_{ef}(v, s)$  associates False or True with a perception and internal state  $PreM_{ef}: \Phi_{ef} \times S_{ef} \rightarrow Boolean$  and  $FunM_{ef}(v, s)$  associates a new internal state with a perception and previous internal state  $FunM_{ef}: \Phi_{ef} \times S_{ef} \rightarrow S_{ef}$ .

$PreM_{ef}(v, s)$  uses a variable  $\mu$  that can detect if an external change is important, in other words:  $PreM_{ef}(v, s) = True$  if  $v_{t+1} \pm \mu \neq v_t$  and False in other cases.

Therefore,  $\beta$  and  $\mu$  can regulate the actions of each functional entity determining when the change in the world is interesting for an entity as its own internal change is crucial to make changes to the outside world. This behavior brings nuances like hormonal regulation in the nervous system.

The execution of actions is defined as  $Exec_{ef}: P \times \Phi_{ef} \rightarrow \Gamma$ , and the influence that provides an execution is defined as  $\gamma_{ef} = Exec_{ef}(p, v_{ef})$ . Considering the definitions made so far,  $Exec_{ef}$  is defined as  $Exec_{ef}(p, v_{ef}) = post$  if  $pre(v_{ef})$  is True and  $\gamma_0$  if  $pre(v_{ef})$  is false.

After this definitions, to specify any functional entity will need to specify their afferent signals, their efferent signals,  $\mu$   $y$   $\beta$ , the function  $FunM_{ef}$  (which gets a new internal state from the perception and the current internal state) and  $FunD_{ef}$  (which obtain the desired influence). The remaining elements have been defined generically to all functional entities.

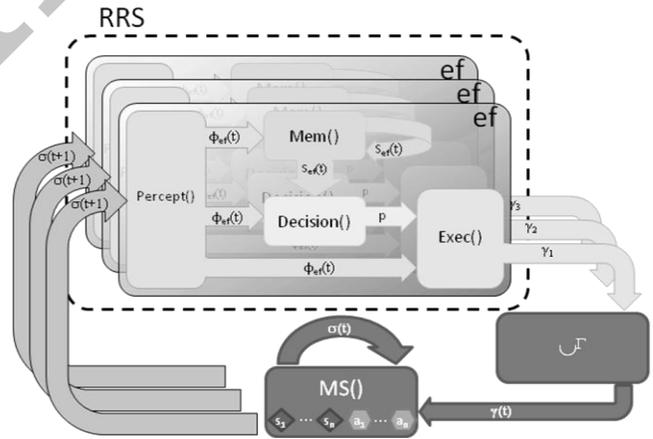


Figure 2. Multi-agent system consists of several functional entities.

Finally mechanical system (MS) is defined by the set of all physical devices as sensors (S) and actuators (A) that form it  $ASD = \langle a_1, a_2, \dots, a_n, s_1, s_2, \dots, s_m \rangle$  and the reaction function that describes how the system reacts to the influences,  $MS = \langle ASD, React_{MS} \rangle$ .

In the case of the robotic system is not necessary to model  $React$  function, the response of the robotic system get

it directly from real or simulated robot and involves physical laws that govern it. In this way, we avoid modeling worlds partially, allowing the system to interact directly with the reality around him and not with abstract entities.

The transformation of the current system state to a new state in response to the influence is defined as  $React: \Sigma \times \Gamma \rightarrow \Sigma$ . The new state of the system can be obtained as  $\sigma(t+1) = React(\sigma(t), \cup^{\Gamma}(\gamma_1, \gamma_2, \dots, \gamma_n))$

The empty influence constitutes the neutral element of React. The execution of the empty actions gives the empty influence, so  $p_0$  can also be considered neutral element.

The dynamics of the system would be defined by the new state of the system  $\sigma(t+1)$  plus internal state of all control centers  $s_n(t+1) = Mem_n(v_n(t), s_n(t))$ , with  $v_n(t) = Percept(\sigma(t))$ .

### V. TESTING AND VALIDATING

For the instantiation of our proposal we rely on autonomous mobile robots. Mobile robots are particularly interesting when used in open environments. In these environments the quantity, quality and accuracy of information is uncertain and therefore can not develop complete models of the world. The control system of a robot must be able to offer a response to any stimulus and therefore it is essential to be able to integrate and process any source and type of information. Other reasons to tackle this type of systems is that can be highly variable, in other words, they may use different motor systems (legs, wheels, chains), several sensory systems, multiple algorithms for estimation of position, route calculation, and so on, which means they can vary the sources of information and therefore requires great flexibility and adaptability of the system. It is also possible to alter the desired behaviors such as scrolling through the environment, goal seeking, avoidance of obstacles and dangers, and so on., which means involving a greater or lesser number of computational processes.

In our work we have tried two behaviors: Behavior1 (B1) - navigating through the environment from a source point to a target point, and Behavior2 (B2) - navigating through the environment from a source point to a target point with obstacle avoidance. B2 will be implemented by adding new services in B1. For our system we used a generic robot equipped with two actuators (right wheel and left wheel) from which we get the current position of the wheel (shaft encoder sensor), a digital compass that indicates the current direction and a front-sensor obstacle detection (fig. 3-a). In the functional analysis of behavior we have divided each of the functions of a robot in a service, isolating each function in an independent entity [1]. Each service is executed independently (fig. 3-b B1 analysis produces the following services: Sensing, services responsible for monitoring the sensing devices; Interpretation, service responsible for translating the values obtained by the sensing to consistent data (for example floating numbers to numbers with two decimal numbers); Situation, service responsible for using the data of Interpretation to obtain an estimate of the robot's position (in this case position in the environment, but it could estimate the position of the arm, relative position, etc.); Reasoner, service responsible for determining the mission to perform, in this case lead the robot from point A to point B;

Planner, service responsible for planning the robot path; Motion, service which is responsible for obtaining the next move to be performed by the robot based on planning; Embodiment, service responsible for transforming the type of motion in terms of physical structure of the robot; Actuator, services responsible for managing communication with the actuating devices.

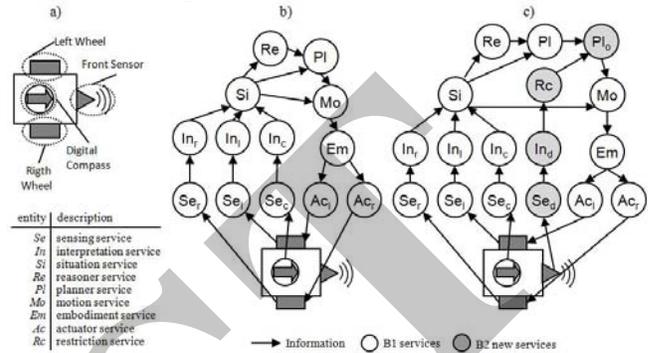


Figure 3. a) Structure of a robot formed by 2 wheels, a digital compass and a front sensor. b) Decomposition of behavior 1 in services. c) Decomposition of behavior 2 in services.

B2 analysis incorporates the new services highlighted in fig. 3-c.: Sensing, control service for distance sensor, Interpretation for the sensing service, a new service, Restriction, service responsible for calculating where the obstacles based on the interpreted data, and a new service Planner which modifies the B1 planning for obstacle avoidance.

Each of the control system services developed a simple function, e.g., Situation service estimates the current position using odometry techniques or Interpretation services translate shaft encoders to distances depending on the diameter of the wheels. By separating each of the functions of a service system we obtain loose coupling between entities. You can modify a feature, such as the diameter of a wheel, and this change only affects a few elements. This lets you develop system quickly and cheaply.

The implementation of each entity will be made using the paradigm of services. This paradigm provides features such as the decoupling between the entities, the possibility of composition, reuse and rapid development, pro-activity and general characteristics of distributed systems [19]. For the implementation we used Microsoft Robotics Developer Studio (MRDS). MRDS is a framework for developing software to control robots and provides an integrated .NET development environment for designing, executing, and debugging highly scalable concurrent, distributed robotics applications. MRDS facilitates dealing with hard software challenges present in robotics such as coordination, observability, configuration, deployment, and reusability [20]. Esta plataforma nos permite implementar cada entidad funcional en forma de servicio con un bajo acoplamiento y un comportamiento similar al expresado en el sistema biológico. In our experiments we used the simulator MRDS and Lego robots, because it demonstrates the adaptability of the control systems based on web services to any type of

robot, although its components are not the most accurate. Fig. 4 show a view of the simulated robot composed of the elements described above, and a Lego robot equipped with the same real elements. Figure 4 shows the simulated robot and real robot navigating through an environment with obstacles. The control system is composed of the services described for B2.

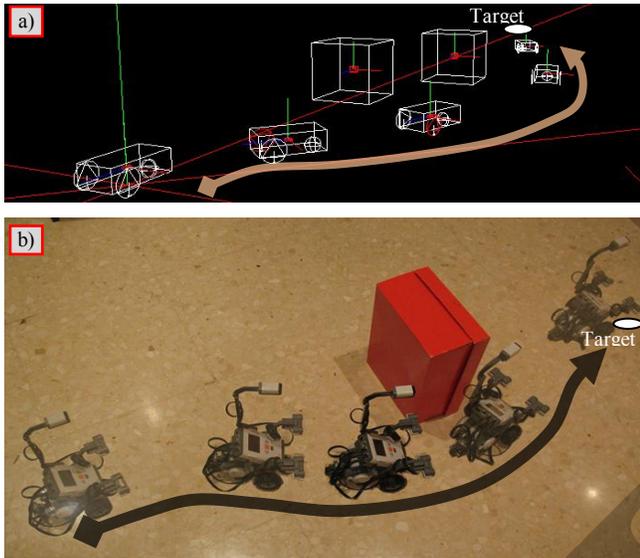


Figure 4. a) Simulated robot executing B2. b) Lego robot executing B2.

The change of variables  $\beta$  and  $\mu$  will be performed by Rc and Re. The value of these variables is initially 1. When the robot approaches an obstacle, the value decreases, when moving away from obstacle, the value returns to 1. When the robot approaches the target position value decreased, and if the robot moved away from the target position would increase to 1. Thus, the robot proves more attentive behavior when close to obstacles or destination.

## VI. TEST RESULTS

After implementing the services and the composition of the control system, we observe that the robot is capable of producing the behavior B1 and B2, both real and simulated. If the system uses the services of C2, the movement of the robot avoid obstacles in the path. Use B1 or B2 only need to add or remove system services without changing any other element. Only need to modify the composition of the control system. Using a simulated robot or a real robot involves changing only the services of sensing and action, connecting to a device or software. The rest of the control system remains constant. Using multiple sensors is very simple, you just need to modify the driver of the device that you are connecting to the service of sensing. Similarly, we can modify the structure of the robot, for example, changing the size of the wheels.

The system has the peculiarity that each service operates at the frequency that requires its own characteristics. For example, the services responsible for monitoring each wheel require 50ms per cycle to obtain the state of the encoder.

This data is transferred to the superior services but if this information does not imply changes (for example, the robot has not moved), Interpretation services will not produce new results. Similarly, the reasoning service starts the system when the current and desired position are not equal (not reached the destination) but during the execution will not release more orders to planning services until it reaches the destination. Each service is independent, uses its own working frequency and its execution can influence whether or not the execution of other services.

The following graph shows how elements of the system behave from the beginning of the movement until it reaches the target. Sensing and position elements alter the intensity of their activity when they are close to an obstacle or target position. Looking at the service of reasoning we can see how it operates only at the beginning of the movement (to start the system) and end (to stop the robot) once it has reached its final position. We can also see how  $\beta$  and  $\mu$  are altered when an obstacle is close or near the target position. These values govern the intensity of the activity centers. This effect is similar to that produced hormones in the human body: excitation and relaxation..

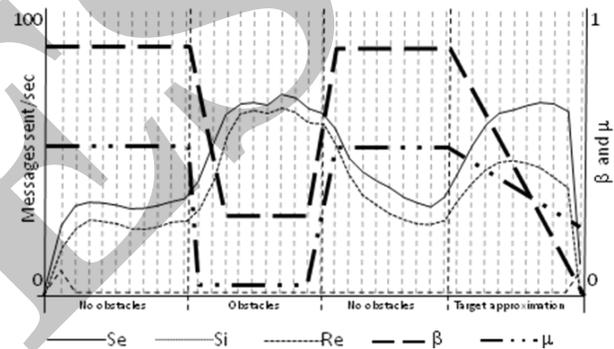


Figure 5. Running B2 in environment with obstacles. Messages transmitted by entities and Se, Si and Re, and variations of  $\beta$  and  $\mu$ .

## VII. CONCLUSIONS AND FUTURE WORKS

This paper has presented a multi-agent system able to capture the main features of the functioning and organization of biological neuroregulatory system. It has also presented an instantiation of the model for autonomous mobile vehicles through implementation using Web services.

The result is a control system that meets the designed behaviors and also allows to reflect characteristics of the human nervous system: hormonal modulation, using influences, flexibility to adapt to new circumstances or to be a decentralized system. The implementation of the control system has used services. This paradigm allows features of distributed applications: decoupling between the entities, composition based on the mission, composition-based devices, the integration of information and different workflows, the ability to locate the functional entities in a distributed way in adequate resources, rapid development and code reuse or low cost.

For these reasons, we stress the appropriateness of the proposal to produce advanced robotic control systems based

on functional elements in the form of services, following the neuroregulatory biological model system. This view connects the advantages of biological engineering and software engineering, blending both worlds. It is the multi-agent system that allows to combine both worlds because it contains sufficient expressive capacity to reflect the properties of one and can be implemented in the other.

Currently our work is aimed at automatic composition of control applications based on the mission. Currently the functions are provided in the form of services, if we can incorporate knowledge about these services by using ontologies and the composition of an application can be made based on expected results, the system could automatically select those most appropriate services for the mission.

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